Structural damage in masonry

Developing diagnostic decision support

Ilse de Vent

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Chapter 1
Introduction

1.1 Research motivation

Damage in buildings is a widespread problem. We all are, every once in a while, confronted with the shortcomings of the premises we occupy or visit. And when one is redecorating one's own house, one can be sure to discover some extra, unexpected defects too. Also on a larger, professional scale, an estimated 50-60 % of today's construction activities consists of renovation works and, hence deals with damage in existing buildings.

Damage indicates a lack of performance, in the broadest sense of the word. Its effects can be merely aesthetic, in the way that discoloured paint on a door can be visually unattractive, but damage may also have functional consequences. Damp walls, poorly fitting windows, leaking roofs or uneven floors can form a serious threat to a healthy and comfortable use of a building.

Structural damage differs from other kinds of damage because it may not only affect aesthetic or functional demands, but may also endanger the physical safety of people. Not surprisingly, its manifestation, typically characterized by cracks, deformations or tilt, is often a reason for more serious concerns, as the newspaper article in Figure 1.1 shows. At worst, it could lead to collapse of a structure: early on Christmas Day 2010, only a few hours after the midnight mass, a church in Diepenbeek, Belgium, came down, presumably under the weight of snow on its roof. Fortunately, there were no casualties. In two other cases, however, similar collapses were fatal: two people lost their lives when the city archive of Cologne, Germany, caved in as a result of settlement in March 2009; the collapse following a gas explosion in an apartment building in Liège, Belgium, in January 2010 killed 14 people and injured another 21.

Keeping this in mind, the observation of symptoms of structural damage raises questions on its consequences and on the possibilities and necessities for intervention. These questions are related to the performance level that a building is expected or required to meet: Is it still safe to use this building? Does the damage hinder the use? Or is the damage only aesthetically unpleasant? The main reason why structural damage is a problem is that, in many cases, it is difficult to answer these questions: there is no consensus on how to assess the severity of the damage, how to repair it or how to prevent its propagation.

To be able to answer these questions and to properly assess the condition of a building, a correct diagnosis of the damage is a prerequisite. A diagnosis gives insight into how the damage has occurred, how severe the present situation is and what is to be expected in the future. Thus, its aim is not only to indicate what has caused the damage, but, moreover, to designate what initiated the damage process and how this process subsequently developed in time.

This understanding of the course of a 'disease' is indispensable, because also in the selection of an adequate repair or intervention method the aspect time plays an important role. In fact, when planning maintenance works, the basic question is: has the underlying damage process stopped and is it sufficient to repair the damage; or is the process still continuing and should that be halted first? If damage is repaired in a way that does not fit or acknowledge its cause, this damage may reappear or even propagate to other areas of the building. A well-known example is the after a repair returning vertical crack in a long wall that lacks appropriate expansion joints. This demonstrates that only with adequate insight into the origin and the development of a defect, it is possible to evaluate which measures could overcome the negative effects of the damage and how further loss of the building's performance could be prevented. Hence, a correct diagnosis is indispensable for a proper assessment of damage.

Not only is the diagnosis the most important phase in the assessment of a building with damage, it is also the most difficult phase. In many cases, it is hard to link the (time of)

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De sluipmoordenaar van de Hugo Molenaarstraat

Paalrot zorgt in Rotterdam voor verzakkende huizen. Gedupeerden worden op kosten gejaagd. „Een feestje durf ik niet meer te geven, uit angst dat de vloer het begeeft."

Door onze redacteur
MARK HOOGSTAD

ROTTERDAM, 30 AUG. Op de bovenverdieping kan hij „bij de buurman een kopje van het aanrecht pakken". Zo groot is inmiddels de scheur in de muur.

Duco Sleeswijk Visser (30) verstaat de kunst van het overdrijven, zo lijkt het. Maar eenmaal op de bovenste verdieping blijkt de bewoner van de Hugo Molenaarstraat in Rotterdam-West niets te veel gezegd te hebben. Hij kan zijn arm letterlijk door de muur steken.

Sleeswijk Visser woont in de kwetsbare zone van Rotterdam: de grotendeels uit veen en klei opgetrokken noordoever van de stad. Een inklinkende bodem en een dalend grondwaterpeil fungeren hier als sluipmoordenaars. Kapotte rioolbuizen bevorderen de waterafvoer, waardoor de funderingspalen nog verder bloot komen te liggen en dus gaan rotten. Gevolg: grootscheepse verzakkingen, vooral van woningen die vóór 1960 zijn gebouwd.

Sleeswijk Visser maakt een wat laconieke indruk, hoewel de paalrot zijn woning ernstig heeft aangetast. „Ik begin zo langzamerhand te wennen aan deze ellende." Twee funderingswerkers hebben zijn woonkamer opengelegd om acuut instortingsgevaar te voorkomen. Een noodmaatregel, legt Sleeswijk Visser uit. „Ik heb geen keuze." Hij overweegt binnenkort in te trekken bij een vriendin, samen met vrouw en kind.

Vrij van zorgen zal Sleeswijk Visser de komende jaren niet zijn, zoveel is zeker. Hij vermoedt dat zijn kosten zullen oplopen tot 60.000 euro. „Mijn probleem is: ik heb maximaal geleend en kan mijn hypotheek dus niet verhogen." Bovendien, zo constateert de werktuigbouwkundige, blijkt niet iedereen in zijn woonblok bereid de funderingsproblemen aan te pakken.

Vandaag krijgt hij bezoek van twee PvdA'ers, Tweede Kamerlid Jan Boelhouwer en het Rotterdamse raadslid Duco Hoogland. Beiden willen zien en horen hoe groot de schade is in dit deel van de deelgemeente Delfshaven. Voorzitter Ad van Wensen van de Belangenvereniging Funderingsproblematiek (BVFP) komt ook poolshoogte nemen. Sinds 1 juli heeft zijn landelijke stichting ook een Rotterdamse dependance. De gemeente schat het aantal gedupeerde huiseigenaren in de stad op maximaal 8.000. Vooral de noordoever (zeven deelgemeenten) is getroffen.

Boelhouwer is bezig met een notitie over paalrot, die hij eind dit jaar de Tweede Kamercommissie hoopt aan te bieden. Opnieuw pleiten voor de oprichting van een landelijk schadefonds funderingsherstel heeft „op dit moment politiek gezien geen zin", zegt hij. Dat voorstel sneuvelde niet voor niets bij de kabinetsformatie. Nederland telt naar schatting 400.000 gedupeerde huizenbezitters, rekent Boelhouwer voor, terwijl het herstel van één woning gemiddeld 60.000 euro kost. En 24 miljard tovert het kabinet niet uit de hoge hoed.

Om slachtoffers toch financieel tegemoet te komen, denkt Boelhouwer aan een laag btw-tarief. Verder pleit hij voor een informatieplicht voor makelaars. „Omdat potentiële kopers niet gewezen worden op funderingsrisico's komen velen later voor onaangename verrassingen te staan." Op aandringen van de BVFP besteedt de Nederlandse Vereniging van Makelaars in de bijscholing van huizenverkopers inmiddels aandacht aan de gewenste funderingsparagraaf in koopcontracten.

Christelle Keizer (31) woont eveneens aan de Hugo Molenaarsstraat en heeft twee bouwkundigen ingeschakeld, voordat zij haar woning, nu ruim twee jaar geleden, besloot te kopen. Beide deskundigen zagen geen noodzaak tot aanvullend funderingsonderzoek. De straat stond destijds bovendien nog niet te boek als risicogebied. „Mijn vader is nota bene architect. Ook hij heeft de woning van binnen en van buiten bekeken. Alles leek te kloppen."

Maar twaalf maanden na de eerste scheur is haar woning veranderd in een bouwval: meerdere scheuren in het trappenhuis en een kromgetrokken achtergevel, waardoor het achterraam niet meer geopend kan worden en het glas op springen staat. „Een feestje durf ik niet meer te geven, uit angst dat de vloer het begeeft." Want „de muren zweven" in haar woonblok, weet Keizer.

Toch zegt ze nog van geluk te mogen spreken. Keizer heeft jarenlang „in de ambtenarij" gewerkt. „Ik ken de wegen, en ik geef niet op. Al heb je er wel een halve baan bij." Haar voorlopige conclusie? „De gemeente zou wat genereuzer mogen zijn, en meer de regie moeten nemen."

Bijvoorbeeld door onwillige woningbezitters „op de een of andere manier" te dwingen om mee te betalen aan het herstel, aldus BVFP-voorzitter Van Wensen. Een woonblok is immers een bouwkundige eenheid, die gelijktijdig hersteld dient te worden. „Gebeurt dat niet, dan openbaren de problemen zich vroeg of laat opnieuw door één zwakke schakel."

Een kromgetrokken achtergevel aan de Hugo Molenaarstraat in Rotterdam-West.

Een scheur in een tussenmuur, waardoor bij de buurman een kopje van het aanrecht kan worden gepakt.

Vastgezette tussenmuur Foto's NRC Handelsblad, Leo van Velzen

Goedkope lening voor gedupeerden in R'dam

De gemeente Rotterdam heeft sinds 1 juli een digitaal loket opengesteld voor huiseigenaren die te maken hebben met paalrot. Daar kan informatie en advies worden ingewonnen. Ook stelt de gemeente begeleiding ter beschikking. Gedupeerden kunnen daarnaast sinds kort een aanvraag indienen voor een lagerentelening om de herstelkosten 'goedkoop' te kunnen financieren. De komende maanden bekijkt de gemeente wie met ingang van 1 januari 2009 daarvoor in aanmerking komt.
Het stadsbestuur heeft verder toegezegd nader onderzoek te zullen doen naar de exacte omvang van de paalrotproblemen in Rotterdam. Sinds 1 januari is de Wet Gemeentelijke Watertaken van kracht: de gemeente heeft de plicht om eventuele problemen met de grondwaterstand in het publieke domein aan te pakken. Voor eigen terrein blijft de eigenaar zelf verantwoordelijk.

Figure 1.1: 'The assassin of the Hugo Molenaarstraat': structural damage is a widespread problem that rouses the emotions of many [2008]. Article reproduced by courtesy of NRC Handelsblad and L. van Velzen.

occurrence of damage to a specific event. But even if there seems to be a clear relation, it can still be very difficult to determine the actual damage process.

Clear illustrations of damage of which the overall cause seems quite obvious, but of which the actual damage process is apparently recognized too late, are those often observed nearby and during the construction of underground car parks in soft Dutch soil. In the past years, several of such construction works have resulted in severe damage to adjacent buildings. Cases in which large cracks and displacements were reported are, among others, the building works at the A-Theater in Middelburg (started in 2003, stopped due to damage in 2005), the Museumpark parking in Rotterdam (start 2005, stop 2006, restart 2007), the Koepoort parking in Delft (start 2006, stop 2006, restart 2007) and the parking next to Panorama Mesdag in The Hague (start 2007, stop 2008).

Another illustrative case is that of the church of Sint Lambertus in Maastricht [de Vent and Hobbelman 2006]. Since its completion in 1916, this church has suffered from a history of settlements and cracking. Over the years, several quite drastic measures were taken, but all turned out to be insufficient to prevent further damage to arise. In December 1985 the church had to be closed for services, because the structural damage made further use of the building irresponsible. New investigations were started, but consensus on the precise cause of the continuing settlements was a long time coming. It took until 2010 before structural repair works were started; it is hoped that the building will reopen its doors in 2012.

Aforementioned cases demonstrate that structural damage is still an often-unsolved problem: it is difficult to diagnose, which hinders adequate repair and effective prevention. Clearly, this means that there is a need for better insight into how structural damage develops. This thesis intends to provide this insight.

1.2 Research objectives

This study aims to facilitate the diagnosis of structural damage, by providing a well-organized overview of how these damages can occur and in what way they can be distinguished visually. It has been triggered by the idea that the symptoms and context of structural damage offer, in principle, sufficient clues to be able to deduce the cause of damage; however, that the interpretation of these signs is not optimal yet.

To reach a sound diagnosis, a surveyor needs to interpret symptoms and context of structural damage to differentiate between damage processes. This, however, is not an easy task. Typically human ways of reasoning can stand in the way and prevent one from noticing alternative options, as will be explained in Chapter 2. We think that some support in interpretation could be helpful; we hypothesize that providing an overview of conditions that are essential and sufficient to reach a diagnosis for structural damage will be beneficial for the field of building pathology.

To allow for the development of a usable overview of conditions, we have chosen to focus this research project and limit it to those structural damages that occur in masonry in the Netherlands. Section 1.3 will elaborate on the choice for this scope.

The main question that is addressed in this research project is, therefore:

- To what extent can structural damage in masonry in the Netherlands be diagnosed from its symptoms and context?

This main question has been divided into the following subquestions:

- What causes lead to structural damage in masonry in the Netherlands?
- What are the symptoms of structural damage in masonry in the Netherlands?
- What context conditions influence the occurrence and the development of structural damage in masonry in the Netherlands?
- In what way can the above-defined symptoms be used to diagnose structural damage in masonry?
- In what way can the above-defined context conditions be used to diagnose structural damage in masonry?
- To what extent can insight into the relations between symptoms, contexts and causes of structural damage in masonry improve its diagnosis?

1.3 Scope

As the above research questions express, this study specifically focuses on the situation in the Netherlands. This has a practical reason: by doing so, intermediary and final results can easily be put to a field test. The implication of this choice is in the accentuation of certain causes of damage.

From the perspective of structural damage, the most important feature of the Netherlands is its geology. As indicated in its name, 'the low countries' are rather flat and dominated by the river deltas of Rhine, Meuse, Scheldt and IJssel. In large parts of the country, the soil consists of river and sea clay, or peat [de Mulder et al. 2003].

Clay grounds and peat are sensitive to settlement. Human actions, such as building activities, tunnelling, interventions in the water management or the withdrawal of gas, regularly lead to lowering of the ground. Hence, soil settlement is characteristic for the Dutch situation, and it is often considered to be the main source of structural damage.

Although settlement appears to be a well-known phenomenon in the Netherlands, constructors often do not know how to deal with it, as can be concluded from the examples we have presented in Section 1.1. This study hopes to improve this situation. Therefore, soil-related damage processes take a prominent place in this thesis.

Another characteristic of the Dutch geology is that it, in contrast to that of countries such as Japan, Turkey or Italy, fortunately lacks large seismic activity. Only moderate earthquakes, with magnitudes M_L up to 6.0 on the Richter scale, sporadically occur in the south-eastern part of the country, while in the northern part minor seismic events ($M_L \leq 3.5$) may sometimes take place, which are induced by gas withdrawal [van Eck et al. 2005; Goutbeek et al. 2008]. For this reason, earthquake damage will only be given a minor role in this thesis. Besides, this process and resulting damage types have already been discussed extensively in the works of Doglioni et al. [1994], Augusti et al. [2001] and Lagomarsino et al. [2004].

Apart from the geographical location, the research questions also indicate that we focus on structural damage in a specific material: masonry. Masonry is the most common construction material in the Netherlands and the majority of the building stock is built with it. It is a composite material, consisting of separate, relatively small units, typically joined with a mortar.

In the Dutch context, masonry generally consists of fired clay bricks. In the Netherlands, natural stone was less frequently used than brick, as the Dutch soil is not rich in natural stone that is both recoverable and suitable for building. Natural stone had to be mainly imported from abroad, usually from Belgium, Germany or France (e.g. from the regions along the rivers Scheldt, Meuse and Rhine). This was expensive, so the use of stone was generally restricted to the construction of prestigious projects, such as churches and other representative buildings.

At the end of the 12th century, northern Europe rediscovered the technique of firing clay bricks, which appears to have been abandoned for some centuries after the decline of the Roman Empire. As from the 13th century bricks became more common, the use of stone was increasingly reduced to elements with structural or decorative importance. In the course of the 19th century, cement increasingly replaced lime in mortars. Also new materials for artificial units were created, such as calcium silicate, concrete and cellular concrete. The introduction of steel or concrete frames reduced the loadbearing function of masonry. Nevertheless, the greater number of Dutch buildings has walls where masonry is used structurally.

Despite its long history of use, and it being regarded as a traditional material, the structural behaviour of masonry is still not fully understood. Its composite nature, which essentially makes it easy to build with, makes it also difficult to calculate. In this respect, research on masonry appears to lag behind that on more contemporary materials such as concrete and steel [Lourenço 1996; van Zijl 2000].

This gap in knowledge especially affects historical masonry constructions, as it puts an extra uncertainty to their assessment. How can one predict the behaviour of such a building, when there is hardly any information on material and geometrical properties available, and the value of each piece of this information for the structural behaviour is not completely clear? With an eye on the preservation of Dutch architectural heritage, the accent of this study is on traditional masonry, which is loadbearing, solid and unreinforced.

Although the problem of structural damage relates to many buildings, this research pays special attention to church buildings. They are used as object of study for the tests and calculations that have been performed during this research. There are three reasons why we made this choice.

One reason to choose for church buildings is related to structural aspects. Church buildings typically incorporate arches, vaults and domes. These structural components are characteristic for masonry construction. Their loadbearing behaviour, especially in complex interactions, is still not easily understood. In combination with the large spans that are also usually to be found in churches, this makes it challenging to study the structural behaviour and defects of this type of building.

Another reason lies in the importance of church buildings in Dutch architectural heritage. According to data from the *Inventarisatie Kerkelijke Gebouwen Nederland* (Inventory of Ecclesiastical Buildings in the Netherlands (IKGN)) [Sonneveld 2006], over 10,000 churches exist today in the Netherlands. Many of them occupy a special position in town centres, in both the literal and figurative sense.

Throughout history, erecting a church has always been a matter of prestige for the community or congregation. With their challenging constructions and large spans, these buildings are not only worth preserving, they are also vulnerable. Considering in particular the current interest in redeveloping sites in city centres, and the tendency to reuse abandoned churches, a growing number of church buildings has to deal with interventions that may affect their loadbearing behaviour. If one wants to preserve this valuable but vulnerable architectural heritage, one needs to keep it in good shape. Insight into its structural condition is highly necessary to be able to fulfil this task.

The topicality of this subject is confirmed by the results of a questionnaire, held at the start of this research project. Circa 350 organizations involved in the maintenance of one or more church buildings were asked what kind of damage they came across in their buildings. Of the 81 respondents, 72 (88 %) indicated that ‘their’ church(es) showed damage. From this group, 79 % (57) reported buildings that had been affected by structural damage, that is: cracks or deformations. Not surprisingly, the majority of all participants endorsed a need for more insight into structural damage within their organization.

But the main reason why we chose to focus on church buildings lies in the fact that church buildings are fairly consistent in their structure. Churches have been built all over

Figure 1.2: Some typical Dutch church buildings: Sint Pancratiuskerk in Godlinze (12th-13th century), Sint Maartenskerk in Zaltbommel (15th century) and Petrus- en Pauluskerk in Everdingen (19th century).

the country, in styles and materials related to the time of their construction and to their location. Some of them date back to the 10th century; others were built only recently. Three typical Dutch church buildings are shown in Figure 1.2.

Despite their differences, all these buildings clearly belong to the same group: they are characterized by a consequent use and configuration of structural elements, such as the arches, vaults and domes mentioned before. This fact will allow us to determine average characteristics for Dutch church buildings. Using these representative characteristics in tests and calculations will yield results that can be extrapolated to the group as a whole. Hence, our choice for church buildings has a methodological advantage for our research.

This research project aims to provide more insight into how the appearance of a structural damage relates to its cause. To add practical value, this insight should take the shape of a guideline, or a series of simple tests, that supports users in the interpretation of symptoms and context conditions. It should address a wide range of masonry structures. Specific attention will be paid to historical buildings, while churches will serve as an inspiration. Although the accent of this study is on the Dutch situation, its result should, as much as possible, allow for profitable use in other countries as well.

With that, the societal relevance of this study is quite obvious: its practical result is intended to lead to a more effective and more efficient way of diagnosing structural damage in masonry. More specifically, we look for a solution that can fulfil three demands. First of all, the desired result should improve the quality of diagnosis. Furthermore, it should help improve the communication between the different parties involved in a restoration project. Finally, it should also support the education of novice surveyors, and in this way help in transferring the knowledge contained in the field of building pathology to a new generation.

The target groups we have in mind for our tool are parties professionally involved in the maintenance of (historical) masonry buildings. A key role is reserved for the *Monumentenwacht* (Monument Watch). This Dutch organization, established in 1973, aims to prevent the deterioration of historical buildings by advising owners on how to keep their property in good condition [Monumentenwacht Nederland 2009]. It offers regular, detailed inspections of the premises, minor repair works executed on the spot and a priority list of required maintenance.

By doing so, Monument Watch inspectors can play a similar role in heritage maintenance as general practitioners do in the Dutch health care system: in the Netherlands, the general practitioner (in Dutch: *huisarts*) functions as a gatekeeper between primary and secondary care, controlling the access to specialist care. Monument Watch inspectors can only fulfil this important task adequately, if they are able to call in the right expert at the right time. In other words, they need to be well aware of the implications that different manifestations of damage have. The tool that will be developed in this thesis should especially be of help for these maintenance professionals, by supporting them in deciding whether or not a structural engineer needs to be called in.

For structural engineers or researchers in the field, some of the results of this research will be common knowledge. Yet, also to them the overview may be of service. Many of these engineers will have specialized in certain types of damage in the course of time. Due to this, they are probably less confronted with causes outside their specialization. Our tool could, then, work as a prompt, reminding them of alternative, perhaps rare, causes of damage.

Finally, for students our product should constitute a first step towards expertise. In being concise, it should give them the opportunity to acquire an overall picture of the rather complex discipline of building pathology. More in general, we hope that it will invite everyone to keep an open mind when looking at structural damage.

The scientific relevance of this research project will lie in structuring the implicit, experience-based and individual 'wisdom' of experts and translating it into explicit knowledge that is available to a broader group of users. With this knowledge, it will be possible to extend the systematic approach as currently proposed for diagnosing specific damages as related to moisture, salt and frost [van Hees et al. 2009; van Hees and Naldini 1995] (see further Section 2.2.2) to the wider field of structural damages in masonry.

Part of the originality of our study lies in its multidisciplinarity, combining the more theoretical field of mechanics with the more practice-oriented field of restoration. In the mean time, it also crosses borders with the field of diagnostics in medicine, which is ahead of the building diagnostics discipline. In fact, by gaining more explicit knowledge, building pathology can keep up with current developments in health care, where emphasis more and more shifts from experience-based towards evidence-based practice.

1.4 Thesis outline

The body of this thesis consists of three parts (see Figure 1.3). After this introductory chapter, Part I starts with a setting of the scene. In Chapter 2, more background information is given on damage and its diagnosis, and on current problems in this field. Next, Chapter 3 describes the methods applied in this research to find an answer to the question: to what extent can structural damage in masonry in the Netherlands be diagnosed from its symptoms and context?

Part II generates an overview of the three components that are essential for diagnosing structural damage. It starts with Chapter 4, where a summary is given of typical causes of structural damage that affect masonry buildings in the Netherlands. Subsequently, Chapter 5 describes the symptoms to which these causes can lead, while Chapter 6 deals with the context of the damage.

Having described the three components separately, in Part III the research data on these components are turned into an operative diagnostic tool. First of all, Chapter 7 examines the relations between symptoms, causes and context conditions by using numerical and small-scale physical tests. Next, Chapter 8 uses this information to construct a diagnostic tool for structural damage in masonry. In Chapter 9, this tool is tested in practice by three groups of potential users.

Finally, in Chapter 10 the answers to the research questions can be found, together with the implications and recommendations that have followed from this research.

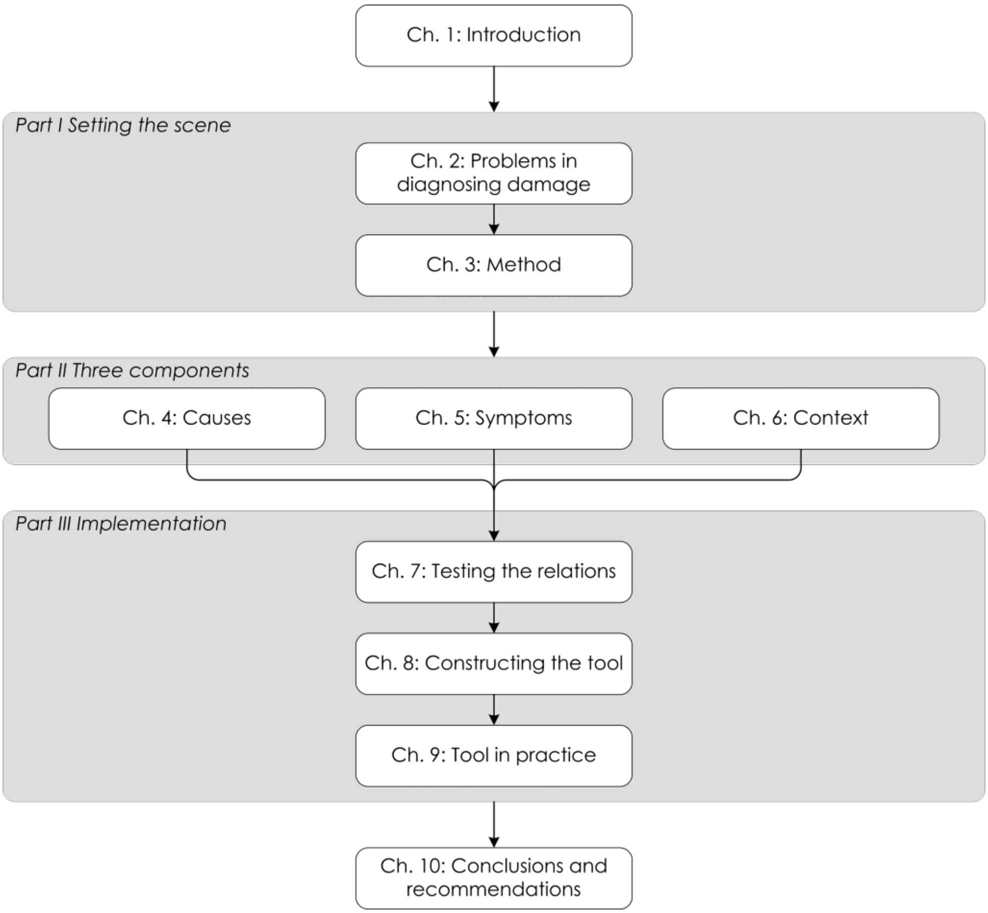


Figure 1.3: Outline of the thesis.

Part I
Setting the scene

As presented in Chapter 1, the objective of this research is to improve the diagnosis of structural damage in masonry. Before going deeper into how this improvement is realized, Part I of this thesis first gives background information on diagnosing damage and on the approach used in this research.

To better understand the problem that is addressed in this thesis, Chapter 2 explains what damage is, how it is assessed and what the drawbacks of the current approach are. Subsequently, Chapter 3 outlines the method that is applied in this research project and the criteria on which it is based.

Chapter 2
Problems in diagnosing damage

As has been stated in the Introduction (Chapter 1), this research aims to improve the diagnosis of structural damage in masonry. Before discussing how this improvement is realized, a sound understanding of damage and its diagnosis is essential. The present chapter supplies this background information.

To better understand how important, but at the same time how difficult it is to establish a diagnosis, Section 2.1 will first of all explain what damage is, in what ways it can be categorized and how structural damage is defined in this thesis. Subsequently, in Section 2.2, a brief overview is given of the process of assessing damage and the place diagnosing has within this process. Also, current ways to improve diagnosis are indicated.

This review of the state of the art in improving the diagnosis of damage will show that, so far, little attention has been paid to improve the first steps in the diagnostic process. Yet, we think that much profit could be gained by enhancing exactly this phase in which hypotheses are generated and classified. Section 2.3 discusses the results of a questionnaire, which has helped us to identify the bottlenecks in the current approach to hypothesizing. On this basis, the aims of our research have been further specified. In this way, the conclusions of Chapter 2 will be the starting point for the criteria and approach of this research, as described in Chapter 3.

2.1 Ways of looking at damage

2.1.1 What is damage?

Damage can be defined as the manifestation of a lack of performance. At least for buildings, this concept of damage is closely related to the demands people pose on their performance. Some are formal and mainly technical, concerning safety, health and usefulness. For the Netherlands, such legal requirements are contained in the *Bouwbesluit* (Building Decree) [VROM 2001], which all structures must comply with. However, there are also more subjective demands, such as aesthetic ones on the appearance of a building. What these requirements have in common is that they all demand that, under more or less well-defined circumstances, a building performs in a predetermined manner or within certain limits from that.

Continuing along this line, one can state that a building has a defect when it can not, or no longer, meet the demands it should implicitly or explicitly satisfy. This defect is shown to us as damage. Hence, damage is the (perceptible) manifestation of a defect.

It is important to note that damage is, at least partly, a subjective concept. It is based on a comparison between the limits within which a building is required to perform and how this building actually performs. As some of the requirements are subjective, these limits are not always explicitly formulated, leaving room for differences in interpretation. Consequently, an evaluation of the level of performance can be open to dispute.

This already shows us one aspect that can hinder the diagnosis of damage: its observation and appraisal may depend on the observer. In many cases, the observer is the one who decides on the level of performance, and he is the one who decides whether he finds deviations from this level acceptable or not. This is not necessarily an objective qualification.

2.1.2 Categorizing damage

When damage is observed, this raises questions on what its consequences could be and if it is necessary to intervene. To allow for an easier communication on this subject and for a better comparison to other damages, the observer needs to designate the damage. This description can point out various features of the damage, such as its location or its extent.

A common way of designating damage is by characterizing its severity. The severity of a damage is defined by the current loss of performance and the risk on a future loss of performance involved with the defect. This risk, in turn, is the product of probability and impact. In other words, a risk is the chance that a negative event will happen, times the seriousness of the consequences that this negative event would have.

For settlement-related defects, the severity of visible damage in walls is commonly classified with a six-point system. This system is based on the damage level, expressed in terms of ease of repair and typical crack width. It was first proposed by Burland et al. [1977] and has only been slightly modified since then. A recent version can be found in the work of Kastner et al. [2003], in which the six degrees of damage are defined as follows:

- Degree 0: Negligible. Hairline cracks less than about 0.1 mm.
- Degree 1: Very slight. Fine cracks which are easily treated during normal decorating. Damage generally restricted to internal wall finishes. Close inspection may reveal some cracks in external brickwork or masonry. Typical crack widths up to 1 mm.
- Degree 2: Slight. Cracks easily filled. Redecoration probably required. Recurrent cracks can be masked by suitable linings. Cracks may be visible externally and some repointing may be required to ensure weathertightness. Doors and windows may stick slightly. Typical crack widths up to 5 mm.
- Degree 3: Moderate. The cracks require some opening up and can be patched by a mason. Repointing of external brickwork and possibly a small amount of brickwork to be replaced. Doors and windows sticking. Service pipes may fracture. Weathertightness often impaired. Typical crack widths are 5 to 15 mm or there are several greater than 3 mm.
- Degree 4: Severe. Extensive repair work involving breaking-out and replacing sections of walls, especially doors and windows. Windows and door-frames distorted, floor sloping noticeably. Walls leaning or bulging noticeably, some loss of bearing in

beams. Service pipes disrupted. Typical crack widths are 15 to 25 mm, but also depend on the number of cracks.

- Degree 5: Very severe. This requires a major repair job involving partial or complete rebuilding. Beams lose bearing, walls lean badly and require shoring. Windows broken with distortion. Danger of instability. Typical crack widths are greater than 25 mm, but depend on the number of cracks.

The six-point classification system classifies damage on the basis of its severity. Although above damage level descriptions are to-the-point and understandable for non-engineers, these classifications are not unambiguous in their use. For instance, the system puts strong emphasis on crack width, while in many cases the sum of all crack widths is more relevant than the typical width of each individual crack. In fact, when creep processes are involved, a large number of relatively thin cracks can appear that can still result in situations with severe danger of collapse. Also, the location where the cracks have occurred has been left out of consideration.

Another point is that this classification system requires insight into the consequences that a damage can have, and into the costs that are involved with its repair. This implies that a diagnosis of the cause of damage is presupposed. As a consequence, this system is pre-eminently suitable for recording and comparing damages that have arisen after a specific event. For example, a similar classification system, included in the European Macroseismic Scale 1998 (EMS-98), is commonly used to evaluate earthquake damage [Grünthal 1998]. Nevertheless, this approach is not suitable for use in this project, where establishing a diagnosis is the ultimate objective, instead of the starting point.

Handbooks on diagnosing damage in buildings categorize damage with the aim to make their content accessible and easy to retrieve. Table 2.1 presents the main and subcategorizations that are used in a sample of 20 of these handbooks. It is apparent from this table that in most cases these categorizations are either based on the location of the damage, in terms of materials or building elements, or based on the cause of damage. The advantages and disadvantages of each approach are discussed in the following paragraphs.

A categorization based on the material in which a damage has occurred makes it possible to emphasize the differences in behaviour between various materials and makes clear what the typical vulnerabilities of each material are. Table 2.2 shows how materials are most frequently grouped. As one can see, most handbooks agree on what they consider to be the four main groups of building materials: masonry, concrete, timber and metals.

Likewise, the handbooks are in an almost entire agreement as to what the most important building elements are, see Table 2.3. Nearly all handbooks that use elements as the main category to organize damage types divide a building into the components: foundations, floors, walls, doors and windows, roofs and services. Less attention is paid to damage in finishes. This is probably due to the fact that, for most types of finishes, the expected lifespan is relatively short. Except for wall paintings and the like, they are renewed quite regularly. This implies that damage in finishes is regarded as less unusual, and its consequences as less serious, than in other elements.

As materials and elements are easy to recognize, these ways of categorizing damage allow for using a handbook as a practical reference during a survey. Nevertheless, in both cases a strict conformation to the organizing system can make it difficult to create an overall picture, especially for those damages for which both the geometry or the function of the element, and its materialization play a role in the damage process. Therefore, out of the ten handbooks that use the location of the damage as main category, in five the materials are used as subcategories to further subdivide the main category of a building element, and in one handbook it is the other way around (see Table 2.1).

The third popular way of categorizing damages is based on their causes. Nine out of the twenty surveyed handbooks use this type of categorization. Table 2.4 lists the main categories of causes as defined in these handbooks.

When comparing the Tables 2.2, 2.3 and 2.4, the most striking difference is that Table 2.4 shows a much larger variety of categories. It is clear that the authors only little agree on how causes should be grouped. Apparently, each of them has his own view on which damage processes are similar and should be discussed together.

Table 2.1: Overview of main categories and subcategories used in handbooks to order damage types

	Categorisation on:											
	Location of damage						**Cause of damage**			**Appearance of damage**		
Reference	**Material**			**Element**								
Addleson 1992		sub		■			■				sub	
Beckmann 1995	■				sub	□		sub		·		
Croci 1998, Croci 2001	·			·			■			·		
Douglas and Ransom 2007		sub		■	sub			sub		·		
Eldridge 1976		sub	□	■					□		sub	□
Feilden 1994	·			·			■			·		
Harris 2001	·			■	sub			sub		·		
Hinks and Cook 1997	■	sub		■				sub			sub	
Loughran 2007	⋇			·			■					□
Maier 2002	⋇			·			■			·		
Marshall et al. 1998		sub	□	■				sub	□	·		
Mastrodicasa 1993	·			■				sub		·		
Pfefferkorn 1994	⋇			·			■			·		
Richardson 1991			□			□	■			·		
Stichting Bouwresearch 1966	·			·			·			■		
Stichting Bouwresearch 1976	⋇			·			·			■		
van Stigt 1995	·			■				sub		·		
Warren 1999	⋇			·			■			·		
Watt 2007	·			·			■			·		
Weaver 1997	■	sub				□		sub		·		

■ = used for main categories; sub = used for subcategories; · = not used for main or subcategories; □ = used as separate category in addition to main categories; ⋇ = not applicable: Handbook concentrates on a specific material

Table 2.2: Overview of materials used in handbooks as main category to order damage types

Reference	Brick and stone masonry	Timber	Iron, steel, metals	(Reinforced) concrete, mortar, plaster	Paints, coatings	Glass	Resins, polymers, plastics, sealants	(Wall) paper
Addleson 1992	·	·	·	·	·	·	·	·
Beckmann 1995	■	■	■	■	·	·	·	·
Croci 1998, Croci 2001	·	·	·	·	·	·	·	·
Douglas and Ransom 2007	·	·	·	·	·	·	·	·
Eldridge 1976	·	■	■	·	·	·	■	·
Feilden 1994	·	·	·	·	·	·	·	·
Harris 2001	·	·	·	·	·	·	·	·
Hinks and Cook 1997	■	■	■	■	·	·	·	·
Loughran 2007	⋇	·	·	⋇	·	·	·	·
Maier 2002	⋇	·	·	·	·	·	·	·
Marshall et al. 1998	□	·	·	·	·	·	·	·
Mastrodicasa 1993	·	·	·	·	·	·	·	·
Pfefferkorn 1994	⋇	·	·	·	·	·	·	·
Richardson 1991	□	□	·	□	□	·	·	·
Stichting Bouwresearch 1966	·	·	·	·	·	·	·	·
Stichting Bouwresearch 1976	⋇	·	·	·	·	·	·	·
van Stigt 1995	·	·	·	·	·	·	·	·
Warren 1999	⋇	·	·	·	·	·	·	·
Watt 2007	·	·	·	·	·	·	·	·
Weaver 1997	■	■	■	■	■	■	■	■

■ = used for main categories; · = not used for main categories; □ = used as separate category in addition to main categories; ⋇ = handbook concentrates on this specific material

Table 2.3: Overview of elements used in handbooks as main category to order damage types

Reference	Foundations	(Upper) loadbearing structure	Floors, ceilings	Walls, façades	Claddings, wall finishes	Doors, windows	Roofs	Services
Addleson 1992	■	·	■	■	■	■	■	·
Beckmann 1995	□	·	·	·	·	·	·	·
Croci 1998, Croci 2001	·	·	·	·	·	·	·	·
Douglas and Ransom 2007	■	·	■	■	■	■	■	■
Eldridge 1976	·	·	■	■	■	■	■	■
Feilden 1994	·	·	·	·	·	·	·	·
Harris 2001	■	■	·	■	·	■	■	■
Hinks and Cook 1997	■	·	■	■	■	■	■	·
Loughran 2007	·	·	·	·	·	·	·	·
Maier 2002	·	·	·	·	·	·	·	·
Marshall et al. 1998	■	·	■	■	■	·	■	■
Mastrodicasa 1993	■	·	·	■	·	·	·	·
Pfefferkorn 1994	·	·	·	·	·	·	·	·
Richardson 1991	□	·	□	□	·	□	□	·
Stichting Bouwresearch 1966	·	·	·	·	·	·	·	·
Stichting Bouwresearch 1976	·	·	·	·	·	·	·	·
van Stigt 1995	■	■	·	■	·	■	■	■
Warren 1999	·	·	·	·	·	·	·	·
Watt 2007	·	·	·	·	·	·	·	·
Weaver 1997	□	·	·	·	·	·	·	·

■ = used for main categories; · = not used for main categories; □ = used as separate category in addition to main categories

Table 2.4: Overview of causes used in handbooks as main category to order damage types

Reference	Gravity	External causes	External loading causing deformations	Internal causes	Mechanical actions	Structural problems	Impact	Movement	Settlement, subsidence	Inflection of floors	Residual stresses	Atmospheric and climatic action	Chemical / physical actions	Destructive processes in brickwork	Changes in length	Thermal stresses	Thermal hysteresis	Shrinkage	Loss of adhesion	Dampness, humidity, moisture	Condensation	Leakage, rain penetration	Frost	Salts	Corrosion	Timber pests, timber decay	Biological actions	Biodeterioration	Natural and man-made pollution	Man-made causes	Noise-related problems	Combustion-related problems	Plumbing-related problems	Fire
Addleson 1992	·	·	·	·	·	·	·	■	·	·	·	·	·	·	·	·	·	·	■	■	■	■	·	·	■	■	·	·	·	·	·	·	·	·
Beckmann 1995	·	·	·	·	·	⋇	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Croci 1998, Croci 2001	·	·	·	·	■	⋇	·	·	·	·	·	·	■	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Douglas and Ransom 2007	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Eldridge 1976	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	□	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Feilden 1994	■	■	·	■	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	■	·	·	·	·
Harris 2001	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Hinks and Cook 1997	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Loughran 2007	·	·	·	·	·	■	■	·	·	·	·	·	·	·	·	·	■	·	·	·	·	■	■	·	■	·	·	·	·	·	·	·	·	·
Maier 2002	·	·	■	·	·	·	·	·	■	·	·	·	·	·	·	■	·	■	·	■	·	·	■	■	·	·	·	·	·	·	·	·	·	·
Marshall et al. 1998	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	□	□	·	·	·	·	□	·	·	·	·	·	·	·	·
Mastrodicasa 1993	·	·	·	·	·	⋇	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Pfefferkorn 1994	·	·	·	·	·	·	·	·	■	■	■	·	·	·	■	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Richardson 1991	·	·	■	·	·	■	·	·	·	·	·	·	·	·	·	■	·	·	·	■	·	·	·	·	·	·	·	·	·	·	■	■	■	·
Stichting Bouwresearch 1966	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Stichting Bouwresearch 1976	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
van Stigt 1995	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Warren 1999	·	·	·	·	·	■	·	·	·	·	·	·	·	■	·	·	·	·	·	·	·	·	·	·	·	·	·	■	■	·	·	·	·	·
Watt 2007	·	·	·	·	·	·	·	·	■	·	·	■	·	·	·	·	·	·	·	■	·	·	·	·	·	·	■	·	·	■	·	·	·	■
Weaver 1997	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·

■ = used for main categories; · = not used for main categories; □ = used as separate category in addition to main categories; ⋇ = handbook concentrates on structural damage

Not only do the different groups of causes from different handbooks overlap, also within some of the handbooks the grouping is inconsistent. Typical is, furthermore, that the causes are not labelled very precisely. For example, in three books the concept of 'structural problems' is discussed as a category separate from 'external loading causing deformations', 'impact' and 'thermal stresses'. Hence, the concept of structural damage is used by many people, but they do not all seem to use the same definition of this concept. In the next section, we will come back to this problem and propose a definition of structural damage that is suitable for this research project.

Despite the above-mentioned drawbacks, the cause-based approach has also advantages. Compared with the categorization based on location of damage, a categorization based on cause gives a better overview of the origins of damage. It shows the different damage processes that are possible and makes it easier to see similarities in the occurrence of damages, regardless of the location where they occur. Yet, it is less suitable for quick referencing at the moment that damage is observed, as it implies that the cause of damage is already known or, at least, presumed. Thus, if one would intend to rely completely on this type of handbook to establish a diagnosis, one would need to read the whole book from beginning to end.

Finally, a few handbooks use a fourth way of categorizing: on the appearance of the damage. Here, a correct and precise definition of the categories of appearances is even more important than it was for the causes. The visible characteristics must be identified and described in such a way that each definition is clear to the reader and unambiguous in respect to other damages.

That defining appearances of damages is difficult becomes clear from Table 2.5. Each book uses its own labels and there is not one label that is used in more than one book. Besides, the descriptions tend to be long and they often include remarks on the location of the damage. Implicitly, each damage pattern (i.e. each characteristic combination of clearly related symptoms and context conditions) is linked to a specific cause and a specific location. While the handbooks list only the most regularly observed damage patterns, they provide little insight into whether slightly different patterns could be explained by the same damage processes. Still, with sound definitions this type of categorization can support the line of reasoning followed during diagnosing, which allows for a handbook to be easy to use in practice.

2.1.3 Structural and non-structural damage

Damages in buildings are often divided into two types: structural damages and non-structural damages (the latter sometimes also being labelled as material decay or deterioration). Although this seems to be a logical distinction, in practice both terms appear to be used and interpreted in quite different ways. Various definitions circulate, which seem to originate from different perspectives.

Table 2.5: Overview of types of appearance used in handbooks as main category to order damage types

Reference	Cracks in walls	Defects in appearance	Efflorescence	Surface defects	Discoloration	Cracks in parapets near or between wall openings	Cracks at discontinued expansion joints	Vertical cracks at corners or end of cavity wall	Cracks in unclad concrete beams	Cracks near supports of lintel above wall opening	Vertical cracks at connection of internal walls, or of internal wall and façade	Vertical crack between two leaves of a wall	Horizontal cracks in inner leaves of cavity wall	Diagonal cracks in loadbearing walls	Horizontal or vertical cracks in loadbearing walls	Vertical cracks in walls near chimneys	Cracks due to shrinkage at interruptions of infill walls	Vertical cracks due to shrinkage of infill walls	Cracks in concrete and modular floors	Horizontal cracks at connection of walls and roof slab	Cracks at discontinuities in plan	Cracks in chimneys	Horizontal cracks in end walls	Vertical cracks near corners	Vertical cracks near loggias	Vertical cracks near wall openings without framework	Diagonal crack above and/or below support of lintel	Horizontal crack just below roof	Cracks in internal walls of communal stairwells	Horizontal cracks above and below parapets	Vertical and horizontal cracks in pier at height of first floor parapets
Addleson 1992	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Beckmann 1995	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Croci 1998, Croci 2001	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Douglas and Ransom 2007	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Eldridge 1976	□	□	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Feilden 1994	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Harris 2001	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Hinks and Cook 1997	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Loughran 2007	·	·	□	□	□	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Maier 2002	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Marshall et al. 1998	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Mastrodicasa 1993	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Pfefferkorn 1994	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Richardson 1991	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Stichting Bouwresearch 1966	·	·	·	·	·	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	·	·	·	·	·	·	·	·
Stichting Bouwresearch 1976	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	■	■	■	■	■	■	■	■
van Stigt 1995	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Warren 1999	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Watt 2007	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Weaver 1997	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·

■ = used for main categories; · = not used for main categories; □ = used as separate category in addition to main categories

As was the case with the term 'damage, the definition of structural damage can be based either on its location or on its cause. The classification of damages proposed in the European Macroseismic Scale 1998 (EMS-98) [Grünthal 1998] uses location to distinguish between structural and non-structural damages. In its five-point damage classification, each grade is characterized by the severity of both structural and non-structural damage. Grade 2, for example, which is labelled as moderate damage, is specified as slight structural damage and/or moderate non-structural damage. For the EMS-98, structural damage refers to "damage to the primary (loadbearing, structural) system". Similarly, non-structural damage is defined as "damage to secondary (non-structural) elements (like infills or curtain walls)." A further explanation on which components should be regarded as primary or secondary elements is not supplied.

Labelling all damages that occur in a loadbearing element as being structural may work for the EMS-98, because it exclusively focuses on damages caused by earthquakes. However, when looking at a wider range of damages, it would imply that graffiti on a loadbearing wall should be regarded as structural damage. This interpretation contrasts with the common usage of the term structural damage. Hence, the EMS-98 definitions are not generally accepted in, for example, conservation practice.

In the field of building conservation, the term structural damage is commonly interpreted in relation to the cause of damage. The definition proposed in the Recommendations of the International Scientific Committee for Analysis and Restoration of Structures of Architectural Heritage (ISCARSAH) of the International Council on Monuments and Sites (ICOMOS) [2003] is a good illustration of this approach. It defines structural damage as the change and worsening of structural behaviour that is produced by mechanical actions, a reduction of strength or both. According to ICOMOS ISCARSAH, structural damage occurs when the stresses produced by one or more actions exceed the strength of a material, either because the actions themselves have increased or because strength has been reduced. Similarly, material decay is defined as the change and worsening of material characteristics, produced by chemical, physical or biological actions. Its main consequences are described as deterioration of surfaces, loss of material and reduction of strength.

Although the definitions of ICOMOS ISCARSAH seem clear enough, in practice it can be hard to apply them strictly. Most of the ambiguity is due to the fact that in these definitions the concepts of structural and non-structural damage are closely linked: the reduction of strength, which is one of the causes of structural damage, can be one of the consequences of material decay. Hence, non-structural damage can be a cause of structural damage. This might lead to confusion: Is rot in timber, because it is caused by biological action, a form of decay? Or should it be regarded as a structural damage, since the structural behaviour is affected? Following the definition, timber rot in itself is a decay phenomenon, but failure due to this rot is a structural damage. However, in practice this distinction is hardly adhered to.

Another remark that should be made is that, by defining a type of damage by its type of cause, a damage can only be identified correctly after its cause has been established. In other words, with the above definition damage can only be labelled as structural after it has been diagnosed. However, in the context of this thesis, we need a definition of structural damage that is applicable from the outset of the diagnostic process. The description of damage ought to be independent from the presumed cause and, preferably, also from its location. The definitions of the EMS-98 and of ICOMOS ISCARSAH are insufficient and not suitable here. Therefore, a complementary definition of structural damage is proposed.

In this thesis, structural damage is defined on the basis of required performance of a structure. A structure should meet three demands, as is illustrated in Figure 2.1:

- It must be sufficiently strong;
- It must be sufficiently stiff; and
- It must be sufficiently stable.

Together, these three qualities compose the loadbearing capacity of a building. If a structure can not, or no longer, fulfil these requirements, it has a structural defect. In line with the three demands, structural defects concern a lack of strength, a lack of stiffness or a lack of stability. These structural defects manifest themselves in three ways:

- Crack development, which results from a lack of strength;
- Deformation, which is the manifestation of a lack of stiffness; and
- Tilt, the turning over of a volume as a whole, which points to a lack of (external) stability.

These three main characteristics, or symptoms, of structural damage are shown in Figure 2.2.

Throughout this thesis the term structural damage will be used to refer to all damage that appears to manifest a lack of strength, stiffness or stability, by showing crack development, deformation or tilt.

This definition of structural damage is independent of the location of the damage and of its origin. Therefore, it can be used without any reserve in the pre-diagnostic phase. Furthermore, it acknowledges the perception of damage, by relating its appearance to the expectations people have of structures. All damages with above symptoms will be taken into account, even though they might turn out not to have structural consequences.

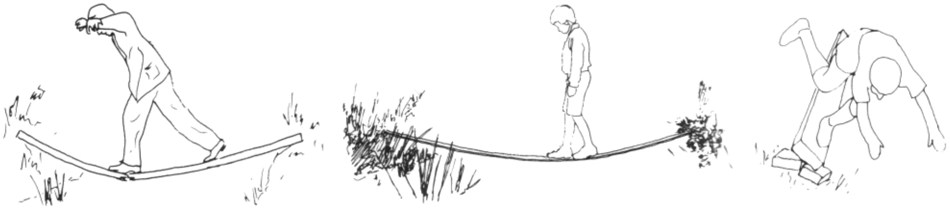


Figure 2.1: Lack of strength, lack of stiffness and lack of stability. Illustrations taken from Beranek [1997].

2.2 The diagnosis of damage

2.2.1 Assessing damage

Since damage is the manifestation of a lack of performance, the observation of damage raises questions on its consequences and on the possibilities and necessities for repair. Damage is often aesthetically unacceptable. However, defects can also have more serious consequences: damage can harm the use of a building or the health of its users. It may even endanger the users' safety if the loadbearing capacity of a structure is reduced.

Assessing damage means evaluating how severe the present loss of performance of a building is, and estimating what loss of performance could be expected in the near future. An analysis of what level of performance is required should be part of this. If an intervention is needed, the evaluation should also pay attention to the selection of a method for improvement or repair.

The assessment of damage in buildings has an approach that is comparable to the one doctors use in health care. There, the approach consists of three steps: the anamnesis, in which the patient's complaints and his medical history are investigated; the diagnosis, in which the doctor tries to determine the cause of the complaints; and the therapy, which focuses on the selection of a remedy. For buildings, the three steps that constitute the assessment are:

- Surveying damage and building;
- Establishing a diagnosis; and
- Selecting a treatment or intervention.

Similar to the medical discipline of pathology, the discipline concerning the systematic investigation of building defects, their causes, their consequences and their remedies is called building pathology [CIB Working Commission W86 - Building Pathology 1993].

Figure 2.2: The main symptoms of structural damage: crack development, deformation and tilt.

Surveying damage and building

The first step in the assessment of damage is the survey. Its aim is to collect as much relevant information as possible both on the damage itself and on its context. As regards the damage, the survey is meant to identify characteristics related to appearance, extent and severity, such as:

- The type of damage: crack, deformation and/or tilt;
- The features of the damage: direction, width, variations in direction and width;
- The level of damage, the extent of degradation;
- The amount of damage, the extent of the affected area; and
- The development of the damage in time.

Apart from this, the surveyor should also pay attention to the context of the damage. This is much wider: it includes the location of the damage in the building and the characteristics of this building and its surroundings:

- The materials used in the building, the materials that are affected;
- The geometry of the building, the construction type, the parts of the building that are affected, the presence or absence of damage in adjacent parts of the building;
- The environment of the building, the site and soil conditions, climate, seismicity, the presence or absence of damage in adjacent buildings; and
- The factor time: the history of the building and its site: changes in its use, in its form, in its construction, earlier repair works, catastrophic events such as floods or fires.

A survey usually starts with a visual inspection of the building. With some standard tools (e.g. tape measure, spirit level, plumb line, crack width gauge; see also Appendix A), it is relatively simple to obtain a first impression of the condition of a building. This in-situ information can be supplemented with archive documentation, for example on the building's history, the site's use and earlier alterations, extensions or repair works. More extensive on-site investigations may be necessary to determine and quantify geometrical or material properties. For monuments, such tests should preferably be performed using non-destructive techniques, to limit the impact on valuable fabric.

The information on the symptoms and context of the damage as collected during the survey serves as evidence in the process of establishing a diagnosis. It is, therefore, necessary to take account of all uncertainties in these data.

Establishing a diagnosis

The diagnosis is essential within the discipline of building pathology and it has its roots in medicine as well. Diagnosing can be defined as the deductive process of distinguishing among diseases (defects, damages) by their signs and symptoms [Douglas and Ransom 2007]. Its aim is not only to indicate what has caused a damage, but, moreover, to try and understand what initiated the damage process and how this process has developed in time. In medicine, this understanding of the course of a disease is indispensable for finding ways to treat symptoms, to cure a patient of his illness and, if possible, to prevent a disease from affecting other people as well.

In theory, the diagnostic process consists of three steps [Grundmeijer et al. 2004]. The first step is to generate hypotheses by listing all causes that could possibly have led to the damage under investigation. Then, the next step is to classify these hypotheses, taking into account both their probability and the risks involved with them. Finally, to reach a correct diagnosis, one by one the hypotheses are verified or falsified and excluded. This testing of hypotheses can be done in sequence of urgency (i.e. risk) or in sequence of likelihood.

In each of the diagnosing steps, thorough insight is needed into all processes that could lead to damage. Based on the data obtained in the survey, the investigator must search for a correlation between the available data on the specific case and his knowledge on damage processes. This can, for instance, be done with help of (mathematical) models. Both the presence and absence of a correlation is relevant and can lead to one or more hypotheses on the cause of damage.

There are several approaches that can be used for diagnosing, including pattern recognition, the use of decision trees and data mining [Grundmeijer et al. 2004]. Pattern recognition can accelerate the process of generating hypotheses, but its success largely depends on the experience of the surveyor. It is less suitable for more complex cases. Another option is the use of explicit algorithms, decision trees or decision tables, which may be based on guidelines. However, as these decision aids can grow large when the number of rules increases, this approach, too, only functions for unambiguous damages with a limited number of hypotheses. Data mining, then, means the use of extensive testing and data gathering, in the hope that a diagnosis will 'pop up'. In Dutch, this method is the called *ongerichte sleepnetmethode*. It is a very time- and money-consuming approach. As a result, it is only used in cases where it turns out to be impossible to formulate any strong hypothesis.

Selecting a treatment or intervention

The selection of a treatment is the last step in the assessment of a damage. To prevent the consequences of a defect, remedial works may be necessary. These interventions intend to bring a building back, or up, to a performance level that does meet the requirements, which were infringed by the damage.

There are several points that need attention when selecting an intervention. First of all, one ought to take into account the effects a damage has had on the condition of a building. What is the current level of performance? Which requirements are met, and which not? And what is the risk on further loss of performance if no measures were to be taken?

Furthermore, one should specify the desired or required result of an intervention. How should the building perform after repair?

Then, one needs to carefully consider the appropriateness of each proposed treatment. The repair work has to be compatible with the building. Both its positive and its negative effects ought to be evaluated as, for example, strengthening of a wall can increase its loadbearing capacity, but it can also impair its cultural and historical values. In addition, the durability of the intervention demands appraisal. Here, too, insight into the development of defect and damage in time is needed. One should investigate whether the situation has stabilized or not: is the damage a result of an ongoing (continuous or cyclic) process, or of a single event? In the case of progressing damage, the best way to prevent new damage is to remove its cause, rather than treat its symptoms. However, one should bear in mind that damage is, more often than not, a result of a combination of processes, which the intervention might need to address separately.

Finally, also the costs involved with each treatment need attention. One should consider whether it is possible to execute an intervention within the available budget. Even more important, the following question must be answered: do the benefits of the intervention balance its price?

These considerations clearly demonstrate that the selection of a treatment must always be based on a thorough analysis of the problem that it is supposed to address. A correct diagnosis of the process causing damage and an evaluation of the effects of the intervention on this process are essential. The diagnosis should be accurate enough to allow for weighing different types of interventions; however, narrowing it down further is only effective if this could lead to another decision on the intervention strategy.

2.2.2 Difficulties in diagnosing and strategies for improvement

Not only is the diagnosis the most important phase in the assessment of damage, it is also the most difficult phase. There are two reasons for this. One is the inevitable incompleteness of data on a building's properties and (structural) behaviour. With a visual inspection alone, one cannot reveal all construction details. Opening up such details may, however, not always be considered acceptable, especially when the building is a monument. Moreover, budget usually limits the possibilities for carrying out experiments to determine material properties to the full extent.

Apart from this, there is a second important reason that makes diagnosing difficult: it is often not easy to interpret the available data in relation to possible causes. Insight into the damage processes is, of course, essential in this context, but their occurrence and the influence of variables in this is not always fully understood yet. Moreover, damage can also be a product of several simultaneously occurring, or even interacting, processes. This complicates the search for hypotheses that fit with the data.

While the call for minimal intervention increases, a correct diagnosis is gaining more and more significance. In the past decades, many studies have sought for ways to improve diagnosis. We classify these studies into two groups, according to their main goal:

- Improvement of the collection of information on damages and damage processes; and
- Improvement of the processing of this information.

Improvement of the collection of information on damages and damage processes

Many studies belong to the first group. Some of them have aimed to improve the completeness and quality of data that can be obtained for symptoms and context of a damage. These studies have resulted in new and better techniques for on-site investigation, for on-site and laboratory testing and for monitoring. In line with the pursuit of minimal intervention, special attention has been paid to the development of a range of non-destructive tests, such as infrared thermography, sonic tomography and radar tomography [Binda and Saisi 2002; Binda et al. 2000]. A thorough overview of the techniques that are currently available is given in the documentation of the EU-project Onsiteformasonry [European Commision 2006].

Tragedies such as the sudden collapse of the civic tower of Pavia in 1989, the Umbria-Marche earthquake of 1997 and the Molise earthquake of 2002 demanded another kind of information. Therefore, the other part of the research projects belonging to this group has aimed at extending the knowledge on specific causes, including both the course of their damage processes and the different types of damage that can result from them. Especially the creep behaviour of masonry and the effects of seismic actions on buildings have been investigated [Binda et al. 1992; Ignoul et al. 2006].

Improvement of the processing of information

The second group of studies has focused on the development of techniques that help surveyors to process all information. This involves the analysis, evaluation and exchange of data. Many of the techniques developed in the past two decades have exploited the growing possibilities in computation.

For analysing the behaviour of structures, various methods for numerical modelling have been proposed. These range from deterministic (e.g. Lourenço [2002]) to probabilistic (e.g. Schueremans [2001]), from discrete (e.g. DeJong [2009], Block [2009]) to continuous (Netzel [2009], Giardina et al. [2010]). With these modelling techniques, it is possible to evaluate the structural behaviour and capacity of buildings under specified loads. Their power lies in calculating the complex interactions between material, geometrical and environmental parameters. This allows one to test a structure virtually, under different conditions and with different properties. The drawback of these models is, however, that they usually require the input of many variables, which are often unknown for existing buildings and can be difficult to determine. In addition, the models are always simplified presentations of reality and, as such, their accuracy depends on current knowledge of processes, which is still imperfect. Consequently, the main value of numerical models for the diagnostic process may not lie in their actual results, but in the insight they provide on how the behaviour of a structure is influenced by internal and external factors.

A multitude of collapse mechanisms due to earthquakes has been elucidated using the macroelement approach [Doglioni et al. 1994; Giuffrè 1993]. This approach classifies main building typologies (e.g. churches, manor houses) and lists their most common ways of seismic failure. Although meant as a support to identify and interpret damages, in practice it works more as a guideline for evaluating the seismic vulnerability of structures [Augusti et al. 2001; Binda et al. 2000; Speranza et al. 2006].

One of the applications of the macroelement approach can be found in the digital, didactic handbook *Manuale di Esercitazioni sul Danno Ed Agibilità* (Practical Handbook on

Damage and Safety Assessment (MEDEA)), which gives an overview of damage patterns in masonry and concrete structures that have suffered from earthquakes [Papa and Zuccaro 2004]. The Multi-Hazard Assessment of Vulnerability method has a wider scope: natural hazards. This method uses the macroelement approach to link building typologies to their characteristic vulnerabilities, and helps to evaluate expected losses of both material and cultural significance [D'Ayala et al. 2006]. Similarly, Vatan and Arun [2009] work on a system for pre-hazard risk assessment of historical domed and vaulted masonry structures. They suggest letting less experienced inspectors (i.e. students in architecture or civil engineering) to visually survey the buildings, while a team of specialists decides, on the basis of the collected data, on preservation or protection measures.

To help surveyors relate data of damages to causes, some experts systems have been developed. Most seem to focus on assisting in the analysis of data by offering visualization techniques (e.g. Appolonia et al. [2007]). Others help manage restoration projects, for example by handling the prioritizing of interventions [Abdel Gawad et al. 2010].

One of the few diagnostic expert systems is MDDS (Monument Damage Diagnostic System, successor of the Masonry Damage Diagnostic System), which focuses on damage related to interaction between materials and environmental factors. A demo version of the system was developed in the 1990s, within the framework of the EC Environment Program [Van Balen et al. 1999]. Since then, several additions and improvements have been made, the most recent of which in the framework of the EU COMPASS project [van Hees et al. 2009].

MDDS intends to facilitate multidisciplinary teamwork by offering a structured, transparent and consistent method for analysing and diagnosing damage [van Hees et al. 2005; Van Balen 2001]. It offers, among other things, a digital survey form. This concurs with a demand for standardized survey forms, as Kelley and Sparks [2006] have signalized during the assessment of damage after the hurricane Katrina struck the New Orleans region in 2005. For damage related to earthquakes, such survey forms are already available [Protezione Civile 2006a]. These *Agibilità e Danno nell'Emergenza Sismica* (Safety assessment and damage in seismic emergency situations (AeDES)) templates have been used extensively after the 2009 earthquake in L'Aquila. They helped to collect data, interpret damages and decide on emergency interventions for 1000 churches and 700 palaces.

The developers of MDDS are also among the ones who have pointed out that a basic need is still to be fulfilled: the need for better communication between all parties typically involved in restoration projects. Especially when aiming at a minimal intervention, for which cross-disciplinary cooperation is crucial, the current lack of a consistent and clear terminology may lead to misunderstandings. Despite the work that has already been done in this direction, up till now no prevailing, universally accepted set of damage definitions has emerged.

Although the development of new techniques and methods for collecting and processing information has certainly contributed to better diagnosis, many of these advanced techniques have so far only been of limited benefit to the day-to-day diagnostic practice. Not only is their use often time-consuming and costly, it can also be difficult to interpret their results and to draw conclusions from them. This is especially true for non-destructive tests, which are highly preferred when dealing with monuments [Binda et al. 2000]. In addition, a considerable number of these techniques are highly specialized, with a risk that their outcomes are of limited value for the actual diagnosis. As a result, their use is generally restricted to the last step in the diagnostic process: the verification of a hypothesis.

Another problem is that many studies have focused on one specific cause. Especially for earthquakes, extensive research has been done. However, handbooks such as MEDEA imply that, before they can be used to determine the exact mode of failure, first the type of cause has to be established with certainty.

Surprisingly enough, thus far less attention has been paid to the improvement of the first steps in the diagnostic process: the phase in which hypotheses are generated. Yet, it would be highly advantageous to improve exactly this phase. After all, the more precise hypotheses are formulated and the more accurate they are classified, the more effective the further process of verification can be and the greater the probability that the final diagnosis will be correct.

The developers of MDDS are among the few that do acknowledge the importance of improving the hypothesizing process. Still, before the start of this study, MDDS did not fully cover structural damages yet, as its main focus was on damages related to moisture, salt, frost and the like. To fill this gap, this thesis lays the basis for a module on structural damage for masonry. But first, the following section will take a closer look at the initial phase of diagnosing, pointing out limitations and weak points of the current approach.

2.3 The initial phase of diagnosing

We take the view that, to raise the quality of diagnosis and to allow for a better use of available techniques, more attention should be paid to improving the first steps in the diagnostic process. In those steps, hypotheses are generated and classified on the basis of symptoms and context of the damage. It is generally assumed that experience and intuition of the surveyor play an important role in this process.

For a better understanding of how the initial phase of the diagnostic process works, we have held an inquiry among experts in this field. With this inquiry, we aimed to investigate how experts reach a hypothesis, and what conditions they deem essential and sufficient to reach a diagnosis. The following subsections present the outline and the results of this questionnaire and discuss the bottleneck of the current, intuitive approach.

2.3.1 Experts questionnaire

To support and improve the diagnostic process, one first needs to understand how the process of diagnosing works. Therefore, we distributed a questionnaire among attendants of an international conference on the technical aspects of heritage care. The 11 respondents (persons present at the conference or business contacts of these persons) had different levels of experience and different specializations, but all worked as advisers in the field of conservation: some as professor at university, others as consulting engineer.

In the questionnaire, these participants were presented with pictures of four buildings with visible damage (please note: these photographs were in colour; as this thesis is printed black on white, we have added drawings, which were not included in the original questionnaire). For each of these cases, they were asked to answer the following questions:

- What could be the cause of this damage?
- On what information do you base this hypothesis?
- What additional data or measurements would you need in order to be able to verify your hypothesis?
- If no initial hypothesis could be established on the basis of the photograph(s), what would be the next step(s) in the investigation process?

With these questions, we hoped to find out how experts come to a first hypothesis.

The cases in the questionnaire were only presented by means of photographs, which raised some obstacles for the participants. First of all, the damage was not always clear to see. For instance, it proved difficult to estimate the direction of a deformation. Furthermore, the context was only partly visible and some of the characteristics may have attracted more attention than they deserved. Most certainly, it would have been easier for the experts to diagnose these damages in reality.

Nevertheless, for the purpose of trying to capture the diagnostic process, the use of photographs did have big advantages. It allowed us to guarantee that all participants had the same (visible) information at their disposal. Furthermore, it stimulated them to be aware of, and to explicitly mention, the facts on which they based their hypotheses. In this way, the responses also show the limitations of the intuitive approach, as will be discussed in Subsection 2.3.2. In the next paragraphs, the results of the four cases are discussed.

Case A

The first case presented in the questionnaire was building A. The damage in the sidewall of this building, as shown in Figure 2.3, forms a typical damage pattern. Most experts immediately referred to the classic 'back-of-an-envelope' yield line pattern, which is the failure mode of a rectangular slab that is supported around its perimeter and is uniformly loaded perpendicular to its plane. The crack pattern, thus, gives a clear indication of the collapse mechanism. In accordance to the plate bending mode, the loading must have been horizontal, out-of-plane and directed outwards. In this way, the symptoms of the damage led the respondents to hypotheses such as overloading due to wind (suction) or due to a horizontal impact load (explosion), but also hindered dimensional changes of a concrete floor incorporated into the wall.

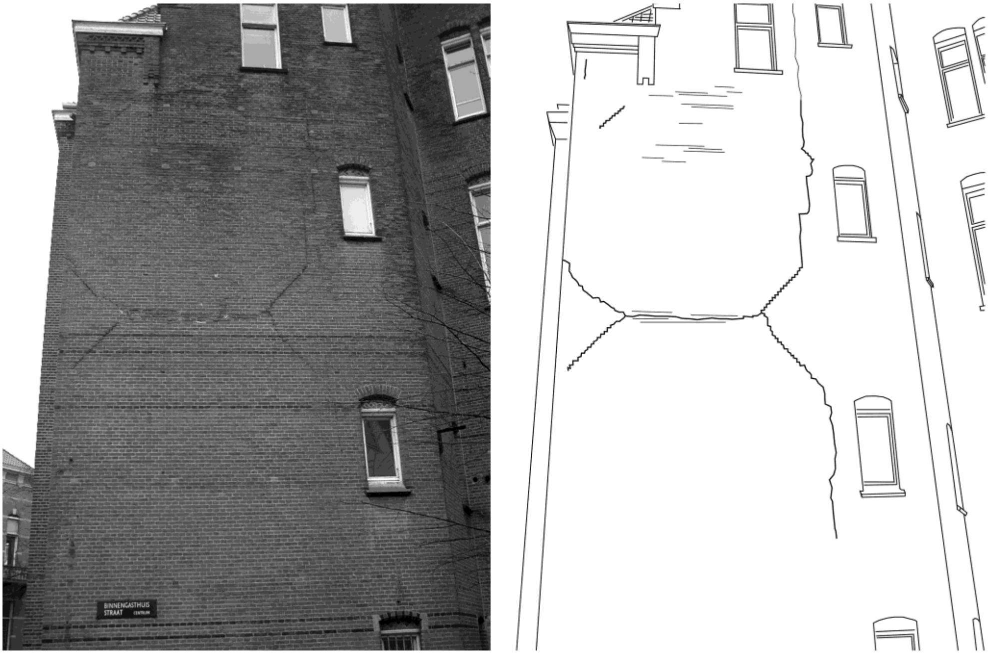


Figure 2.3: Building A, the first case in the questionnaire. Photograph by R.P.J. van Hees, drawing by author.

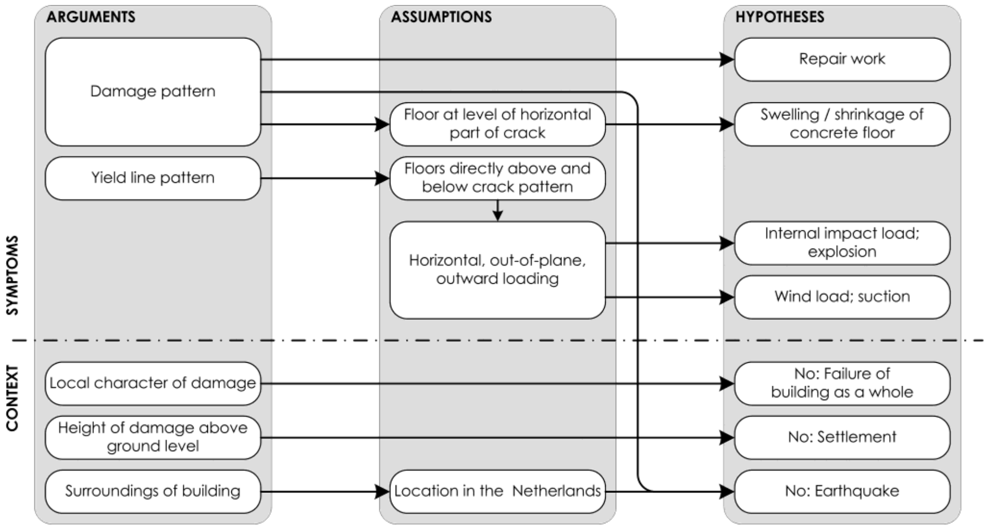


Figure 2.4: Overview of the hypotheses and supporting arguments that were brought forward for building A.

The experts used the context of the damage to exclude some specific causes. The local character of the damage and its distance to the ground led them to omit the possibility of settlement as initiator. Furthermore, some experts (correctly) assumed the building to be located in the Netherlands, which made them conclude that an earthquake would be a less likely cause.

Figure 2.4 gives an overview of the different hypotheses and anti-hypotheses that were brought forward by the participants. It also shows the arguments and the assumptions that they used to frame and support their hypotheses. It appears that, despite the typicality of the damage pattern, the cause of damage is not so obvious. Hence, in response to the third question, experts asked for more data on the properties of the building, on its construction history, on the nature of the location and on the characteristics and distribution of the damage.

Case B

The damage in building B, the second case, is less evident than the damage in building A. It can be described as an in-plane deformation of the façade (see Figure 2.5). Skewing of the windows at the first floor, visible in Figure 2.6, is accompanied by severe crack development in the lintels and sills of the windows and in the arch above the door opening. The edges of the cracks show displacements and demonstrate that the parts on either side of the fracture have undergone a clockwise rotation.

Concerning the information on the context of the damage, the participants particularly focused on the construction of the building. For example, they pointed out the difference between the timber-framed construction of the sidewall and the stonework façade. In addition, the relatively large openings in the façade, the apparent age of the building, and speculations on the adjacent building on the left side and the open area on the right side led them to the assumption that building B may have little or no lateral stability. This assumption helped them to explain the lateral displacements in the façade.

Figure 2.7 shows that, in this case, both the symptoms and the context of the damage were used to formulate hypotheses. These hypotheses vary from environment-related processes, such as differential settlement, to overloading due to a lack of horizontal restraint, and hindered dimensional changes due to corrosion of the anchors. The hypothesis of differential settlement appears to be supported by many arguments and assumptions. Nevertheless, its precise cause remains unclear, although several options were expressed.

Figure 2.5: Building B: overview of the façade and sidewall. Photograph by R.P.J. van Hees, drawing by author.

Figure 2.6: Building B: detail of the damage in the façade. Photograph by R.P.J. van Hees, drawing by author.

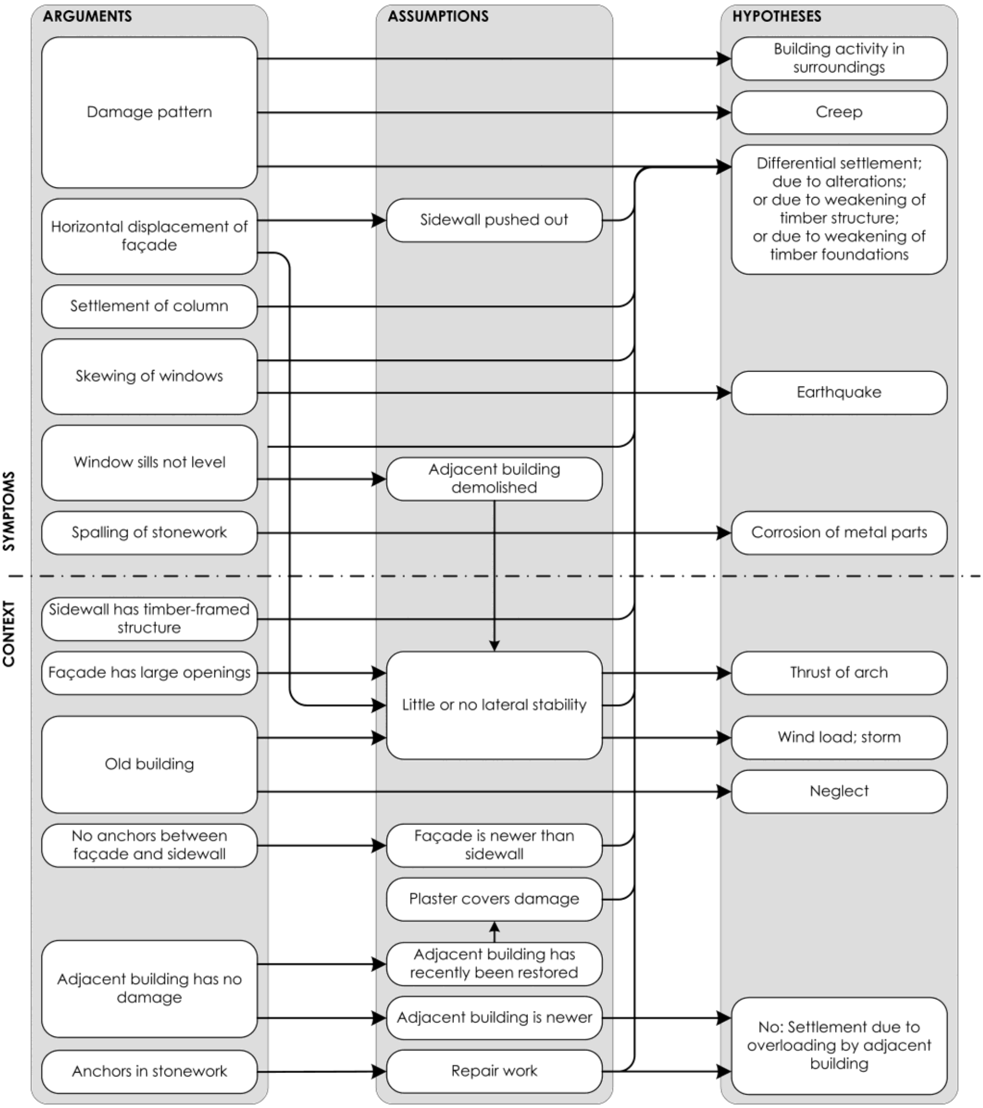


Figure 2.7: Overview of the hypotheses and supporting arguments that were brought forward for building B.

Case C

Case C of the questionnaire consisted of three pictures of the façade of a building (Figure 2.8). The first picture gives a general impression of the building and its surroundings. The façade is made of masonry and has relatively large windows. A lower wall is located at the right side, and a tree at the left side of the building. The second picture shows part of the façade below the window to the right. The masonry is cracked and deformed. In the last picture, the horizontal displacement out-of-plane at the edges of this crack can be observed.

Figure 2.9 gives an overview of the responses for case C. As in case B, both arguments related to the symptoms and those related to the context of the damage were used for framing hypotheses. In addition, the context of the damage was further used to exclude some specific causes. Four anti-hypotheses were stated: the type of building and its surroundings led to the exclusion of high stresses, an earthquake, a high traffic load and tunnelling as probable causes.

As can be seen in Figure 2.9, most of the arguments mentioned point towards the hypothesis of differential settlement. In fact, 7 out of 13 responses (NB some respondents gave more than one explanation for this case) indicated differential settlement as the most likely cause of damage, against 4 non-settlement hypotheses.

Figure 2.8: Case C. From left to right: the façade; damage below the window; and a detail of this damage. Photographs by R.P.J. van Hees, drawings by author.

Naturally, the diagnostic process would not stop at this point. To be able to evaluate different proposals for intervention, one would need to know what had initiated the settlement and why it was differential. In other words, one would like to have insight into the underlying process from initial cause to damage. When taking a more detailed look at the answers of the respondents who indicate settlement as a cause, one must, however, conclude that there is little consensus on this process leading to the settlement (see Figure 2.10).

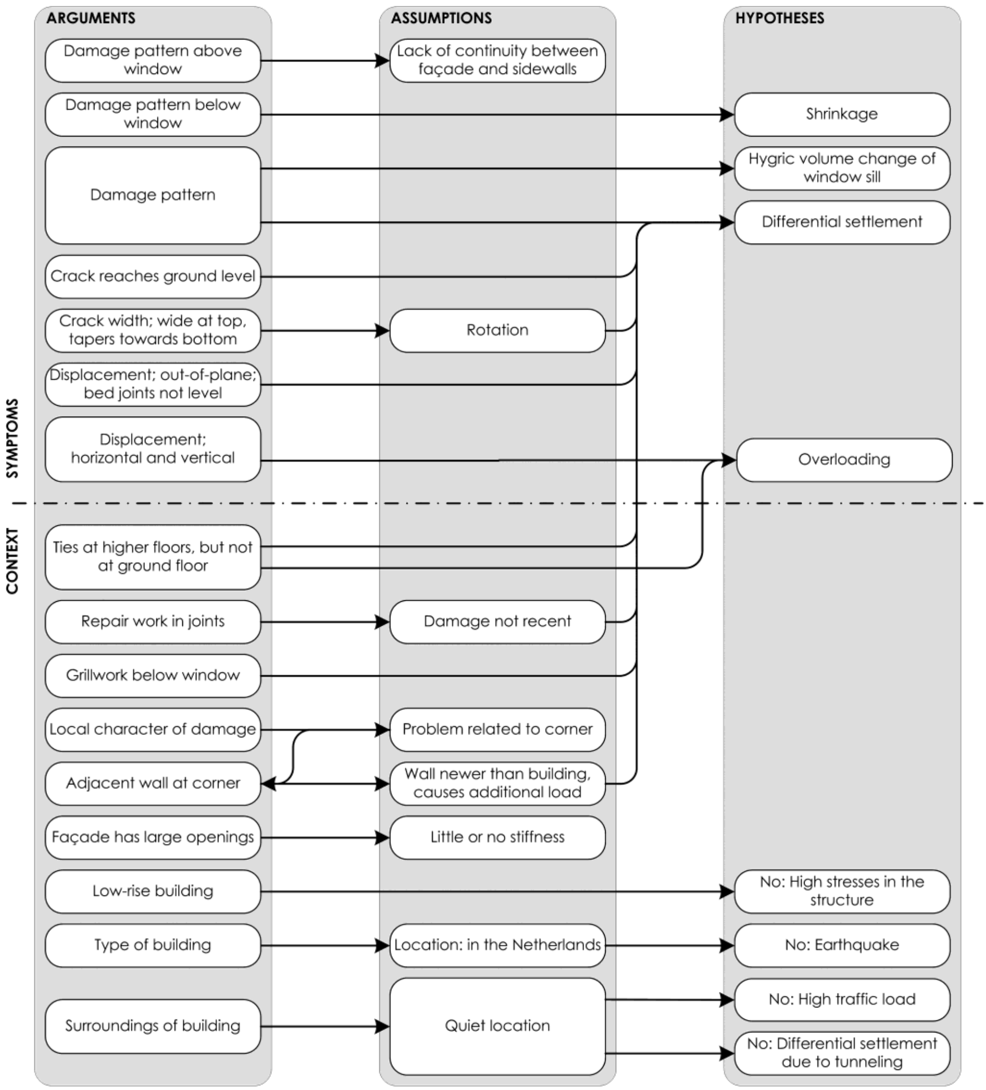


Figure 2.9: Overview of the hypotheses and supporting arguments that were brought forward for case C.

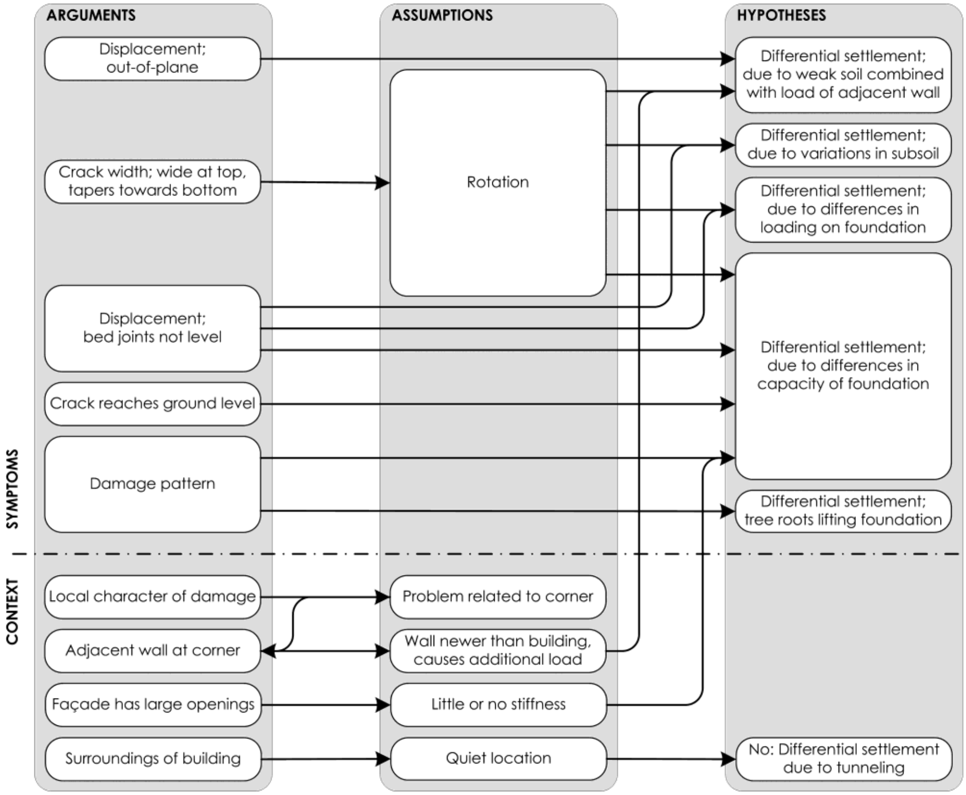


Figure 2.10: The hypotheses and arguments that indicate underlying processes leading to differential settlement (case C).

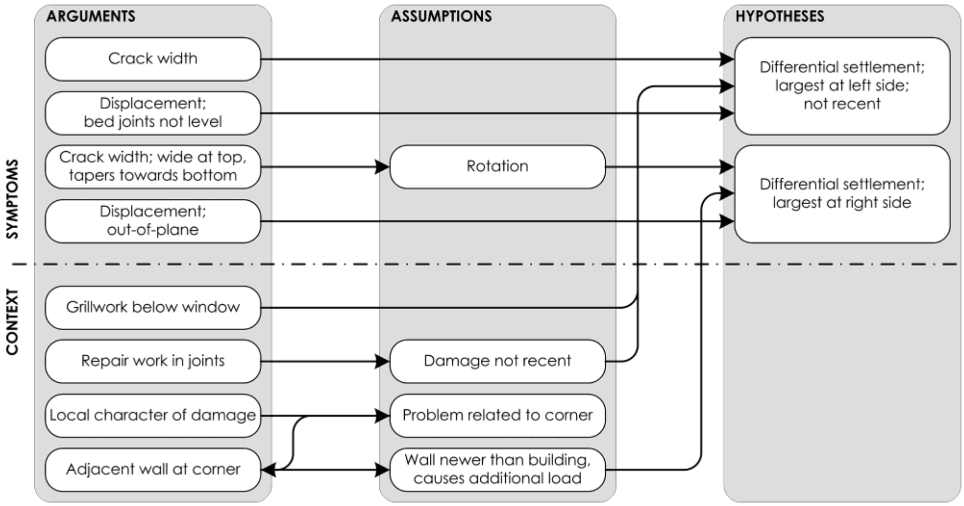


Figure 2.11: The hypotheses and arguments that relate to the side where settlement is largest (case C).

The participants suggested several causes possibly underlying the settlement process. It could be an effect of variations in loading or of differences in the loadbearing capacity of the foundation. Or it could result from differential settlement of the soil, due to local variations in the subsoil or due to underground construction works. This last option, however, was excluded by some participants, on the basis of assumptions on the location of building C.

For the other options, the experts did find supporting arguments. Interestingly, as Figure 2.10 shows, several arguments were not exclusively used to support one hypothesis, but for two or even three. The variation in crack width, for example, was, via the assumption of rotation, generally seen as an indicator for differential settlement. However, this rotation was subsequently used to support different underlying causes. The same can be said of the argument of unlevel bed joints, which was connected to variations in subsoil, differences in loading and differences in loadbearing capacity. Apparently, above two symptoms cannot be used to discriminate between these types of settlement. More characteristic conditions would be needed to be able to draw this distinction. Thus, in response to the third question of the questionnaire, the experts asked for more information on construction details, specifically of the foundation, on the soil conditions and on adjacent buildings. Also monitoring of the cracks was recommended.

The responses concerning case C allowed for another interesting observation. As is illustrated in Figure 2.11, some of the participants also indicated where they assumed the settlement to be largest. Surprisingly, they did not agree on this aspect, although here no argument was used for more than one hypothesis. While reasoning on the direction of the settlement, the experts appear to have interpreted the symptoms of the damage differently. The crack width and displacements visible in the bed joints were used as arguments for a differential settlement that is largest at the left side. Contrarily, the variation in crack width and the out-of-plane displacement were used to support the hypothesis of a differential settlement that is largest at the right side.

This last hypothesis was related to observations regarding the context of the damage. The local character of the damage led one of the experts to the assumption that the problem had something to do with the right corner. This brought into mind the adjacent wall (see Figure 2.8) and the assumption that this wall would be newer than the building and, hence, could have added an additional load on the soil near this corner. This line of reasoning would support a settlement that is largest at the right side of the façade.

Case D

The last case, D, pictured a brick masonry wall with saddleback coping (see Figure 2.12). Two anchors are contained in the masonry and fixed with anchor nuts. The masonry appears not to be in good condition, generally. Near one of the anchors is a large vertical crack, while between the other anchor and the corner of the wall cracks and displacements can be observed.

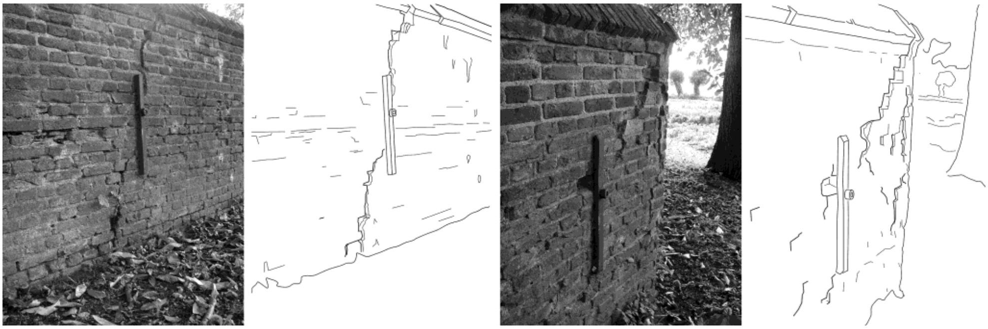


Figure 2.12: Case D: overview of the wall and its damage. Photographs by R.P.J. van Hees, drawings by author.

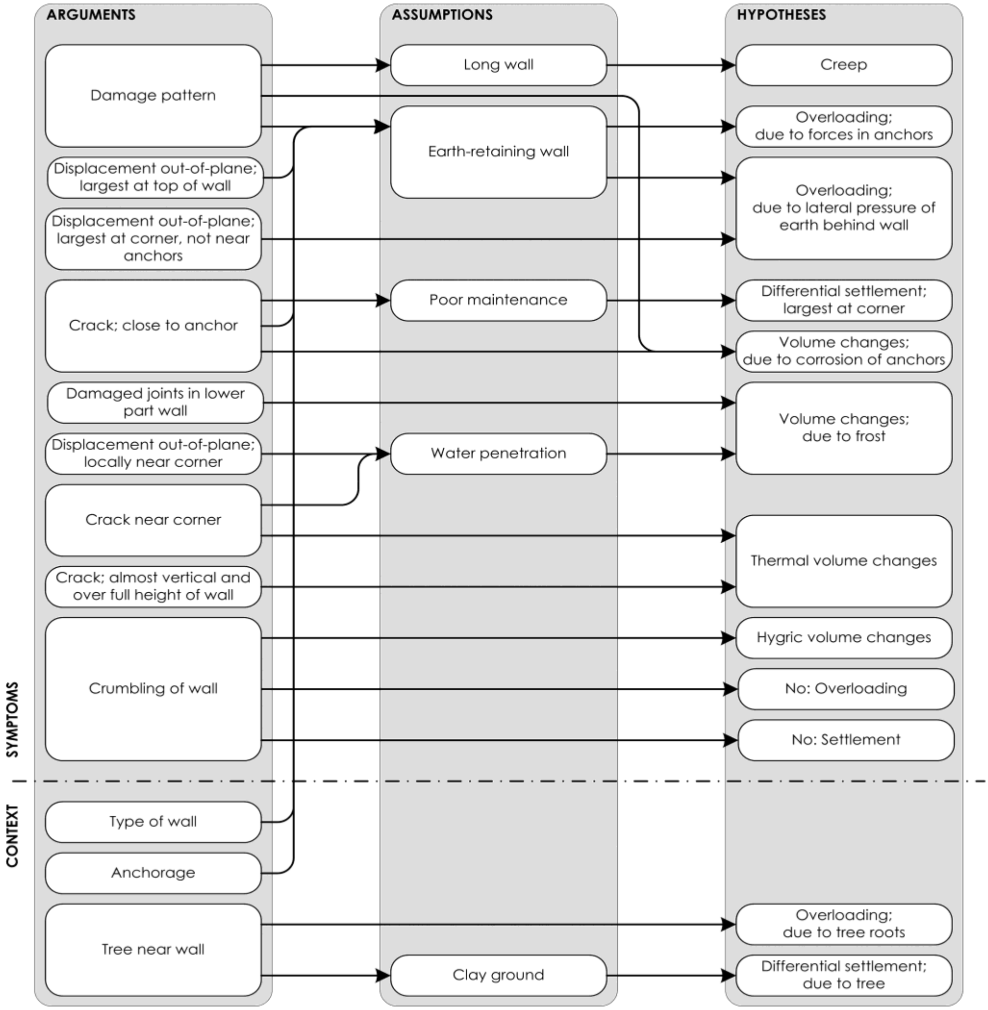


Figure 2.13: Overview of the hypotheses and supporting arguments that were brought forward for case D.

Although the damage and its context seem to be clearer from the pictures of case D than of case C, the responses to case D showed more variety regarding the cause of damage. Out of 18 responses (again, some participants proposed a number of alternative hypotheses), 7 indicated hindered dimensional changes as the most probable cause, but still another 6 pointed to overloading, and 3 to settlement. There were 2 blank responses. The arguments, assumptions and hypotheses of the participants are summarized in Figure 2.13.

The anchorage is the most prominent characteristic of the wall. In two ways it could be related to the damage. Some experts assumed corrosion of the iron anchors to have caused the large cracks. Others presumed that the anchorage indicates that the wall has an earth-retaining function and that the lateral pressure of the earth could have led to the cracks and the out-of-plane deformation.

Noticeable is also the tree in the background. This led to two hypotheses: the tree roots could have caused overloading, or they could have led to differential settlement due to desiccation of the (assumed) clay ground.

Figure 2.13 also demonstrates the parallel argumentations for the different types of hindered dimensional changes. Apart from corrosion, thermal dimensional changes were suggested, supported by the location of the crack near the corner and by the verticality and full height of the other crack. Finally, the deformation out-of-plane, the damaged joints and the crumbling of the masonry led to the moisture related hypotheses of hygric dimensional changes and frost.

2.3.2 Discussion: bottleneck in current approach

With the questionnaire, we intended to find out how experts in building pathology come to a diagnosis. Our goal was not so much to obtain sound diagnoses, since this is hardly possible without a site visit, but to investigate the process of hypothesizing. The results of the inquiry have shown us, not quite unexpectedly, that both symptoms and context of damage are used to formulate or exclude hypotheses. Even though they had only some photographs to rely upon, the respondents were able to identify the characteristics of damage and context and employed these symptoms and contextual attributes to explain how the damage might have occurred.

Evidently, this identification process is a form of pattern recognition: the expert, wittingly or unwittingly, compares each new case of damage with cases that he has investigated before, searching for similarities. Similar cases are, then, used as a reference to help him reach a diagnosis.

Pattern recognition can be regarded as a basic skill in diagnostics, both in building pathology and in medicine. In medicine, the development and training of this skill is described to take place in four subsequent phases [Grundmeijer et al. 2004]. The first phase consists of collecting information on diseases and their symptoms. In the second phase, students learn to see the relation between these separate facts and to structure their knowledge accordingly. Subsequently, by frequent use and practice, the combinations of interrelated facts are condensed into ‘patterns’. Diseases are more and more recognized without consciously going through the whole reasoning process on which the pattern was based. Finally, in the fourth phase, students learn to deal with more complex and atypical patterns. Experience now allows for knowing when something is not compatible to a pattern as well.

Especially for relatively simple and frequently occurring damages, pattern recognition offers an efficient approach to diagnosing. It helps to identify and interpret symptoms and context conditions, allowing one to readily formulate the most probable hypothesis. However, this approach is not without drawbacks.

In addition to showing how experts reach a diagnosis, the questionnaire has also revealed the bottleneck in this approach. In all four cases, the combination of symptoms and context conditions gave rise to several alternative hypotheses. From this, we can conclude that most conditions cannot be exclusively linked to one damage process. Moreover, the combinations provided here were, apparently, not sufficient to verify or falsify these alternatives, i.e. to establish a definite diagnosis.

To reach a diagnosis, it is important to be aware of the conditions that are a prerequisite for the damage process. We can carefully state that the current intuitive and experience-based approach may lay too little emphasis on explicitly checking whether all these necessary conditions are present. The bottleneck may be that the current approach is largely a subconscious process. As a result, pattern recognition may keep someone unaware of the assumptions he makes during the diagnosis, and of alternative explanations.

We can illustrate this unawareness with an example from the questionnaire. For building A, most experts identified the crack pattern as a classic yield line pattern and suggested it to be caused by out-of-plane loading of a slab supported around its perimeter, for instance due to wind suction or an explosion. These hypotheses imply that the respondents apparently assumed the perimeter of the crack pattern to match with the borders of a room behind the wall. Yet, in reality one of the floors lies at the level of the horizontal crack. This leads to a totally different hypothesis: hindered dimensional changes of the floor. Only few participants seem to have been aware of this alternative explanation. More importantly, less than half of all respondents brought forward the internal layout as essential condition that should be checked. It is clear that assumptions on conditions like this one should be mentioned explicitly when formulating a hypothesis.

It is important to emphasize that the experts that participated in our questionnaire should by no means be blamed for displaying these drawbacks: these problems are simply inherent to pattern recognition. With its quick subconscious identification process, it is not value-free, as it depends on a person's interpretation.

Human cognition in general is sensitive to bias. In this context, it is worth referring to the results of a research project in which cognitive scientists closely collaborated with a magician [Macknik et al. 2008]. Magicians have, in their professional capacity, explored techniques to exploit the shortcomings of human vision and awareness. By studying these techniques, neuroscientists have been able to learn powerful methods to manipulate attention and perception in laboratory. For our study, knowledge of these techniques is valuable because it tells us something about the cognitive inadequacies that appear to be inherent to human consciousness.

Many of the techniques used by magicians, for instance, make use of the fact that people have a natural, intrinsic tendency towards interpreting two events that follow each other as having a causal relation. By making sure that event A always precedes event B, a magician can make his audience incorrectly conclude that A causes B. On the other hand, by introducing a delay between method and effect, the spectator is prevented from causally linking the two. Hence, in many magic tricks the secret action occurs when the spectators think that the trick has not yet begun, or when they think that the trick is over.

People are trained to see correlations and, in this, their expectations (based on previous experiences) strongly influence what they pay attention to. First of all, people tend to be more aware of things they are familiar with. For pattern recognition, this implies that people, while selecting their references more or less at random, tend to overestimate the probability of a certain possible cause of an event if this cause is readily available in their memory [Tversky and Kahneman 1974]. In this way, a cause that is distinct, specific and easily envisioned, such as something one has experienced before, undeservedly gets a greater credibility.

In addition, people are inclined to see what they are used to seeing so much so that they can thereby fail to notice things they do not expect. This condition is called inattentional blindness and it is a condition all people periodically exhibit. Magicians make use of it to draw their audience’s attention away from the secret method and towards the effect of a trick. Inattentional blindness is a phenomenon that has long been known. It should be noted that it is by no means related to ‘ignorance’ of the audience. In fact, the evidence is otherwise: ironically, experts are more susceptible to inattentional blindness than beginners, as it is precisely their expectations which allow them to quickly and accurately assess a situation.

These expectancy effects are even strengthened by another human tendency: people who hold a belief or expectation tend to seek evidence which confirms this belief and ignore or avoid evidence which refutes it. Apart from the fact that experience is not necessarily correct, another pitfall of pattern recognition is, thus, that it can also make people jump to a conclusion: one is likely to pay more attention to facts that support ones ideas, while one may overlook facts that are contradicting. This so-called confirmation bias is highly effective in situations where the correct hypothesis is generated early on. However, if this initial hypothesis is inaccurate, it may keep one from noticing alternative hypotheses that could explain the damage as well [Patel et al. 2002].

Summarizing, pattern recognition offers a quick way to retrieve knowledge, but it is also vulnerable to mistakes. To prevent errors, it is essential that assumptions are carefully checked. By explicitly assessing the presence of as many prerequisite conditions as possible, the reliability of a hypothesis can greatly be increased.

2.4 Conclusions

Chapter 2 has shown us that diagnosing is the most important, but probably also the most difficult phase in the assessment of damage. To diagnose, one must be able to distinguish between different causes of damage; and the only data on which one can base this distinction are the symptoms of the damage, and the context in which these symptoms have occurred. Hence, a part of the difficulties of diagnosing lies in the inherent incompleteness of information on these symptoms and context conditions.

To overcome this problem, much effort has already been put into the development of advanced techniques for obtaining and analysing data. Although these advanced techniques have certainly improved the field of building pathology, many of them have a major disadvantage: they are complicated, which makes them time- and money-consuming. As a result, they are mainly used in the last step of the diagnostic process, to verify the most likely hypothesis.

To allow for a better use of these techniques and to improve diagnosis in general, more attention ought to be paid to the formulation and ranking of hypotheses. For a better understanding of how hypotheses are established, we have held a questionnaire among experts in the field. The results of this questionnaire have given us a unique insight into how experts approach damage. Pattern recognition is a basic skill in this, just as it is in medicine.

Although generally efficient, pattern recognition has some limitations. The most important bottleneck is that the reasoning process behind it is largely subconscious, due to which assumptions are often not checked explicitly. The responses to the inquiry made clear that many an argument can be used to support more than one hypothesis. The surveyor ought to be aware of these alternative explanations.

To prevent incorrect or incomplete interpretations of symptoms and context, better insight is needed into what basic data are sufficient to reach a sound hypothesis. Therefore, essential conditions have to be defined, the presence of which needs to be assessed in order to verify a hypothesis. The questionnaire has shown us an excellent opportunity to do this: by uniting the knowledge of the participating experts, we have created an overview of alternative hypotheses and related essential conditions. Hence, if we could collect and share the experience and expertise of many experts, it should be possible to identify the essential conditions that allow for distinguishing between damage processes. Our research project aims to provide such an overview of how symptoms and context conditions should be interpreted in relation to possible causes.

Chapter 3
Method

As has been argued in Chapter 2, the prevailing approach to diagnosing structural damage has limitations. In our opinion, an overview of conditions that are essential for diagnosing structural damage can help to overcome these limitations. The present chapter describes the method applied in this study to develop such an overview.

As a starting point, the observations formulated in Chapter 2 are now translated into criteria that this overview should address. On one hand, these criteria state what data are essential for diagnosing. On the other hand, they also indicate in what way these data should be presented to guarantee their accessibility.

Section 3.2 addresses the line of approach followed in this research to ensure that our end result will satisfy above criteria. We will discuss how we intend to gather the data needed to develop diagnostic support. Furthermore, we will explain the damage mechanism concept. This concept allows for a systematic description of the occurrence of structural damage.

The damage mechanism functions as a framework in which the relations between symptoms, contexts and causes of structural damage can be represented. Section 3.3 describes how these three components and their relations have been investigated and how the resulting mechanisms have been tested. Subsequently, Section 3.4 summarizes the general principles for Part II and III of this thesis.

3.1 Criteria for results

To enhance the diagnosis of structural damage in masonry, we aim to specifically facilitate the formulation and ranking of hypotheses. As shown in the previous chapter, this initial step in the diagnostic process tends to be based upon pattern recognition. Skill and experience can make pattern recognition an efficient way of starting a diagnosis. Unfortunately, the inherent subjectivity can also make it vulnerable to bias.

Chapter 2 has demonstrated that the main problem one faces in hypothesizing lies sometimes in a lack of data, but of even more importance is a lack of overview on how these data can or should be interpreted. This lack of overview may result in an incomplete differential diagnosis: some alternative causes may be overlooked as a potential hypothesis. This can be especially dangerous when dealing with so-called look-alike damages: damages that look similar, but have completely different causes. When diagnosing such look-alikes, one really needs to identify every condition to assess the real cause. The question is, thus: what combination of symptoms and context conditions is sufficient to reach a sound diagnosis? In other words, what aspects characterize damage processes in such a way that discriminating between different causes is possible?

The present research intends to answer this question and fill the gap by providing an overview of how characteristics of damage relate to causes. To attain our goal, overcome current problems and, thus, truly support and improve the framing of hypotheses, this overview must address certain criteria. These criteria can be divided into two groups:

- Criteria on the data needed for diagnosing; and
- Criteria on the presentation and accessibility of these data.

3.1.1 Required data: symptoms, context conditions and causes

This study has departed from the hypothesis that the characteristic symptoms and context conditions of a structural damage (which can be obtained by observations, measurements or simple in-situ tests) give sufficient clues to be able to deduce its cause. In medicine, such characteristics of an illness that trigger a diagnosis are called 'activating findings'. In fact, everything that differs from the normal or average situation can be an activating finding.

To facilitate the formulation and ranking of hypotheses, an overview of activating findings should include three sets of components: symptoms, context conditions and possible causes. Furthermore, the relations between each of these components need to be specified. Hence, consistent with our supposition, the data that are required in our overview are:

- The possible causes of structural damage;
- The symptoms of structural damage, i.e. the characteristics of the damage itself. In line with Section 2.1.3, the symptoms of structural damage should be defined in such a way that they do not preclude any assumption on the cause of damage. The definitions should also be, as much as possible, independent of the location of the damage, since this is a context condition;
- The relation between each symptom of structural damage and the possible causes of structural damage;
- The context conditions, i.e. the characteristics of the material, the geometry and the environment in which damage occurs, in so far as these aspects can influence the initiation and propagation of damage processes; and
- The relation, in type and in amount of influence, between each context condition and the possible damage processes. The type of influence concerns whether the condition is prerequisite or contributory. If a condition is prerequisite, the damage process will not take place without its presence. However, if a condition is only contributory, the damage process will take place independently of its presence, but it does affect the rate at which the damage process occurs or the extent of damage to which the process leads. An example of these influence types will be elaborated in Section 3.2.1.

3.1.2 Access to data: overview, insight, applicability and ease of use

The above list of data that are required for diagnosing may seem rather obvious or even redundant. There is already much information on various types of damages and causes. However, this information appears to be quite scattered. From the vast number of scientific publications, many deal with either a certain test situation or a particular case study. Leaving the question aside whether the more practice-oriented public has access to such publications, the information they contain may be too specific for direct implementation in the diagnostic process. On the other hand, handbooks that do give an overview of aspects related to structural damage tend to lack a consistent structure, as was pointed out in Section 2.1.2. This, too, makes it difficult to find the information one is looking for.

The consequences of this fragmentation of knowledge are twofold. First of all, it makes it difficult to keep complete overview of damage-cause relations. Secondly, it can also hinder the retrieval of specific information. The former aspect is particularly relevant in the first steps of hypothesizing, in which all possibilities need consideration. Once the direction of an investigation has been defined, the second aspect gains in significance. At that point, a surveyor usually wants deeper insight into one particular matter.

To obviate the first problem, we need to make sure that the data as presented in Section 3.1.1 are easy to access. We have formulated three criteria to ensure this. Our result should provide:

- Broad overview of structural damage and its causes in a general picture; and
- Insight into structural damage and its causes in detailed descriptions.

In addition, it should also be applicable in practice, and therefore:

- Easy to use.

All three access criteria benefit from a clear data structure.

3.1.3 Outlook: implementation in a diagnostic decision support tool

In the foregoing, we have mentioned that structure is an important concept in keeping data accessible. Structured data storage is, in fact, a feature that is typically associated with the highly systematic way of data cataloguing inherent to computerized databases. Hence, implementing our overview in a knowledge-based system would be a logical choice for presenting the relations between activating findings and causes in a ready-to-use way.

Knowledge-based systems are computer programs that help to collect, organize and retrieve knowledge. They consist of two components: a knowledge base, in which data are stored, and a rule base, which makes these data accessible and retrievable. To do this, the rule base can generate a simple traditional index, but it may also provide more advanced functions, such as text-based search, hyperlinks or a ‘wizard’: a tool that guides a user through a list of questions, to determine which specific piece of information is asked for, or to find a solution to a specific problem. Especially these options to retrieve data are an advantage of using computerized diagnostic tools instead of versions on paper.

Knowledge-based systems are not a new phenomenon: especially in health care, they are already widely used. Accordingly, in no other field have the effects of using these systems been investigated in more detail. Hence, to find out what additional criteria would need to be addressed if we could further develop our overview into a system for diagnostic decision support in building pathology, we have examined the benefits and disadvantages of similar systems used in medical diagnostics, and identified the critical factors for a successful implementation and use. In the following paragraphs, the results of this literature review are highlighted.

Support systems in health care: benefits, disadvantages and success factors

In the past decades, the growing use and increasing possibilities of computers have induced a range of digital information systems for health care. The most basic facility these systems offer is a structured way to store and share data, and one of its most promising applications to date may be the electronic health record [Patel et al. 2002]. Main feature of this digital patient file is that it offers an efficient way of sharing patient data among the various physicians from whom a patient may receive medical treatment. Furthermore, it can also structure a doctor-patient encounter and so help the physician in gathering more relevant information.

A special category of health information systems form the decision support systems. These systems match input data to their computerized knowledge base and use their rule base to generate output that is specifically related to this input. In this way, they can simplify access to data needed to make decisions, for instance by graphically displaying laboratory data [Miller 1994; Payne 2000] or by generating order sets for tests commonly ordered in similar input situations [Sittig and Stead 1994]. Decision support systems are also deployed in medical education, to simulate doctor-patient encounters. These patient simulators allow students to independently practise medicine and train their clinical reasoning on virtual patients, without the legal and ethical drawbacks that the use of real patients would entail [Alers et al. 2003; Scalese et al. 2008].

Decision support systems can also assist in diagnosing, and that is the reason why we are so interested in them. To offer patient-specific advice, these so-called diagnostic decision support systems evaluate the input data (e.g. historical and physical findings, results of laboratory tests), deduce which disease processes could explain the symptoms or signs, and, subsequently, list all alternative hypotheses [Payne 2000]. The basis of this deduction process is a causal network, in which antecedents (diseases, risk factors) are linked to consequents (symptoms, test results). The connections between the nodes of the network can be based on if/then rules (being deterministic or fuzzy) or on probabilities.

The main benefit of using a diagnostic decision support system is obvious: it can help in finding the most likely hypothesis. To attain this goal, the information contained in the system should be as complete and precise as possible, since the performance of a system depends for a large part on the quality of its knowledge base. This has been demonstrated by Berner et al. [1994] who tested four medical diagnostic decision support systems by entering 105 cases based on real patients and comparing the diagnoses generated by these systems to the diagnosis considered to be correct. For all 105 cases, an average of between 52 % and 71 % of the diagnoses generated by each system were considered to be correct or almost correct. However, many of the input cases had less common diagnoses, which appeared not to be contained in the systems under study. In fact, for the 63 cases for which all systems did include the correct diagnosis, between 71 % and 89 % of the diagnoses were (nearly) correct. From this one can conclude that the comprehensiveness and the level of detail of the knowledge incorporated in a diagnostic system are decisive factors in the success of the system. Especially since diagnostic systems are most likely to be used when dealing with more complicated diagnostic problems, such as atypical presentations of symptoms, the premonition of a rare disease or multiple disorders presenting simultaneously, diagnostic decision support systems should include as many diseases as is possible, both common and rare ones.

Another benefit pointed out by Berner et al. [1994] is that part of the added value of using a diagnostic system may lie in its serving as a prompting function, alerting and reminding the user of alternatives. In the same 1994 experiment, each of the four tested systems generated an average of two additional appropriate diagnoses per case, i.e. diagnoses that were not included in the list of six appropriate diagnoses generated by experts for comparison, but that should have been taken into account. In this way, using a diagnostic support system may help to overcome availability and confirmation biases. Still, the user always needs to be critical with respect to what information is relevant to a case, as, for an atypical case, the correct diagnosis might appropriately be ranked fairly low if other diagnoses are more likely [Berner et al. 1994].

As decision support systems are intended to augment to an expert's capacities [Miller 1994], one of the main barriers to a successful implementation of decision support systems may be a failure to consider this expert's workflow [Dorr et al. 2007]. Successful systems are easy to use, with minimal effort, and give the user some benefits in the short term. For instance, the effort needed for input can be minimized by providing a connection between the decision support system and an electronic record system [Dorr et al. 2007]. However, this requires the use of a consistent and well-defined terminology [Kappen and Neijt 2002].

A short-term benefit for the user may be direct help during the diagnostic process. For example, some systems can suggest which test (or question, examination) would be most useful to exclude alternative hypotheses (e.g. the Probabilistic Medical Diagnostic Advisory System (Promedas), described by Kappen and Neijt [2002], see Figure 3.1). Indeed, one of the most important success factors for decision support systems appears to be a real-time feedback to the user, for instance through screen dialog boxes. This computer generated advice works best when provided automatically, as part of the user's workflow. However, an excessive use of alerts since this is a context condition must be avoided, since this could decrease confidence in the system and could even cause users to simply ignore the alerts entirely. Instead, feedback should be specific to the input and it should, preferably, include actionable recommendations, although the latter may only work if the system is used by someone who can implement these recommendations himself [Kawamoto et al. 2005; Kuperman et al. 2006; Payne 2000; Sittig and Stead 1994].

For an optimal integration into the user's workflow, the diagnostic system should fit the expert's way of thinking [Patel and Groen 1986; Patel et al. 2002]. Although expertise, of course, depends for a large part on knowledge, research has shown that it is also expressed in the approach to diagnosing. Experts prove to be better able to isolate relevant facts from a case, and they make more inferences from these facts. In addition, they devote considerably more time to representing a problem, due to which they tend to generate not more, not quicker, but better hypotheses [Norman 2005; Patel and Groen 1986; Patel et al. 1990; Patel et al. 2002]. Furthermore, diagnostic expertise appears to be associated with the ability to use multiple coordinated mental representations: causal knowledge, diagrams of relations between symptoms, signs and diagnoses, and exemplars based on experience with past cases [Grundmeijer et al. 2004; Miller 1994; Norman 2005; Patel et al. 1990; Patel et al. 2002]. Consequently, it is advisable to make the information contained in a system accessible in various ways.

Finally, it is important to keep in mind the limitations of (computer) systems. Diagnostic support systems are expected to improve practitioner performance, increase efficiency and enhance effectiveness. In health care, they may enable a better evaluation of the quality of care, increase compliance with guidelines and reduce errors in information exchange [Chaundhry et al. 2006; Georgiou et al. 2007; Wong and Knaus 1991]. However, it must be noted that, although there is evidence that decision support systems can improve efficiency and reduce costs, the effect of these systems on the quality of health care (i.e. on the patient's health) still remains understudied [Garg et al. 2005]. All the more reason to keep the user in charge during the process: for a proper use in practice, the information contained in a diagnostic decision support system should always be verifiable by the user. Hence, the system should not give a fixed answer in the form of a final

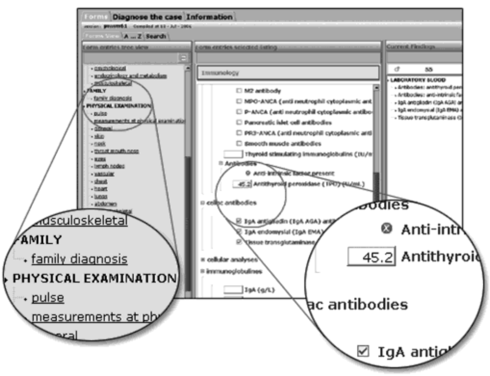


Figure 3.1: A screenshot of the Promedas medical diagnostic support system. Image taken from the website www.promedas.nl, reproduced by courtesy of Promedas BV.

diagnosis, but, instead, it should offer insight into how symptoms and contexts can be linked to causes.

A diagnostic decision support system in building pathology: MDDS

In building industry, only few diagnostic decision support systems are available at the moment. One of the most mature systems is MDDS (see Figure 3.2), which has been introduced in Section 2.2.2. As the objectives of this study are closely related to those of MDDS, it is interesting to take a closer look at the merits of this system. MDDS is in ongoing development and not commercially available yet; therefore, its user group is still limited. As a consequence, the effects of using MDDS have not been measured on a large scale. Nevertheless, its successive development phases have been evaluated by Lucardie [1994] and Schilstra [2002]. Their studies provide some additional recommendations for building a diagnostic decision support system.

First of all, Lucardie has stressed the importance of always keeping the project goal in mind while collecting and structuring the knowledge. Decision tables or trees can be of help in this: as graphical tools, their clear representation of knowledge allows for a relatively easy way to check the completeness, consistency and correctness of a system. In this way, the use of decision tables has made it possible to let the knowledge model of MDDS be developed by experts themselves, with only occasional support of knowledge engineers. Major advantage of this approach, as pointed out by Schilstra, is that the diagnostic process and information used by MDDS closely resemble those used by an expert. In other words, MDDS fits the expert's way of reasoning.

The process of explicitly representing knowledge in a knowledge system is just as important as making this knowledge available to (end-) users. In line with this, Schilstra has argued that the process of developing MDDS may be as much a contribution to building pathology as the actual system itself: building MDDS has led to a common terminology, explicit and agreed-upon knowledge based upon shared experience, and the revelation of current gaps.

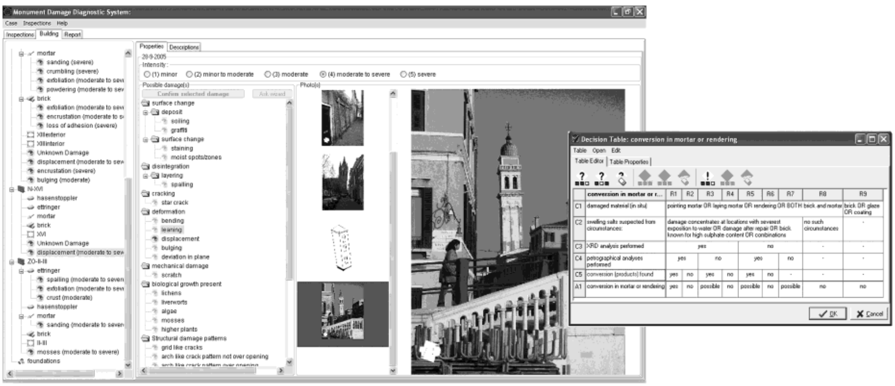


Figure 3.2: A screenshot of the Monument Damage Diagnostic System (MDDS), by TNO-Netherlands Organisation for Applied Scientific Research. See also van Hees et al. [2008].

Above information does not only provide us insight into which factors are critical to create a successful knowledge-based system, it also gives us useful hints for optimizing our paper diagnostic tool. These additional criteria are related to:

- Comprehensiveness: A diagnostic tool should comprise information on both common and less common causes of damage;
- Verifiability: The tool should always keep the user in charge. It should not give a fixed answer in the form of a final diagnosis, but explicitly list alternative hypotheses and let the user decide; and
- Supportiveness: Wherever possible, the tool should offer feedback on which tests would be most conclusive for distinguishing between alternative hypotheses and reaching a final diagnosis.

3.2 Line of approach

In the previous section, some considerations have been introduced in relation to creating diagnostic support. It has been shown that not only the content itself, i.e. the knowledge that is incorporated, is important, but also the way in which this content is presented to the user. In the current section, we will explain our line of approach on acquiring the necessary data, and our thoughts on the organization of these data.

3.2.1 Data: analysis of representative cases

This study aims to develop a diagnostic tool to be of support during visual inspections. The study has been started from the presupposition that symptoms and context of a damage are the basis from which a cause can be deduced. With this research project we want to determine which characteristics are essential for diagnosing, and what these characteristics tell us.

Chapter 2 has shown us an excellent opportunity to gather this knowledge. In a questionnaire, experts were asked to give their opinion on four cases of structural damage in masonry. Their responses have provided valuable insight into the visual characteristics they consider as reliable indicators of a certain cause. Moreover, combining and comparing their approaches has proved to be a suitable way to create an overview of hypotheses and corresponding conditions.

The questionnaire in Chapter 2 has demonstrated, on a modest scale, that uniting the knowledge of experts in the field makes it possible to identify those conditions that are essential for distinguishing between damage processes. We will use the same principle to gather the data needed to develop diagnostic support. However, for the remainder of this research project we turn to cases from published material as source of information. The reason for this is that we assume that an analysis of case studies as put down in writing will provide more valuable information than would emerge from a questionnaire based on cases picked out by us. Published cases are selected by an author to help him clarify his opinion. Hence, these must be cases that this author designates as important and representative. Quite literally, they are casebook examples. We think that analysing how these cases are approached will give us the information we need for our tool.

3.2.2 Access: the damage mechanism concept

A clear, structured data configuration is essential for the well-functioning of a knowledge-based system, so it is important to give some consideration to what layout our overview of damage characteristics and associated damage processes should have. As has been indicated in the previous section, the basis of a decision support system is formed by a causal network, in which antecedents are linked to consequents. In line with this, our overview should take the shape of such a network, with nodes corresponding to the symptoms, context conditions and causes; and with connections between the nodes representing the relations between these three components. To prevent any ambiguity or overlapping in the entries, all data contained in the system need to be of uniform language, in vocabulary and in syntax. This asks for clear definitions of damage, as has been pointed out in Section 2.1.3, but also for a logical way of describing damage processes. The latter issue will be discussed here.

Since networks tend to grow exponentially with the inclusion of more and more data, they need to be structured carefully. To guarantee a clear data configuration, we have developed the damage mechanism concept. Essential aspect of this concept is that it differentiates between processes and factors. Damage processes describe the relation between symptoms and causes; factors, on the other hand, are not part of these processes but do influence their course or the extent of their effects. The combination of a damage process and its influencing factors is called a damage mechanism (see Figure 3.3).

One should keep in mind that it is often too simplistic to describe damage in terms of one single cause. Instead, it is recommendable to regard damage as the result of a sequence of events and conditions [Payne 2000]. Therefore, within the damage mechanism concept, each damage process is represented by a chain of interrelated steps (subprocesses), which have each been linked to the scale level on which they take place: on the level of the area, on the level of the building or on the level of the building component.

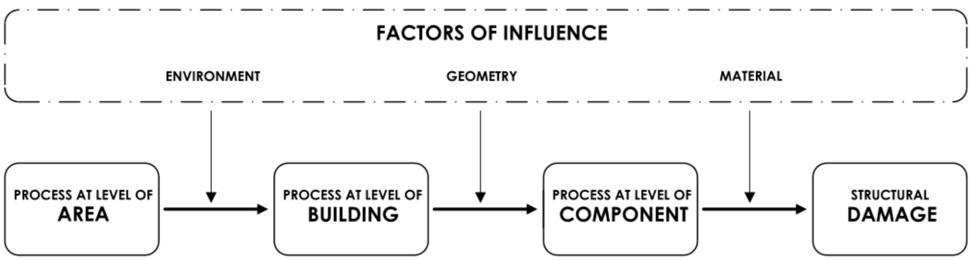


Figure 3.3: Scheme of the damage mechanism concept.

We can illustrate this damage mechanism layout with an example. A cause of structural damage could be the drainage of an excavation pit. This drainage may have a local impact on the ground water level, lowering it, which could lead to soil settlement in a certain area. This soil settlement may affect the building located within this area: parts of its foundations could subside, leaving the building components above it unsupported. This may lead to damage in the above-ground masonry: cracks or leaning of a wall (see Figure 3.4).

To each step of the damage process, influence factors can be assigned. Three of these factors, which can be either prerequisite or contributory, are related to the scale level on which the subprocess takes place. We have distinguished between environmental variables, geometrical variables and material variables. Please note that, within this PhD study, the focus for these conditions will be on the Netherlands, church buildings and masonry, respectively.

In the example mentioned before, soil type is a contributory factor: the settlement process will take place irrespective of the type of soil present, but the presence of a clay soil instead of a sandy soil may lead to a larger extent of the settlement. Correspondingly, the type of foundation (shallow or on piles) will influence the effect that the settlement has on the building. This is a prerequisite factor: if the piles are founded below the level of the excavation, the drainage may hardly affect the building. Finally, the type of mortar (lime-based or cement-based) used in the masonry wall may influence the type of damage: deformations or crack development.

Apart from the above three, scale-related context conditions, there is a fourth factor that influences damage processes: time. Sequence and rate are the key words here: the factor time has to do with the order of subprocesses and their duration.

The main advantage of the damage mechanism concept is that it makes it possible to efficiently establish and visualize damage-cause relations. It allows for an explicit description of all steps in the damage process, from cause to damage, including all material, geometrical and environmental factors that may influence this process. Furthermore, the division of the damage process into four main steps enables an easy comparison between different processes. However, it must be noted that for optimal use in diagnosing these steps may need further subdividing.

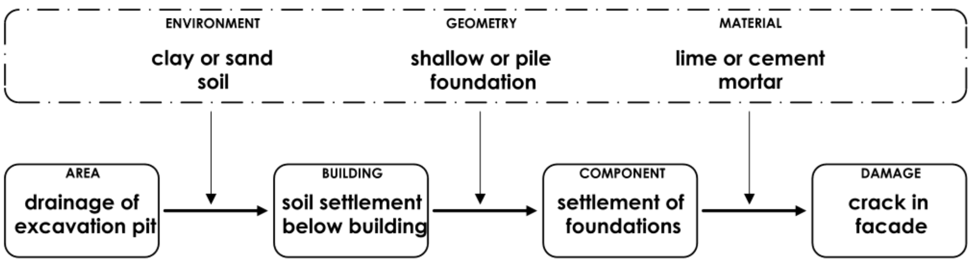


Figure 3.4: Example of a damage mechanism.

3.3 Research procedure

In the previous two sections, we have investigated the criteria for a useful diagnostic support system, we have determined which raw data can provide us with the information we need, and we have designed a suitable layout to store and access these data. The next step is now to plot a course for the practical realization. This section will discuss the procedure that we have adopted to select the literature, compile the required data, link these data into a tool and verify the functioning of this tool.

3.3.1 Selecting the literature

As has been demonstrated in Chapter 2, uniting the knowledge of experts makes it possible to create an overview of conditions essential for diagnosing. It is our intention to use this principle for developing diagnostic support. To give our tool a firm and verifiable foundation, we will base it on published material. Our procedure, therefore, begins with selecting relevant literature.

The backbone of our literature sample is formed by twenty handbooks on building pathology, as introduced in Section 2.1.2. The majority of these handbooks have been selected from the TU Delft library collection, in the subcollections 'Building maintenance', 'Stone structures, masonry structures' or 'Historic monuments: preservation and restoration, building historical research'. Others have been chosen on the recommendation of colleagues.

The twenty handbooks have been supplemented by publications with a more specific scope, such as publications dealing with a single type of structural damage. Most of these papers have been identified through an electronic database search in ScienceDirect (www.sciencedirect.com). Applying the search string: (structur* AND damage AND masonry) AND NOT (seism* OR earthquake) to the abstracts, titles and keywords of all publications from January 2005 to January 2010 resulted in 40 articles. After having reviewed the abstracts of these 40 papers and excluded those publications that turned out to be not germane to our scope, 27 papers have been added to our sample.

Further publications have been selected from proceedings of recent conferences and from other TU Delft library subcollections. Finally, our literature sample has been completed with items from the reference lists of above publications.

3.3.2 Compiling the data

After having selected the literature, it is time for the main part of the work: to compile the data. First and foremost, this means identifying all relevant causes, symptoms and context conditions. However, it also includes formulating sound definitions for all these options.

Collecting representative examples

The first step in compiling the data is extracting relevant data from our literature. Since we aim to combine the knowledge of individual experts within our diagnostic support system, we need to determine how these experts diagnose structural damage in masonry: Which visual characteristics do they pay attention to? And what do they consider as reliable indicators of a certain cause?

To find an objective answer to this question, we have decided to focus our literature review specifically on illustrated examples of damage in masonry. The authors use these examples to clarify their opinions. Hence, these must be cases that they designate as important and representative. We presume that analysing how these cases are approached will give us the information we need for our tool.

The first step of compiling the data consisted, thus, of building up a collection of damage cases. Scanning through our literature, we have isolated all examples of (structural) damage in masonry. After having confirmed that the damage is indeed structural (according to our definition: by showing crack development, deformation or tilt), we have checked whether each example provides:

- A clear photograph or drawing of the damage; and
- A statement on the cause of damage.

If so, illustration plus accompanying text have been selected. This has resulted in a collection of more than 500 cases.

These cases have been gathered from the following publications: [Addleson 1989; Bakker 1963; Barthel 1993; Beckmann and Bowles 2004; Binda et al. 2000; Ceci et al. 2010; Cook and Hinks 1992; Croci 1998; Douglas and Ransom 2007; Eldridge 1976; Feilden 2003; Harris 2001; Harvey 2004; Hendry and Khalaf 2001; Heyman 1985; Heyman 1995; Hinks and Cook 1997; Huerta 2005; Kastner et al. 2003; Loughran 2007; Lourenço 2005; Maier 2002; Marshall et al. 2009; Mastrodicasa 1993; Meichsner and Rohr-Suchalla 2008; Naldini et al. 2007; Ochsendorf 2004; Ochsendorf 2006; Onsiteformasonry et al. 2002; Pfefferkorn 1994; Pieper 1983; van der Pluijm 2000; Protezione Civile 2006b; Richardson 2001; Schubert 2009; Stichting Bouwresearch 1966; Stichting Bouwresearch 1975; Stichting Bouwresearch 1976; van Stigt 1995; TNO DIANA BV 2008a; Total Wall Concept 2006; Warren 1999; Watt 2007; Weaver and Matero 1997; Zhao et al. 2009].

Defining the components

The collection of cases should contain all information we require; however, this raw material needs refining. Therefore, the second step consists of dissecting each example into separate components: the building blocks of our damage mechanisms. This means analysing the texts and illustrations and carefully identifying all symptoms, causes and context conditions.

To make sure that our overview will be concise and surveyable, related terms have been clustered. For the context conditions, this subdivision is rather straightforward. In accordance with the damage mechanism concept, we have classified them into environmental, geometrical, material and time-related factors, which will be described in Chapter 6.

The causes have been subdivided into three subgroups: one related to settlement, another related to overloading, and the third related to hindered dimensional changes.

This classification, too, fits in with the three scale levels discerned in the damage mechanism concept, as will be explained in Chapter 4.

For the symptoms, we have first of all distinguished between three main characteristics: cracks, deformations and tilts. This arrangement, introduced in Section 2.1.3, has been based on mode of failure. For the damage types of deformation and crack, further, more specific characteristics have been defined. The resulting list of symptoms will allow us to delineate damage patterns later on.

Finally, to prevent ambiguous or overlapping entries, we have 'synchronized' all descriptions. Equivalent concepts, originating from different publications, have been compared, and redundant terms eliminated. The remaining entries, the building blocks of the damage mechanisms, are described in Part II of this thesis.

3.3.3 Relating the data

With all components defined individually, the next phase consists of knitting these loose causes, symptoms and context conditions together into an operative diagnostic tool. Apart from (re-)establishing the connections between these components, this also includes the translation of these relations into a system, and testing this system in practice. The methods used in this phase are both qualitative (literature) and quantitative (parameter studies using the finite element software DIANA and a small-scale physical model).

Examining some relations between components

With all components defined, we would now like to know how these causes, symptoms and context conditions correlate. What effect does the actual point of application of a load have on the eventual appearance of damage? And what are the consequences of the presence, absence or value of a certain context condition?

This kind of insight can be provided by testing, for each factor separately, the extent of influence it has on the damage presentation. Hence, we need to examine the effects that a change in one variable has on each of the damage mechanisms, for instance by performing a series of experiments under well-controlled conditions. Due to the different scale levels and the large number of variables involved, the best option here is to follow a numerical approach and simulate the damage mechanisms with computerized models. Therefore, we will model a sidewall of a representative Dutch church building and analyse its behaviour in the finite element analysis program DIANA 9.3 [TNO DIANA BV 2008b]. Complementary to this numerical approach, we will also test a small-scale physical model.

As these parameter studies are time-consuming, it is not possible within this research project to apply them to all relations. Therefore, we have chosen to set an example and focus on two aspects, both related to settlement. Firstly, we will examine the influence that location and relative size of a settlement trough have on the appearance of damage. To do this, we will apply five settlement troughs to the models. Secondly, we will test the influence that two conditions have on the extent and appearance of damage: material properties and the presence of openings in a wall. By comparing the results from the different models, it should be possible to evaluate the effects of each variable on the damage process. More details on the outlines of these parameter studies can be found in Chapter 7.

Determining the relations between all components

With the numerical and physical tests, we have developed a sense of how causes, symptoms and context conditions correlate. The next step is, then, to establish explicitly the relations between all component options as brought forward in Part II. This is not done by further testing, but will be achieved by analysing the information contained in our literature sample from a mechanics point of view.

Three types of relations will be determined: the first one between symptoms and context conditions, composing damage patterns; a second one linking these damage patterns to causes; and a third, connecting the causes with (distinguishing) context conditions. For each of these types of relations, the procedure follows a separate track.

First of all, we will define damage patterns. A damage pattern is, in fact, a characteristic damage presentation, composed of a typical combination of symptoms and context conditions. These patterns are gathered from our collection of cases, by clustering those cases with similar features and describing them using the definitions proposed in Part II.

The relations between causes and context conditions are determined in a rather straightforward way. Wherever possible, they are derived directly from the original case descriptions as found in the literature. Further provisions, such as on the intrinsic sequence of events, are stipulated using the descriptions of damage processes as presented in the handbooks and, of course, common sense.

To define the links between damage patterns and causes, we follow an additional approach beside the one stated above. This approach is retrospective: starting from the result, the damage, we thoroughly examine in what way and under what circumstances it must have occurred. The interpretation of relative movements is taken as a starting point. In short, principles of applied mechanics are used to relate symptoms to stress states, and then stress states to internal reaction forces, and finally internal reactions to external (applied) loads. Both orientation and support of the damaged element, as well as prevailing directions of loads are of influence, which implies that here, too, some relations between context conditions and damage processes may emerge.

Following above procedure, all components will be correlated explicitly. Chapter 8 combines the results of these three tracks: the damage mechanisms are complete. They are the backbone of our diagnostic tool, which can now be developed.

3.3.4 Building and testing the system

Pursuing the procedure as described in the previous subsections yields an overview of damage mechanisms. These mechanisms contain all information we need. Now it is time to translate this information into a tool that is ready for use, and to check whether it works correctly. The broad outlines of these steps are presented below, but they will be discussed in more detail in Chapter 8 and 9.

Translating the relations into a system

The main difference between a pile of data and a valuable reference work is a register: a table of contents or a subject index that helps the reader to find the information he is looking for. The same is true for our diagnostic tool: it can only be a true support if the user can find his way. Preferably, this should be an easy way, too.

Our tool should allow a user to quickly reach the information that is applicable to the damage he has under investigation. We think that the best way to ensure this is to provide an index based on the appearance of damage. In other words, the damage patterns we have defined should form the main entries to our diagnostic support system.

When starting the tool, the first thing the user should do is determining which damage pattern corresponds best with the damage he investigates. To help him do this, we will build a decision tree. In this tree, our damage patterns are discerned on the basis of their most distinguishing characteristics. By answering simple questions on the visual appearance of a damage, the user is directed to the appropriate pattern. In this way, a visual inspection should suffice to determine the damage pattern at hand. Subsequently, this damage pattern will function as reference to corresponding causes and relevant context conditions.

This PhD research results in a paper version of the support tool. However, as has been argued in Section 3.1.3, the ideal we pursue is to use this version as the basis of a computerized and interactive diagnostic decision support system. Setting up software and actually building such a digital system lies beyond the scope of this study. Nevertheless, we intend to present our results in a way that allows for an efficient and effortless conversion into a digital tool: a logical step to take after completing the thesis.

Testing the system

Using our tool should offer support in the diagnosis of structural damage in masonry. But will the tool indeed be experienced as useful? The final step is to hand the tool over to potential users, and let them evaluate our product in practice.

The participants we invited for this usability test belong to the four target groups for our diagnostic support system: Monument Watch inspectors, engineers, researchers and students. Each of these groups has a different level of experience in and knowledge of structural damage. We expect that our tool can offer support on these different levels.

The participants are asked to deploy our tool in a visual inspection that is part of their work routine. With a questionnaire based on the criteria formulated in Section 3.1, we collect their opinions. The review report based on these opinions will end in conclusions on the tool as presented in this thesis and in recommendations for further development. These are presented in Chapter 9.

3.4 Conclusions

This chapter has presented the method applied in this research project. We have formulated criteria for content and access to content that the product of our study should fulfil. This end product, a diagnostic decision support tool, will be a paper version. Nevertheless, additional demands have been taken into account to make sure that our tool can successfully be developed into a digital system in a later phase.

On the basis of these criteria, a line of approach has been determined. We have argued that the data for our tool will be extracted from cases published in literature, since we assume that these have been selected by the authors for their importance and representativeness. To structure these data, the damage mechanism concept has been developed. Essential part of this concept is that it differentiates between damage processes and factors (context conditions) influencing the course and extent of these processes. In addition, it organizes both subprocesses and factors on scale level.

The actual procedure has been based on this line of approach. Having selected the literature, it is now time to compile the data, relate these data and build and test the system. This procedure will be put to practice in Part II and III of this thesis.

Part II

Three components

The previous introductory chapters have stated that, to improve the diagnosis of structural damage, more insight is needed into how symptoms and context of a damage can help in retrieving its cause. Part II of this thesis gives an overview of the causes of structural damage, its symptoms and those context conditions that may influence the occurrence or extent of this type of damage. Each of these three components is discussed in a separate chapter.

Chapter 4 starts with a review of typical causes of structural damage that can affect masonry buildings in the Netherlands. Next, Chapter 5 describes the symptoms to which these causes can lead, and the combinations in which they typically appear. Finally, Chapter 6 deals with the context conditions of the damage: the environmental, geometrical, material and time-related factors that influence damage processes.

Chapter 4
Causes of structural damage

A diagnosis should answer the question what has caused a certain damage. To be able to establish such a diagnosis, one needs thorough insight into all processes that could possibly have affected the building under investigation. The present chapter intends to provide an overview of typical causes of structural damage in masonry buildings in the Netherlands.

Section 4.1 starts with explaining how we have classified the different causes. We discern three main groups: settlement, overloading and hindered dimensional changes. In the subsequent sections, 4.2-4.4, we will sketch in broad outlines how each of these groups of causes develops. The last section, then, recapitulates these causes of structural damage in a diagram.

Together with the results of the next two chapters, the causes presented here will be used in Part III of the thesis to create a diagnostic tool.

4.1 Defining causes of structural damage

In this chapter, we will present an overview of possible causes of structural damage in masonry. In line with Section 2.1.3, we will include those processes that can lead to cracks, deformation or tilt, as these may be taken as signs of insufficient loadbearing behaviour of a building. Both course and effects of the damage processes will be described in broad outlines.

To have an overview of the causes that can lead to structural damage is of vital importance in the diagnostic process. To reach a sound diagnosis, all possibilities should be considered and compared. Especially in the initial phase in which hypotheses are formulated, an inspector needs to be aware of the full range of options: overlooking an alternative in this phase may well lead to an incomplete or even incorrect diagnosis.

Passing every possible cause under separate review, however, is not an easy task: the number of processes that may lead to structural damage is large. In his book *De lotgevallen der Nederlandse kerkgebouwen* (Vicissitudes of Dutch church buildings), Janse [1968] has given ample proof of this situation by depicting a variety of cases of damage in church buildings. We have summarized and exemplified the most important occasions in Table 4.1.

With his enumeration, Janse has demonstrated how closely the construction histories of church buildings are connected to the ups and downs of the societies of which they are part. It is evident that people and buildings have been struck alike by acts of war, floods and fires. Rightly, Janse poses the question whether there is any (church) building at all that has not suffered from some kind of damage.

To create a clear and useful overview of causes, it is first of all necessary to group them in a logical way. But before discussing our proposal for structuring, we first want to draw attention to the fact that there are three ways of looking at causes of structural damage.

Table 4.1: Events that caused damage to historical church buildings, according to Janse [1968]

Types of incidents leading to damage	Examples of such incidents
Acts of war	Plundering
Building site is awkward	Building site previously partly built-on, partly undeveloped Burials beneath the church floor Caving-in of the building site Ground pressure of a dike Systematic lowering of the water level of a polder Undermining of the building site
Earthquake	Earthquake
Erroneous demolition	Erroneous demolition of flying buttresses Erroneous demolition of piers to increase the bay size Erroneous demolition of tie beams
Explosion	Explosion of gunpowder store
Fire	Arson Careless handling of fire during maintenance works City fire spreading to church Stroke of lightning
Flood	Collapse of a dike
Foundation problems	Decay of timber foundation piles Differences in foundations between building parts
Ill-advised use of materials	Portland cement used to plaster a wall Zinc roofing to replace the more durable lead
Increased load	Overloading of nave due to leaning of the tower Reuse of the church as a warehouse Overloading of piers of the crossing due to tower
Lack of coherence in structure	Lack of connection within the roof structure
Poor maintenance	Dereliction Disuse
Storm	Hurricane Whirlwind

4.1.1 Three ways of looking at causes of structural damage

In Section 2.1, we have defined damage as the manifestation of a lack of performance: the behaviour of a building under imposed actions does not meet the expectations or requirements claimed by its occupants. From this definition, it follows that there are two aspects to the occurrence of structural damage: either the behaviour of the building is less than expected, or the loads on the building are larger than was estimated. Both viewpoints emerge from the descriptions of damaging events by Janse [1968], as presented in Table 4.1.

Of course, these are two sides of the same coin: whether one considers a defect as a shortcoming of the building or as the result of an unforeseen incident, both interpretations can in some way be justifiable. We have decided to include both points of view in our overview. Not only does this avoid a chicken-or-egg dilemma, in this way the mechanisms will also clearly demonstrate that there are two ways to deal with structural damage: change the behaviour, or change the loads. Both approaches can then be readily envisaged when selecting an intervention strategy.

A third aspect that could lead to the observation of damage is an increase in the demands that people make upon buildings. Although one may argue that increased performance requirements can be regarded as sociological sources of damage, they are not causes in the technical sense. Therefore, this aspect will remain outside the scope of this thesis.

4.1.2 Organizing causes of structural damage

To relieve the diagnostic task of reviewing all optional causes separately, it is common practice to use a classification. Clustering causes with similar characteristics allows one to determine more quickly which sets of processes may or may not underlie a particular damage. Once the relevant sets have been established, further investigations can focus on their subgroups. In this way, hypotheses can be eliminated in an efficient way.

This principle of categorizing causes of damage may sound rather self-evident. However, Section 2.1.2 has shown that it is not at all easy to set up a classification that is unambiguous. There simply is no standard approach towards classifying causes of structural damage.

The handbooks included in our literature sample each follow their own arrangement of organizing causes, as has been illustrated earlier in Table 2.4. Some handbooks distinguish between imposed forces and imposed or restrained deformations, others discriminate between active and reactive, static and dynamic, or permanent, variable and exceptional loads. As a result, groups of causes overlap between the handbooks, and sometimes the clusters within one book are not exclusive either.

Diagnostic handbooks and tools would gain in serviceability when this lack of clarity could be removed. Fact is that the clearer information is structured, the more it can provide overview and insight to the user: not only is a well-organized categorization more self-explanatory and, thus, easier to comprehend, it is just as well more instructive, since it allows users to find connections. Hence, in this thesis, we propose an improved classification of causes.

The classification that this thesis puts forward is primarily based on scale level. This is in line with the damage mechanism concept, as introduced in Section 3.2.2. The damage mechanism concept discerns three scale levels. From largest in size to smallest, these levels are area, building and component.

For the classification of causes, we use these three scale levels to distinguish between the prevailing loads working in and on a building. To be more precise: we discern types of loadings by looking at differences in their points of application. This brings us to three categories of causes. These are:

- Settlement;
- Overloading; and
- Hindered dimensional changes.

Each of these categories relates to a scale level, as is illustrated in Figure 4.1: Settlement is about the interaction between building and ground, which takes place at the level of the area, while overloading occurs at the level of the building, as it concerns the way loads are transferred and balanced within a building. The group of hindered dimensional changes, on the other hand, refers to stresses and strains at the component level, resulting from swelling or shrinkage of individual building parts.

We anticipate that adhering to the scale levels proposed in the damage mechanism concept will provide the best opportunities to define clear and mutually exclusive categories. In addition, we expect it to result into groups of causes which share essential and, thus, distinguishing characteristics, regarding both their origins and their effects. Finally, we suppose that this classification of causes will help us later, in Chapter 6, to point out the role of material, geometrical and environmental influence factors.

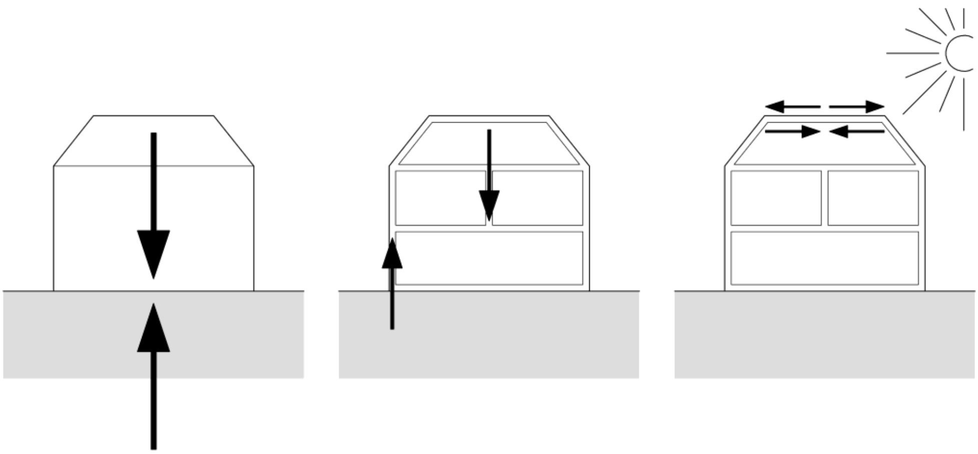


Figure 4.1: The three categories of causes of structural damage distinguish themselves by the scale level at which they affect the load equilibrium. From left to right: settlement, overloading, and hindered dimensional changes.

In the following sections, we will examine the processes behind settlement, overloading and hindered dimensional changes. Specific attention will be paid to their triggers, as this gives insight into possible remedies: removing the trigger may stop an ongoing process and prevent further damage to arise.

In the analysis of these damage processes, we start from the idea that structural damage always results from a change (in time or in place) in the force equilibrium. A stable situation becomes unbalanced and, in search for a new equilibrium, the building needs to adjust itself. The only way it can do this is by deforming or cracking, and it is these adjustments that, as soon as they exceed certain limits, may be regarded as damage.

In the descriptions of causes of structural damage, we have confined ourselves to a level of detail that is helpful in the initial phase of diagnosing. In other words, causes are not specified further than where they could still be distinguished on the basis of a visual inspection, simple tests or archive material. For the selection of hypotheses, this is the information one needs; determining the exact, case-specific cause is reserved for the subsequent diagnostic stages.

4.2 Settlement

The previous section has pointed out that the occurrence of structural damage can always be linked to a change in force equilibrium. Settlement processes, are those processes that are initiated by changes in the balance between building and soil. Foundations play an intermediary role in this balance: they transfer the forces from building to soil and vice versa.

General occurrence of settlement

The process that is generally associated with settlement is as follows. A load is imposed on soil – for instance, a new building is constructed. To reach an equilibrium situation, the total load resulting from this building needs to be counterbalanced by a support reaction offered by the ground on which it stands. Support reactions, however, do not appear without side-effects. To counterbalance imposed loads, the ground must supply internal reaction forces. These cause local stresses and strains, leading to deformations and displacements in the soil. As a result of and as a reaction to the load, the soil volume is compressed and compacted. Depending on the stiffness ratio between building and soil, the building that stands, via its foundations, on this soil has to follow the soil deformation and settles. We speak of settlement-related problems when this interaction between building and soil leads to damage in a building.

Although settlement processes have a bad reputation, especially in the Netherlands, it is important to note that they should not automatically be regarded as problematic. The weight of a superstructure will always lead to some compression of the soil and, thus, to settlement. As Beckmann and Bowles [2004] state: ”No foundation carries load without settling! Settlement is an inherent part of foundation behaviour and is not, per se, a sign of deficiency or danger.”

From the above, one can deduce that there are three actors involved in the balance between building and soil:

- The resultant load, imposed by a building;
- The foundations, which should transfer this load to the ground; and
- The subsoil, which should balance the imposed load to support the building.

A change in one of these actors that is not counterbalanced by an equal change in its opponents will inevitably lead to a disturbance of the equilibrium situation and, as a consequence, to movement.

Based on this analysis, we propose to distinguish between three types of settlement processes: those resulting from a change in load, those brought forward by a change in the foundations, and those induced by a change or transition in soil conditions. Figure 4.2 illustrates these three types of triggers. Each of them will be amplified in a separate subsection. But first, we will briefly consider the effects settlement can have on a building.

General effects of settlement

Despite differences in origin, the effects of settlement on a building can best be distinguished by looking at the direction of the movement and at its distribution, its position in relation to this building. For the direction of movement, it is important to realize that settlement-related processes do not exclusively lead to purely vertical, downward displacements, which are usually labelled as settlement. Changes in the soil-structure balance can also lead to vertical upward movement. This is called heave. In addition, the displacement may have a horizontal component, too. Nevertheless, since the term settlement is far more current than heave or horizontal soil movement, we have chosen to adopt this term as *pars pro toto* name for this group of causes.

More decisive for the development of structural damage than the direction of movement is the distribution of this movement over the base of a building. We discern

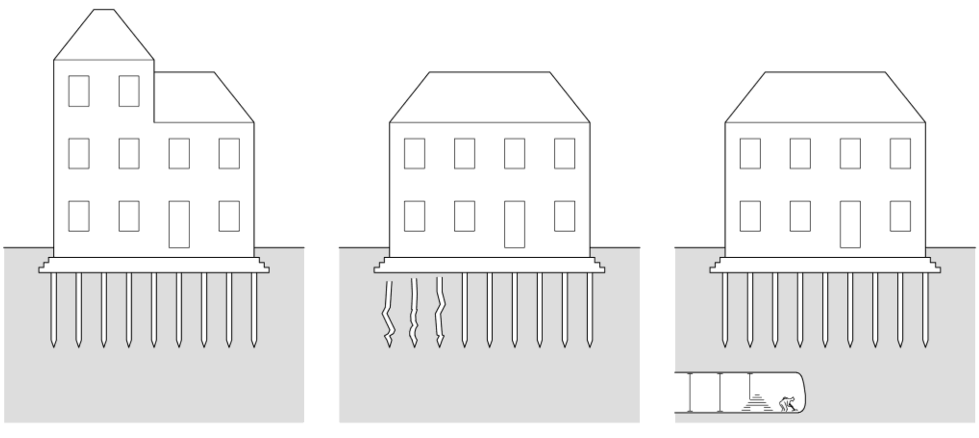


Figure 4.2: Settlement can be attributed to three types of changes: a change in load, a change in foundation behaviour, or a change in soil behaviour.

three options: uniform, inclined or differential displacement. These options are illustrated in Figure 4.3.

By uniform displacement, we understand a displacement that is the same for the whole building. Usually, this does not affect the loadbearing behaviour within the building. However, problems may arise with the connections between the displaced building and its unmoved surroundings. One can think of the sewerage system, or service pipes for water, electricity and gas, which are usually not able to accommodate much movement. In more extreme cases, access to a building can be obstructed: what used to be the ground floor is slowly turning into a basement. This effect can, for instance, be observed in the tower of the church of Sint Jacob in Leuven (Belgium), see Figure 4.4.

Under inclined settlements, on the other hand, one side of the base moves more than the opposite side. This leads to a rotation: horizontal planes start to slope. Nevertheless, flat planes remain flat. This effect is called tilt. Tilting may affect the normal use of a building, as floors tend to deviate from the horizontal. Also, the drainage of roof gutters and the like can be hindered, which may result in leakage.

The third option is differential movement, in which one point of a base displaces more than the surrounding points, and horizontal planes distort: they are not flat anymore. This distortion makes that differential movement results in damage sooner than uniform or inclined movement would. Even when the absolute movements are small, it can lead to severe damage and serious discomfort and alarm.

The occurrence of differential movement can be seen as a catalyst in settlement-related damage processes. Returning to the three actors involved in these processes allows us to specify what underlies its occurrence: differential settlement arises when one of the three actors (load, foundation or soil behaviour) is distributed unequally over the area (or

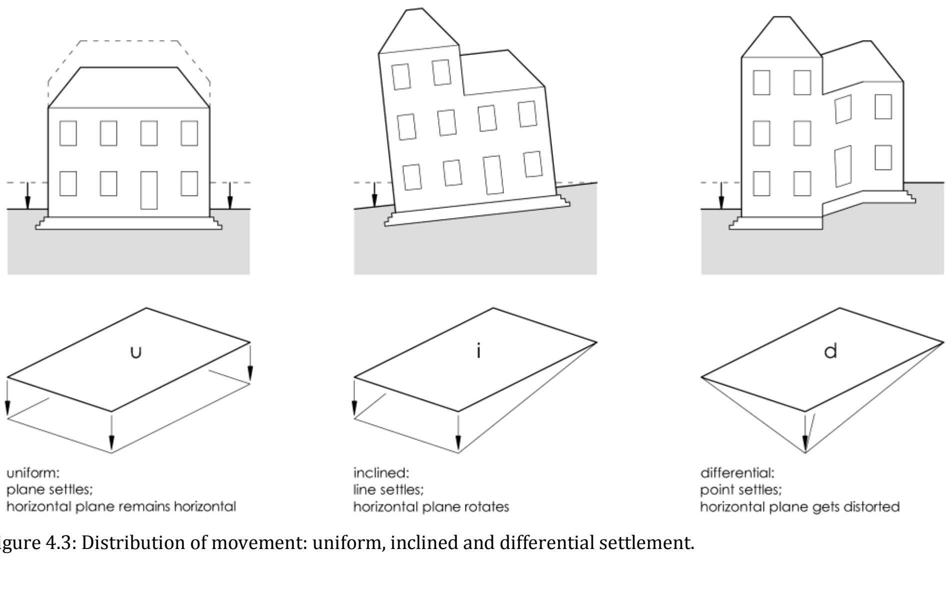


Figure 4.3: Distribution of movement: uniform, inclined and differential settlement.

Figure 4.4: The original entrance to the tower of the church of Sint Jacob in Leuven (Belgium) now lies almost two metres below ground level.

along the perimeter) of a building, and is not counterbalanced by an equally uneven distribution of its opponents. For example, structural damage may arise when the same foundation system is used for a three-storey building and for its one-storey extension.

Summarizing, we can state that a change in one of the three actors involved in the balance between building and soil suffices to initiate a settlement process. However, if there is an unequal distribution of this change, be it in time or in place, the probability that structural damage will arise increases dramatically. Hence, it is the unequal change in one of the actors that is the most important cause of settlement-related damage.

4.2.1 Settlement due to a change in load, imposed by the building on the soil

A change in load, imposed by a building on the soil below it, is one of the three triggers we have identified to initiate settlement processes. As described under the heading 'general occurrence of settlement', imposing a load on soil will generally lead to consolidation of this soil, the only exception being when the soil has already been subjected to much higher pressures earlier. The latter concerns so-called overconsolidated ground. Consolidation, as will be further explained in Section 4.2.3, is accompanied by a decrease in soil volume, which in turn leads to settlement.

In a similar way, removing a load that had been imposed on the ground earlier can bring about relaxation, volume increase and, thus, heave. However, this volume increase usually constitutes only a fraction of the volume decrease once endured when the load was applied. Part of the deformation due to loading is irreversible, and will remain even after unloading.

In this subsection, we focus on a change in direct loading: that is, in the load resulting from the building that suffers the damage. Indirect loads, imposed on the soil by objects adjacent to the damaged structure, are discussed in Section 4.2.3. From the direct loads, gravity loads make up the lion's share. Especially the weight of a building itself is a heavy contributor. This self-weight, imposed when the building was constructed, can change during the lifetime of a building. Most obviously, this occurs when an extra floor is built on the roof, or when an extension is added to one of the sides. However, also renewal of the roof covering can entail an increase in weight, if one opts for a more weighty roofing material.

Apart from this self-weight, another change in load that is important for settlement processes is that resulting from a change in use. In those cases where factories or warehouses are converted into apartment blocks, the resultant load will usually decrease: this situation rarely leads to damage. Nevertheless, adding floors and, thus, floor space in previously not so densely used buildings, such as churches, can mean a substantial increase in weight. Especially when the new function is characterized by a high floor load per square meter, as is the case for libraries and archives, for example, a change in use can yield settlement.

In line with the remarks made under the heading 'general effects of settlement', the probability that structural damage arises increases when loads are not distributed uniformly over the foundations. This occurs, for instance, when a building consists of several volumes with different heights – and, thus, weights –, while these differences in volume are not reflected in the foundations. Similarly, interventions in an existing structure can alter the load path in this structure in such a way that the loads are no longer distributed evenly over the foundations.

Uneven distributions of loads along the length of a foundation can lead to differential settlement. However, also an uneven distribution over the width of a foundation is unfavourable. This eccentric loading may form the onset of tilt, which in turn increases eccentricity. Ultimately, this might result in progressive leaning.

Summarizing, the origin of the type of settlement dealt with in this subsection lies in a change in load. This typically results from a change in self-weight or a change in use load. Since differential movement brings about the biggest risk on damage, we have focused on load situations that are most likely to give rise to this type of movement. This leads to the following variants of causes:

- Differential settlement due to differences in self-weight of the building;
- Differential settlement due to differences in use load; and
- Differential settlement due to an uneven distribution of loads on the foundations.

For these three options, it is assumed that the differences in loading occur for the same foundations and the same soil conditions.

4.2.2 Settlement due to a change in foundation behaviour

A change in the foundations is the second trigger that can initiate settlement processes. Foundations play an intermediary role, transferring loads between building and soil. One can think of the overall equilibrium system as consisting of three superimposed zones: building, foundations, and subsoil. In fact, the system's composition may be compared to that of a bird table, see Figure 4.5.

The analogy with a bird table draws attention to the fact that it is the soil below the footing of the foundations that actively offers most of the support. Hence, the choice of depth of this footing determines on which layer of soil the load is placed. Where the top soil is firm, a shallow foundation may suffice. However, in many regions in the Netherlands this is not the case, and pile foundations of more than 20 m can be needed to bypass weak layers and find support in deeper zones.

Figure 4.5 also nicely illustrates that foundations may take up only a small part of the basal area of a building. It points out that load transfer can involve load concentration. This concentration, too, depends on the type of foundation system used: shallow foundations can distribute load over a strip, but usually draw on a limited layer of soil height, while pile foundations find support at their pile tip, but also, to some extent, along their shaft.

A change in the foundations automatically implies a change in the load transfer between building and soil. This can be the onset of a settlement process. Apart from the phase in which it is constructed, a change in the foundation usually comes down to a decline in its behaviour. For timber (pile) foundations, this is associated with wood rot. It is good to notice that there are two main types of wood rot. The most diffused one is fungal wood rot. This can only occur in situations where both moisture and oxygen are present, and is often associated with lowering of the ground water level. Bacterial degradation, on the other hand, can also take place in anoxic conditions, e.g. below ground water level.

Another process that we would like to bring forward in this subsection is salt attack on foundations. Masonry and concrete foundations can be affected by sulphate salts that may react with components contained in Portland cement or hydraulic limes. This reaction generates swelling compounds (formation of ettringite or thaumasite), resulting in an upward pressure from the foundations on the building. This may, eventually, lead to heave.

Strictly speaking, the process of salt attack belongs to the category of hindered dimensional changes, as will be discussed in Section 4.4. However, this specific variant where salt affects the foundations can lead to effects identical to those of true settlement processes, and it may only be discerned from the true ones by digging a trial pit. Therefore, we have decided to include this cause in the category of settlement.

Summarizing, a change in foundation behaviour can originate settlement. This change can lie either in construction works (initial or repair), or in degradation of the material, due to wood rot or salt attack. As differential settlement poses the biggest threat, we have focused on possible causes that would have this effect. We distinguish between the following options:

- Differential settlement due to differences in foundation type or depth;
- Differential settlement due to differences in basement layout (i.e. a basement that extends only below part of the building);
- Differential settlement due to local decline in foundation behaviour, due to wood rot; and
- Differential heave due to salt attack on the foundations.

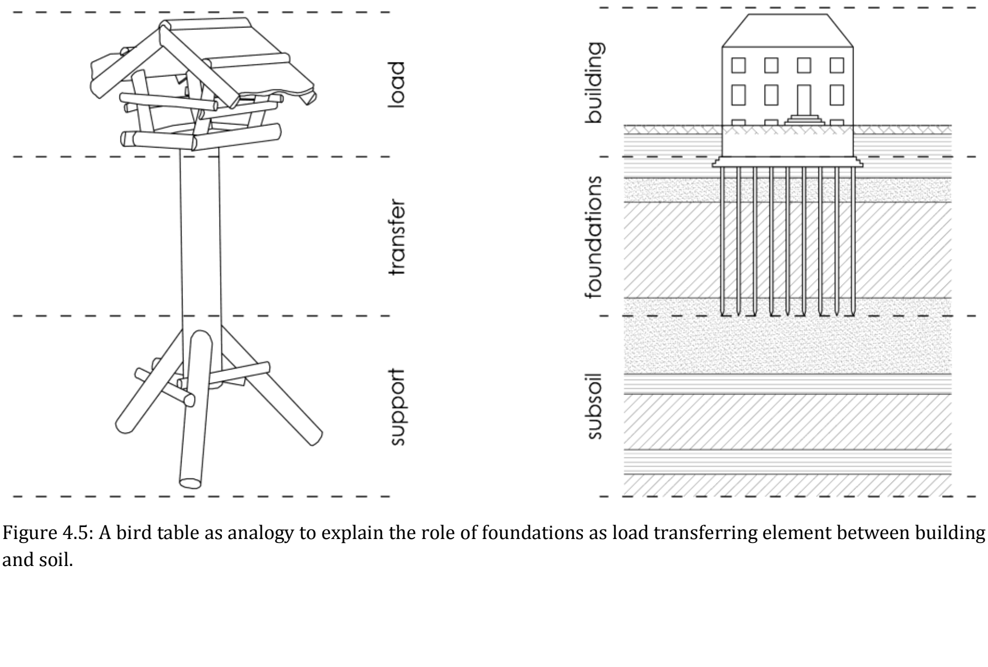


Figure 4.5: A bird table as analogy to explain the role of foundations as load transferring element between building and soil.

For these four options, it is assumed that the differences in foundation are not counterbalanced by load or soil conditions.

4.2.3 Settlement due to a change in soil behaviour

The third trigger that can initiate settlement processes is a change in soil behaviour. It implies a change in the support ground provides to a building. This, in turn, can affect the force flow in the building, and may result in structural damage.

Before discussing the different processes that can underlie a change in soil behaviour, it is useful to examine the material soil a bit further. Since it lies outside the scope of this thesis to treat the complex behaviour of soil in all its aspects, we will limit ourselves to the basics. For a more comprehensive description, reference is made to specialized books in the field of soil mechanics. The following explanation has been based on the work of Verruijt and Van Baars [2005].

General characteristics of soil

Soil, like masonry, is a composite material. It contains granular particles, the grain size and chemical composition of which determine the soil type. The packing of the particles can vary from loose to dense. Still, even when densely packed, the particles do not make up the total volume: there are always voids in between. These voids, or pores, can contain either liquid (e.g. water) or gas (e.g. air). As most soils have a porosity of 30-45 %, 1.0 m^3 contains an average of 0.30-0.45 m^3 of water or air. Hence, soils consist of particles, water and air. To understand how soil behaves, one needs to understand the interaction between these three components.

One of the characteristics of soil is that its bearing capacity depends not only on the grain skeleton, but also on the water contained in the pores. In other words, a load imposed on soil is carried by both the particles and the water. The total support a soil can deliver is, thus, the sum of the pore pressure and the stress acting in the contact points between the particles, the so-called effective stress.

The relation between pore pressure and effective stress should be seen as a force equilibrium. It is a matter of interaction: lowering the water pressure in a soil inevitably leads to a decrease in pore pressure, which needs to be counterbalanced by an increase in effective stress. This results in a denser package, a decrease in soil volume and, thus, settlement. Conversely, an increase in water content will eventually lead to a decrease in effective stress, an increase in soil volume and, ultimately, heave.

With this, it is also possible to explain the effect that imposing a load on soil has: it increases the pressure on the water in the pores. The reaction to this is that water will slowly be squeezed out of the pores, leading to consolidation. Hence, an increase in load imposed on a soil can trigger a similar process as a decrease in water pressure, for instance by lowering of the polder water level.

From the above, one can infer that soil does not behave in a linear elastic way. A denser package makes soil stiffer and stronger. In other words, the behaviour of soil depends on the imposed stress level.

Although above-mentioned mechanisms apply to soil in general, distinct soil types can – when exposed to identical conditions – show quite different reactions. Most notable is the difference between cohesive and granular, non-cohesive soils. Granular soils, such as sand, combine a high permeability with a low compressibility, while cohesive soils, such as clay, are much less permeable and much more compressible. These differences in properties show as differences in both rate and amount of settlement. Especially in clay ground and peat, settlement processes can continue for many decades after a load has been applied.

These differences between soil types are all the more important since ground usually has a layered composition. It consists of superimposed strata where, for instance, clay, sand and peat alternate. The exact composition is site-specific. Moreover, the thickness of layers can vary locally, even within the area of a building.

Apart from a non-uniform composition of soil strata, further natural local variations in soil composition include the presence of a peat lens or a geological fault line. Nevertheless, human intervention can also play a role here. The presence of a filled-in canal or remains of an earlier building are good examples; another one, situated more deeply, is the proximity of a coal-face of mining activity (see Figure 4.2).

The role of soil in settlement processes

From the above, one can draw conclusions on the role that soil plays in settlement processes. It is clear that soil behaviour cannot be assumed constant – in space nor in time. Changes in soil behaviour that initiate settlement processes fall into three categories: they are due to either a change in the effective stress between soil particles, or a change in the pore (water) pressure, or a change in the load imposed on the soil. We will give a few examples of changes for each category.

For the first group, the change can be described as a direct intervention in the amount of soil particles present at a certain location. One can think of soil extraction, due to mining, tunnelling or digging of a deep excavation, but also of accidental washing away of soil, owing to leakage, flooding or landslide. In all these cases, the removal of soil leads to a reduction in its lateral stability and, thus, to a decrease in effective stress.

An additional option belonging to this category is the decay of organic soils, such as peat. Such soils may rot away. Much like wood, this typically occurs in situations where lowering of the ground water level has led to an increase in oxygen content. This phenomenon is particularly relevant for the Dutch situation, as peat can be found in many areas in the Netherlands.

The second category includes those changes that alter the amount of water contained in the soil. These changes can be a result of the weather, but they can also be man-made. Fluctuations in weather conditions can bring about an alternation of drying out and rewetting of the ground. If this drying out is more than usual, it may lead to irreversible consolidation. Some clay grounds, on the other hand, can swell to such an extent due to rewetting that a building may experience heave. In this context, it should be mentioned that growth of a tree or its removal might have similar effects on the water content of the soil.

Another weather-induced change is that of freezing of the soil. If the footing of a foundation has not been planned deep enough (in the Dutch situation, a depth of 0.70-1.20 m is advised), water in the soil below this footing can freeze and expand. Especially cohesive soils are susceptible to this phenomenon, which may result in frost heave.

Frost heave should not be confused with heave resulting from tree roots. The growth of tree roots below shallow foundations can lead to physical uplift of a building. Although in principle a form of overloading, we have decided to range this process within the category of settlement, since it has identical effects and can only be discerned from true settlement processes by digging a trial pit.

Man-made interventions in the water content are characteristic for the Netherlands, where the polder water level is highly regulated. The country even has specialized, regional public bodies, the *Waterschappen* (Water control boards), that are specifically charged with controlling and managing surface waters. Lowering of the polder water level can be necessary when consolidation results in wetting of the topsoil. Unfortunately, such a lowering usually causes even more settlement, turning out in a vicious circle.

Please note that raising the water level may also have negative effects. An increase in water content reduces the shear strength of the soil, with flowing of the soil as a possible consequence. In this way, more water leads to fewer particles, as these are washed away.

The third category concerning loads has some overlap with the options discussed in Section 4.2.1. However, while there the focus was on loads imposed by the damaged building itself, we here widen the scope to loads imposed by other objects, as an adjacent load can affect the behaviour of soil below a building. Examples of such a change in load are, for instance, the construction of an embankment or new premises next to an existing building (that may get damaged), or even periodical heightening of the street. But also vibrations in the soil, caused by an earthquake or machinery, belong to this category.

After this elaboration on how changes in the soil can initiate settlement processes in general, we now turn to those situations that typically lead to differential movement. We discern the following alternatives:

- Differential settlement due to differences in soil composition;
- Differential settlement due to differences in effective stress due to removal of soil;
- Differential settlement due to differences in pore (water) pressure;
- Differential settlement due to differences in load imposed on the soil (not resulting from the damaged building itself);
- Differential heave due to differences in pore (water) pressure;
- Differential heave due to local uplift by tree roots; and
- Differential soil movement due to vibrations in the soil.

For these alternatives, it is assumed that the differences in soil behaviour are not counterbalanced by foundations or loads resulting from the damaged building.

In closing Section 4.2, we want to emphasize that settlement processes are characterized by a strong and often complex interaction between the various actors and subactors. For instance, soil compaction may, via negative skin friction, put extra load on a pile foundation. Establishing the exact cause of settlement-related damage can, therefore, be an utterly complicated affair. Nevertheless, we hope to have provided the reader with an overview of possibilities that may not only help in formulating appropriate hypotheses, but might also assist in selecting a suitable remedy.

4.3 Overloading

The second group of loads is clustered under the umbrella term 'overloading'. Generally speaking, it is about failure that can be attributed to a situation in which loads imposed on a structure are higher than (part of) this structure can bear. The damage processes included in this category are induced by changes in the force equilibrium at the scale level of the building. The focus point in this section is, therefore, on the force flow between building components.

General occurrence of overloading

There are quite a lot of loads that act in and on a building. In equilibrium situation, all these loads must be transferred through this building down to the ground on which it stands. Hence, each load travels along a chain of building components, running between point of application and point of support. This chain is called the load path.

Each building component that is part of a load path must balance the imposed load, support it and transfer it to the next component. Considering self-weight, this implies that subsequent links together carry the weight of all their predecessors. The components along a load path should, of course, have sufficient capacity to fulfil their task. Overloading occurs when one of them is not capable of resisting its share of the burden.

Buildings, and especially traditional ones, generally have statically indeterminate structures. This means that not just one possible load path is provided, but a number of more or less equivalent alternatives. If that is the case, loads will always travel down along the path that is most resistant. As Feilden [2003] puts it: "… loads will take the path through the stiffer routes and by-pass those parts that give way more readily." Or, to look at it from the reverse side, building elements that are flexible enough to avoid loading will deflect, leaving the supporting task to those components which are not so flexible.

Please note that this also implies that elements that have not been designed to carry loads other than their own weight may, nevertheless, become part of the loadbearing structure. Partition walls, for instance, can unintentionally be forced to carry a deflecting floor. In extreme situations, structural alterations can even turn kitchen cabinets into loadbearing components, as Harris [2001] recounts to have happened in a colonial vintage stone house in Germantown, Philadelphia.

Failure of one loadbearing component always means that the load(s) involved have to change their route. As long as there is an alternative path along which force equilibrium can be reached, failure of one component does equal failure of the whole structure. In other words, structural damage in itself is not a bad sign, but merely an indication that a building has been able to adapt to altered circumstances.

We consider three elements important to the occurrence of overloading:

- The loads imposed in and on a building;
- The prevailing load path that these loads follow within this building; and
- The individual resistance of each building component along the load path.

A change in one of these actors will disturb the force equilibrium at the scale level of the building. This may cause structural damage.

Based on this analysis, we propose to distinguish between three types of overloading processes: those initiated by a change in load; those introduced by a change (intervention or disruption) in the load path; and those triggered by a change in the resistance of a loadbearing building component. Each of these three groups will be discussed in a separate subsection. But first, we will briefly turn to the effects overloading can have.

General effects of overloading

Support reactions to balance and transfer loads evoke local stresses and strains. As has been stated in Section 4.2 regarding settlement, no load is carried without deformation. Feilden [2003] puts it this way: "Under applied loads each element tends to give way to some extent and it is through this limited 'giving way' or deformation that the necessary resistance is developed." If such deformations become large enough, they may be regarded as structural damage.

Generally speaking, overloading starts with local stress concentrations. Depending on strength and stiffness of the building component in question, this may lead to structural damage: If stress exceeds strength, cracking will occur. However, if a building component has a relatively low stiffness, high stresses will rather lead to large deformations. Apart from this, also the stability of the structure may be jeopardized.

Although loads follow a path along the stiffest elements, weaker components that 'stand in the way' can still be affected: they have to deform up to the point where the stiffer element can take over. Thus, the observation that a relatively weak component shows structural damage may imply that it has carried – and possibly still does carry – part of the total load.

The extent of damage caused by overloading depends on two factors. First and foremost, it is determined by the extent of loading. The higher the load is, the more probable it is that the capacity of one of the loadbearing components is exceeded.

Nevertheless, the effect that this load has also depends on the (over-)capacity of the loadbearing elements on which it is imposed. This capacity is determined by strength and stiffness. Both are ruled by material as well as the geometrical properties, such as the layout and dimensions of the component.

4.3.1 Overloading due to change in load

A change in load is one of the three initiators we have defined for overloading processes. A change in load always results in a change in the force equilibrium within a building. It does not necessarily imply a change in the load path, though.

The loads that act on a building are mainly vertical and static, but there are also loads with a horizontal component and dynamic loads. We expect it to be relatively easy to discern the direction of loading from a damage presentation. Therefore, we propose to organize the loads according to their (dominant) direction. We distinguish between those acting mainly vertically, those working in horizontal direction, and those of which the horizontal and vertical component are equally important and oscillating: vibrations. These three groups will be discussed in the following subsections.

Overloading due to change in vertical load

Most of the loads working on buildings are gravity loads. They act, in principle, in vertical direction. Still, they can lead to horizontal actions as well, as the next subsection will show. The loads discussed in the current subsection all result from gravitation.

To a traditional masonry building, the most dominant load is its own weight. In general, this self-weight is reasonably predictable or, for existing buildings, estimable. Relative weight has always been a decisive factor in the selection of building materials: church vaults, for instance, have often been constructed with units that are lighter than those used for the walls and columns [Pieper 1983]. In fact, in the western parts of the Netherlands, timber instead of masonry was commonly adopted for vaults to minimize weight.

A change in self-weight only takes place in two situations: when a building is constructed, or when it is altered. The former is sometimes labelled as early-age loading. Damage resulting from it, if any, is typically associated with arches, vaults and domes. After removal of their centrings, they tend to settle slightly under the now-imposed self-weight [Harvey 2004].

In the latter case, one can think of extra floors added on top of a building, or internal changes that involve an increase in weight. Examples range from reroofing of slated roofs with concrete tiles, to pouring concrete bathroom floors and dividing open-plan spaces with extra partition walls. Reversing these processes would, of course, also change the self-weight; however, this only leads to damage if the removed component was bearing more than just its own weight.

Besides these so-called permanent loads, there are also more variable loads acting on buildings. These are called live loads or use loads. The weights of people, goods and furniture belong to this category. Especially for libraries, archives and warehouses, floor loads can be substantial. A change to these kinds of use can seriously affect the total load a structure has to carry.

The weight of precipitation is also a live load that acts in vertical direction. Particularly snow loads can lead to problems, since snow can accumulate more easily than rain. Where wind can blow snow into corners and against walls, considerable heights are possible [Cook and Hinks 1992]. This can cause sagging of the roof, which may aggravate the situation further. Although dangerous, with a risk of roof collapse, snow loads did not appear to have a huge direct impact on masonry. Therefore, they have not been included in our tool. After the recent church collapse in Diepenbeek, Belgium (see Section 1.1), we are inclined to reconsider this decision.

This brings us to three options of changes in vertical load that can lead to structural damage in masonry. These are:

- Overloading due to a change in load, vertical, due to an increase in self-weight, at time of construction (early-age loading);
- Overloading due to a change in load, vertical, due to an increase in self-weight, due to extensions built in or onto the building; and
- Overloading due to a change in load, vertical, due to an increase in use load.

Overloading due to change in horizontal load

The most important horizontal load working on buildings is that resulting from wind. Wind causes pressures on walls in the direction in which they are weakest: perpendicular to their plane. Especially in coastal areas, the forces created by wind can be substantial. Feilden [2003] reports that wind speeds of over 97 km/h mean, with gusts of 162 km/h are to be expected. This (roughly) corresponds with mean loads of 0.5 kN/m^2 and peaks of 1.3 kN/m^2 [Wendehorst et al. 2000].

It is, however, not only wind pressure that needs to be resisted, but also wind suction. This suction, acting on the lee side, imposes horizontal tensile forces, which especially connections between building elements may fail to withstand. Detached and blown-off elements such as roof tiles can be the consequence.

Since wind comes in gusts, pressure and suction may rapidly alternate. This dynamic loading can cause oscillation. For low-rise masonry buildings, which are well damped, the effects will be minimal. However, tall, slender buildings such as church bell towers can be susceptible to these vibrations [Hinks and Cook 1997]. They may lead to similar effects as the vibrations described in the next subsection.

Wind is a highly variable quantity. The force it actually imposes on a building depends on speed and gustiness, which are influenced by environmental and geometrical conditions. Location is an important factor in this, both in terms of the distinction between coastal and inland areas, as with regard to sheltering provided by mountains, woods or surrounding buildings [Cook and Hinks 1992]. The height of a building is of influence, since wind speeds increase with altitude. Finally, the orientation of a building determines which façades tend to receive the highest wind loads from prevailing wind directions.

Another source of horizontal loading is thrust. Thrust is the lateral force that can result from a vertical (gravity) load imposed on an inclined or curved building component. When this load is transferred axially (that is: without bending action), its direction is changed so that two outward, inclined forces are exerted on the supports of the component. This is illustrated in Figure 4.6.

Thrust is a geometry-dependent phenomenon. It is characteristic for arches, vaults and, to a lesser extent, domes. Also flat arch lintels can load their supports laterally, just as roof trusses when no tie beam or tie rod is provided at their springings.

The amount of thrust exerted by such a component depends on the load that it transfers and on its slope. This slope is defined by rise and span. Hence, the horizontal thrust is proportional to the total load and to the span between the abutments, and is inversely proportional to the rise [Beckmann and Bowles 2004].

As with wind, thrust often loads walls in the direction in which they are weakest, but in this case the load is always directed outward. If unrestrained, the effect of thrust is spreading of the supports. Provisions such as buttresses or ties should be made to counter this effect.

A third type of horizontal load appears in retaining walls. A retaining wall is a wall that separates two different levels of soil. It can be freestanding, creating a step in ground level, but also basement walls are effectively retaining [Beckmann and Bowles 2004]. Another component that can be regarded as retaining is the spandrel wall of an arch bridge, on which backfill exerts horizontal pressure.

Retaining walls must resist the lateral pressure generated by (loose) soils and groundwater. As was the case with thrust, this lateral pressure results from gravity: coarse-grained soils are not cohesive, and cannot keep steep slopes by themselves. Their internal structure is comparable to a close packing of spheres, as is shown in Figure 4.7. Where a steeper transition is to be created, the load of the additional fill, tending to slide off the 'natural' hill, needs to be counteracted.

According to Beckmann and Bowles [2004], the magnitude of horizontal force on a retaining wall depends on four factors. These are the difference in level of soil on the two

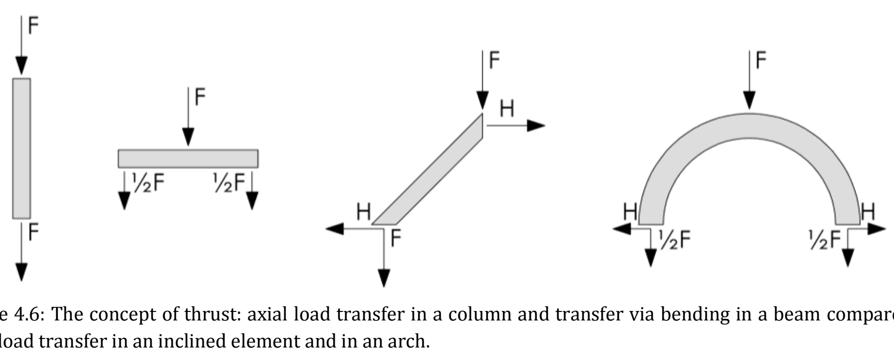


Figure 4.6: The concept of thrust: axial load transfer in a column and transfer via bending in a beam compared to axial load transfer in an inclined element and in an arch.

sides; the density of the soil, including the respective groundwater levels; the slope of the ground on the ‘high’ side; and the presence of any surcharge, e.g. in the form of cars, on this high side. They explicitly state that “any change of any of the above-mentioned parameters will … affect the horizontal forces acting on the retaining wall and will hence affect its stability. Excavations, other than small exploratory pits, at the low side of a retaining wall are particularly to be avoided.”

A last point that should be made in this context concerns the growth of plants in the retained earth. This can also introduce horizontal actions: tree roots penetrating into masonry and beneath foundations can lead to substantial rupture over time [Richardson 2001].

A less frequent, but more dramatic horizontal load is caused by impacts. Especially relevant for indoor spaces are gaseous explosions. They generate an omnidirectional pressure, of which the horizontal components acting perpendicular to the wall planes are the most harmful for masonry. Nevertheless, if weak parts such as doors or shutters are blown out, the resulting pressure release will reduce the impact (and damage) considerably.

Impact loads are often accidental, and associated with vehicles or other objects. Usually, it is about traffic or pedestrians hitting the edge of a building while turning round the corner. However, frontal collisions happen, too. In war zones, bullets and the like may also have left traces. Façades close to pathways, roads and drives are relatively vulnerable to this kind of attack [Cook and Hinks 1992].

Summarizing, horizontal loads can result from a number of different sources. Structural damage due to a change in horizontal loading can be due to one of the following options:

- Overloading due to a change in load, horizontal, due to push of wind;
- Overloading due to a change in load, horizontal, due to thrust of an arch, vault or dome;
- Overloading due to a change in load, horizontal, due to thrust of a flat arch lintel;

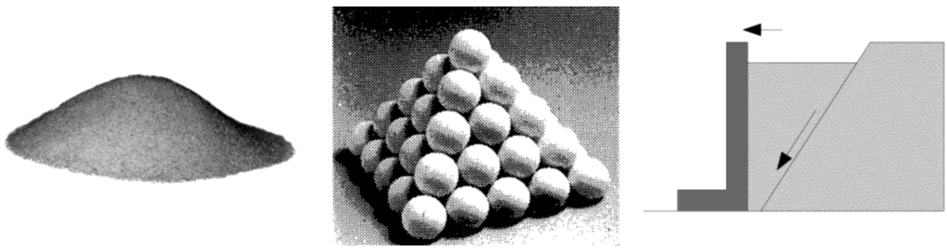


Figure 4.7: Granular materials such as masonry, concrete and coarse-grained soils cannot keep steep slopes by themselves (left). Their particle skeleton is comparable to a regular assemblage of equal spheres (middle, photograph by Beranek and Hobbelman [1993]). Any ‘additional’ fill beyond this slope tends to slide off, which needs to be counteracted by a retaining wall (right, drawing after Verruijt and van Baars [2005]).

- Overloading due to a change in load, horizontal, due to thrust of a roof truss;
- Overloading due to a change in load, horizontal, due to push of backfill;
- Overloading due to a change in load, horizontal, due to push of retained earth;
- Overloading due to a change in load, horizontal, due to push of tree roots;
- Overloading due to a change in load, horizontal, due to impact of object hitting an edge;
- Overloading due to a change in load, horizontal, due to impact of frontal collision;
- Overloading due to a change in load, horizontal, due to impact of internal explosion; and
- Overloading due to a change in load, horizontal, due to impact of acts of war.

Overloading due to change in combined vertical and horizontal load: vibrations

The third group of loads that may cause overloading are vibrations. They are characterized by oscillating movements back and forth (shaking), which produce both horizontal and vertical forces. In particular the horizontal components tend to lead to damage or even collapse, because constructions, and especially historical ones, are normally much better resistant to vertical loading [Croci 1998].

Vibrations can be natural or man-made. Wind gusts leading to oscillations certainly belong to the former, but the most powerful natural sources of vibrations are earthquakes. Earthquakes are due to sudden shifts of the earth's crust. Major shifts take place along edges of tectonic plates, but they also occur along smaller geological fault lines. In general, it is well known in which areas such earthquakes are to be expected. Nevertheless, the time of their occurrence is still difficult to foresee.

Feilden [2003] gives an overview of the factors that determine the extent of damage that earthquakes may cause at a certain location. The forces generated by an earthquake depend first and foremost on the absolute energy release, which is expressed in degrees on the Richter scale. Furthermore, they depend on how far a location is situated from the epicentre, what the main direction, frequency and amplitude of the seismic waves is, and what the local ground conditions are. Finally, the form, design and maintenance level of the building has a strong influence on the type and amount of damage.

Man-made vibrations can also be either ground-transmitted or airborne [Feilden 2003]. Apart from machinery placed within the building itself, the sources are usually outside the control of the user, designer or owner: traffic, railways [Cook and Hinks 1992], pile-driving or even induced earthquakes, which can result from mining activities and are quite common in the northern part of the Netherlands.

For church towers, bell-ringing poses an extra threat. The forces evoked by the swinging of the bells depend on the size of the bells and the way they are mounted [Pieper 1983]. The traditional Dutch mounting uses straight shafts, but replacing this by a crankshaft can substantially reduce the (most adverse) horizontal loads.

Vibrations cause buildings to shake. For earthquakes, especially the difference in reaction between building and soil can lead to damage: when, at some point, they move in opposite directions, horizontal shearing forces are created within the structure [Cook and Hinks 1992].

Buildings have a natural frequency, related to their dimensions and construction methods. Due to this, they can damp and counterbalance imposed oscillations. However, if a vibration has a frequency that is similar to one of the natural frequencies of a building, resonance can occur, coupled with even larger displacements and resulting damage [Cook and Hinks 1992].

For our tool, we propose to distinguish between two types of vibrations that may cause structural damage. These are:

- Overloading due to a change in load, vibrational, due to a (natural or induced) earthquake; and
- Overloading due to a change in load, vibrational, due to machinery or traffic.

4.3.2 Overloading due to change in load path

Apart from a change in load, overloading can also be provoked by a change in load path. This can be due to an active intervention in the loadbearing structure, or result from a more passive disruption of part of this structure. In any case, it involves a redistribution of forces.

We discern three types of processes that can underlie a change in load path: intervention, bending and displacement of supports. These are discussed in the subsections below.

Overloading due to change in load path, due to intervention in structural layout

As has been discussed under the heading 'general occurrence of overloading', earlier in Section 4.3, the path along which a load is transferred through a building depends on the layout and the stiffness ratios of the loadbearing components. Alterations to a structure, be it by removing (part of) a component or by putting one in, always entail a redistribution of forces. If such an intervention results in a weaker load path, structural damage may arise.

Local weakening of a structure can result from small-scale interventions that, when viewed apart, may look quite harmless. The notching of (timber) joists and beams, for example, can lead to problems. This notching is often done to make way for the installation of services [Cook and Hinks 1992]. This so-called plumber's or electrician's rot can have equally serious effects as fungal or insect deterioration [Richardson 2001].

In line with this, the ill-advised demolition of building components may lead to substantial damage. A frequent cause of problems is the erroneous removal of partition walls in houses and shops. Also the loadbearing function of tie beams, purlins, wind braces and struts is not always appreciated, so that seemingly innocuous works such as cutting an extra doorway or constructing a dormer can have unexpected and unpleasant effects [Cook and Hinks 1992; Richardson 2001].

The removal of lower portions of a chimney is inadvisable, too: the remaining upper portion may then act as an eccentric load on the wall it originally buttressed. Particularly dangerous can be the demolition of post-tensioned structures, as Cook and Hinks [1992] observe. Since these structures rely on the imposed loading to keep their shape and position, removal of this load can involve such a stress release that possible explosive failure of the elements and instantaneous collapse cannot be ruled out.

Local interventions can have large-scale effects, too. If essential partition walls have been removed in a terrace of shops or houses, the stability of an entire street may come down to one intact building. Removal of (part of) that building can then deprive the other premises from their last remaining lateral restraint. This may cause progressive leaning of the party cross-walls, or even make the whole street collapse [Cook and Hinks 1992; Richardson 2001].

Even replacing part of a structure can lead to structural damage. One example is façade renewal, which is quite commonly done to shops. With a trend to larger and larger shop windows, sometimes only (too) minimal space is left for a proper structure. Another example is the replacement of beams or bonding timbers that are partly incorporated in a masonry wall. Temporary removal of these elements may lead to a temporary change in the load path through the wall. Local bulging of the wall may be the result, which will show even after the beams have been substituted and the eccentricity cancelled out.

Above-mentioned alterations can all lead to an instantaneous weakening of the structure. Nevertheless, one should note that the effects may perhaps only become apparent under extreme wind or snow loads [Richardson 2001]. The interventions that are associated with examples of structural damage in masonry are:

- Overloading due to a change in load path, due to intervention in structural layout, due to removal of lower portions of a chimney;
- Overloading due to a change in load path, due to intervention in structural layout, due to removal of a mid-terrace building;
- Overloading due to a change in load path, due to intervention in structural layout, due to replacement of large part of the façade; and
- Overloading due to a change in load path, due to intervention in structural layout, due to replacement of a beam incorporated in the wall.

Overloading due to change in load path, due to bending

All loads lead to deformation. Relatively flexible building components may deform or deflect to such an extent that the load that was imposed on them is transferred to a stiffer component. In this way, bending of a component can change a load path.

Bending of a component can be regarded as structural damage in itself. However, in this subsection we focus on the effects it can have for adjacent building elements. In that context, one can state that bending can be harmful in two ways. On one hand, it can lead to additional loads on neighbouring elements. Especially when these extra loads are imposed eccentrically, or when neighbouring elements were never designed to carry loads other than their self-weight, this may lead to structural damage. Typical examples of this type of process are deflecting floor or roof slabs that gradually come to rest on partition walls, or frames that deform to such an extent that their infill is put under strain.

On the other hand, bending may also result in a loss of support for elements that were designed to rest on the now-deformed element. A well-known example is bending of a lintel that leaves the wall above it unsupported. The same may happen to floors and partition walls. Its effects may be observed clearly near cantilevered floors: if these deflect, all components supported by them will deflect in turn [Cook and Hinks 1992]. In addition, bending of floor or roof slabs may also lead to a loss of connection between this slab and its (end) supports [Pfefferkorn 1994].

The extent of damage that is caused depends on the stiffness of the element that bends, as well as on the stiffness of the adjacent element(s) that are discredited. The amount and distribution of loading plays a double role: an increase in load may lead to an increase in deflection, but it can also counteract this deflection if it increases the restraint offered at the end supports. Cumulative effects should be considered, too, since the change in load path resulting from one deformation can easily lead to another one. Finally, creep and shrinkage should be taken into account, as these can aggravate the initial deflection.

For bending leading to structural damage in masonry, we discern the following options:

- Overloading due to a change in load path, due to bending of a floor that is supported by damaged wall;
- Overloading due to a change in load path, due to bending of a floor that supports the damaged wall;
- Overloading due to a change in load path, due to bending of a frame; and
- Overloading due to a change in load path, due to bending of a lintel.

Overloading due to change in load path, due to displacement of supports

The third kind of geometrical change that can invoke a change in load path is typically associated with arches, vaults and domes. If the supports of these structures move in different directions, their springings are forced to do so, too. Arches can only accommodate such movement by adjusting their shape. This entails an alteration of the load path within the arch, which will, possibly, show as damage. The option belonging to this type of cause has been labelled:

- Overloading due to a change in load path, due to horizontal displacement of supports.

4.3.3 Overloading due to change in resistance of the building component

The third trigger to overloading is a change in resistance. It concerns changes or discontinuities in geometrical or material sense, occurring in the building element in which the damage appears. The two variants are discussed below.

Overloading due to change in resistance, due to a geometrical discontinuity

In the same way as stiffness ratios of structural components determine how load is distributed over these components, local variations in stiffness within a single element control the load path through this element. Geometrical discontinuities lead to such variations and may induce stress concentrations. Since, in principle, elements fail where stresses are highest, these stress concentrations point out the locations where structural damage is most likely to occur.

A good example of where stress concentrations are to be expected is near openings. Loads cannot travel through openings, but have to be transferred around them to the wall piers at either side. As a result, these wall piers need to carry a higher load than would have been the case if no openings existed. At the same time, the wall parts directly above and below such an opening lose some of the load that would have been imposed on them if the wall was continuous [Hinks and Cook 1997]. These local variations in stress level can lead to damage.

A second location where structural damage due to overloading is likely to appear is below a concentrated load. The end support of a beam is such a location. Spalling of masonry could be averted by incorporating a (beam) element in the wall, via which the load would be introduced in a more distributed way [Martens et al. 2007].

A comparable process may take place within the masonry, as Beckmann and Bowles [2004] describe. If individual units only bear on each other over a small proportion of the bed joint surface, the bearing stresses at the contact points may be very high and exceed the strength of the material. This type of failure is commonly linked to dry-jointed masonry and masonry where the stones have been worked with hollow beds.

Geometrical discontinuities can also result from a loss of bonding within a masonry component. Typical example is the loss of connection between the leaves of a cavity wall, either due to corrosion of the cavity wall ties, or simply because the required number of ties was never put in at the time of construction [Beckmann and Bowles 2004]. The leaves of a cavity wall are designed to act together, and they need the wall ties to do so. If this connection fails, the stability of the whole wall may be compromised: the slenderness of the separate leaves will make them liable to bulging [Cook and Hinks 1992].

A similar situation may occur in rubble-core masonry, where the skin may fail by buckling if it is not sufficiently connected to the core, or if mortar of this core is washed away [Beckmann and Bowles 2004]. It can also take place at a smaller scale. Some types of natural stone have a layered composition. When such a stone is not laid on its quarry bed, imposed loads may lead to delamination of these layers and, thus, to high local stresses.

When diagnosing, one should be aware that the effects of geometrical discontinuities may only show many years after a construction is completed [Richardson 2001], but that they can gradually weaken a structure up to failure, especially when eccentricity of loads comes into play. We will list the geometrical discontinuities that are relevant to masonry:

- Overloading due to a change in resistance of the building component, due to geometrical discontinuities near an opening;
- Overloading due to a change in resistance of the building component, due to geometrical discontinuities below a beam;
- Overloading due to a change in resistance of the building component, due to geometrical discontinuities within dry-jointed masonry;
- Overloading due to a change in resistance of the building component, due to geometrical discontinuities within stonework worked with hollow bed;
- Overloading due to a change in resistance of the building component, due to geometrical discontinuities in a cavity wall (wall tie deficiencies);
- Overloading due to a change in resistance of the building component, due to geometrical discontinuities within rubble-core masonry; and
- Overloading due to a change in resistance of the building component, due to geometrical discontinuities in stones not laid on their quarry bed.

Overloading due to change in resistance, due to decrease in capacity of masonry
The second type of change in resistance is related to a decrease in the material properties of the masonry. We distinguish between short-term and long-term changes. The former are usually related to moisture [Richardson 2001]: severe wetness lowers the resistance of masonry.

For long-term decrease in properties, creep behaviour should be mentioned. Creep is defined as the time-dependent deformation of an object under constant loading [Verstrynge 2010]. Primary creep occurs in the first years after construction, and hardly leads to damage. But if the process continues, the slow increase of deformations may lead to changes in the internal force flow.

Especially where stress levels are high, such as in the lower parts of tall, slender towers, creep can lead to slow but progressive damage accumulation. Cracks may develop very slowly, over decades or even centuries, and may long go unnoticed. This can lead to stress redistributions that may eventually result in a sudden collapse.

The following two options have been defined in this context:

- Overloading due to a change in resistance of the building component, due to a decrease in capacity of the masonry, due to wetness; and
- Overloading due to a change in resistance of the building component, due to a decrease in capacity of the masonry, due to creep.

4.4 Hindered dimensional changes

The group of hindered dimensional changes encompasses those processes in which swelling or shrinkage of an individual building part, or of an inclusion in such a component, leads to damage. This damage may appear in the element that has undergone the dimensional change, or in an adjacent element that hindered the movements of the former. In both cases, the damage can be attributed to the constraints that these elements impose on each other.

Hindered dimensional changes upset the force balance at the scale level of the building component. Although environmental conditions such as temperature play a role, material properties are of overriding importance here. After amplifying on the general occurrence and general effects, the various processes underlying hindered dimensional changes are discussed in separate subsections.

General occurrence of hindered dimensional changes

Materials are not static: they react to changes in their environment. This reaction may involve dimensional changes. In other words, materials can shrink or swell.

Whether these dimensional changes are reversible or irreversible, they need to be accommodated. In an ideal situation without restrictions, this would mean that all strains take shape in a deformation. However, within a building, the connections between different components and materials may suppress part of these strains. This suppression leads to stresses and, possibly, to cracks. Hence, dimensional changes can disturb the force equilibrium locally, and may result in structural damage.

There are two types of causes that can lead to dimensional changes in building components: physical changes and chemical changes. Physical changes, in turn, can result from two sources: a change in temperature, or a change in moisture content. As thermal and hygric conditions are partly interdependent, these two sources will be discussed together. However, one variant we do set apart. That is phase transition, which, in fact, occurs under changes in temperature or pressure. For structural damage in masonry, it is the process of freezing of moisture contained within a building component that is especially relevant in this respect.

For chemical changes, we discern two sources that often lead to structural damage in masonry. The first one is corrosion of metal, and particularly iron, elements. The second one is the formation of swelling compounds out of salts and certain mortar components.

Summarizing, we distinguish between four main sources of hindered dimensional changes that can lead to structural damage in masonry:

- A change in temperature and/or moisture content;
- Frost action;
- Corrosion; and
- Salt attack.

These variants will be dealt with in the subsequent subsections. But first, we will briefly discuss the general effects that hindered dimensional changes can have.

General effects of hindered dimensional changes

The primary effect of a dimensional change is, of course, expansion or contraction – be it uni-, bi- or triaxial. Such changes are, in themselves, usually not considered to be troublesome, but problems may arise when these movements are restrained. It is this restraining that leads to stresses and, eventually, to damage.

In buildings, the fact that elements are connected implies that they cannot move freely. If they expand, they press against each other; and when they contract, they exert tensile forces. These forces may lead to damage in the element that swells or shrinks, or in adjacent elements that hinder these changes.

In general, expansion can lead to crushing, buckling or simply pushing away of neighbouring objects. Contraction, on the other hand, puts elements under tension. As masonry has a relatively low tensile strength, this may lead to the development of cracks: the stresses induced by shrinkage can exceed the tensile strength. Hence, while its compressive strength may allow masonry to displace under swelling, at shrinkage it is sometimes not strong and coherent enough to be able to slide back and return to its original position.

In this context, one should also note that the presence of high compressive stresses, for example due to self-weight of the structure, may overrule tensile stresses acting in the vertical direction. However, such compressive stresses are present in lesser extent in the horizontal direction. Due to this effect, triaxial shrinkage may only show in vertical cracks, while horizontal cracks are suppressed.

The magnitude of the stresses or strains that occur due to hindered dimensional changes depends on two factors: the extent of the dimensional change on one hand, and the degree of restraint to this movement on the other hand. The former is determined by the type of material and by the physical or chemical conditions imposed. The latter is dependent on stiffness: the capacity of adjacent elements to accommodate movement, and the flexibility of the changing material itself to deform. It is clear that the combination of large dimensional changes and a high degree of restraining constitutes the most unfavourable situation and is most likely to lead to damage.

From the above, it is obvious that material properties have a strong influence on this type of damage process. They determine both the extent of dimensional change and the way in which a building component reacts to this change. Problems typically arise when there are differences in reaction between mutually restraining elements. Hence, the classic location where damage due to hindered dimensional changes may occur is at or near the connection between two materials. However, also a situation in which one material is subjected to different conditions at the same time is potentially problematic. This is, for instance, the case when a long wall is only partly heated by the sun. But already the common situation in which a wall starts below ground level leads to a temperature gradient in this wall between the part above and the part below the soil.

The possible effects of hindered dimensional changes are often underestimated. Although such changes only affect the force balance locally, the resulting damage can assume substantial proportions. This is especially the case when dimensional changes occur in a cycle, which is characteristic for most of the physical changes. Under cyclic conditions, the movement undergone at expansion is sometimes not fully removed at contraction. This can be either because the limited tensile strength of masonry prevents the object from sliding back, or because, in the mean time, cracks have become filled with dirt, sand or grains of masonry, which prevents them from closing. The crack width will then increase in the next cycle. A similar progressive effect can be observed in a frost action. When water can get into a crack, the expansion caused by frost will gradually wedge this crack wider and wider [Beckmann and Bowles 2004]. In these cases, damage will accumulate in the course of time.

4.4.1 Hindered dimensional changes due to changes in temperature and/or moisture content

The effects that changes in temperature and changes in moisture content have on buildings are discussed together. The reason for this is that they are, to a certain extent, interdependent: an increase in temperature can lead to a lowering in moisture content, as some of the moisture contained in a material will evaporate. This evaporation, in turn, brings about a lowering of the surface temperature. Reversely, an increase in moisture content decreases the thermal resistance of a material, so that it works less as a thermal insulator.

The general mechanism behind the type of damage process under discussion here is that an increase in temperature leads to an increase in volume, while a decrease in temperature results in a decrease in volume. Similarly, materials typically swell when they absorb moisture, and shrink when this moisture evaporates.

There are, however, some exceptions to this rule. An important one is water, which reacts differently to temperature dipping below 4 °C. While most other liquids decrease in volume when they freeze, water has its highest density and, thus, minimum volume at 4 °C. As a result, it swells when it is frozen. This effect can lead to damage, as will be discussed in Section 4.4.2.

In addition, the presence of certain salts, such as sodium chloride, can invert the reaction of a material to changes in moisture content. Instead of swelling at the absorption of moisture, mortar containing sodium chloride shrinks. This is due to dissolving of the salt. At subsequent evaporation, the salt crystallizes and the material shows an (often irreversible) expansion [Lubelli 2006].

All (building) materials exhibit dimensional changes when their temperature shifts. Usually, these changes occur in all directions, although the exact ratio depends on the iso- or orthotropy of the material. For hygric dimensional changes, only porous materials are susceptible. In most cases, this hygric movement is reversible. However, some materials can also be subjected to irreversible moisture movement. Clay bricks, for example, are very dry after being fired, and tend to absorb moisture from their environment in the period directly following their production. The expansion that attends this moisture absorption is irreversible, and it will exceed greatly the reversible hygric and thermal dimensional changes of this type of unit [Douglas and Ransom 2007]. In a similar way, unfired calcium silicate and concrete units are liable to shrink upon drying and hardening. Of course, the negative effects of these irreversible moisture movements can easily be averted by not using (too) freshly produced units. Nevertheless, in the case of cast in-situ concrete floors or roofs, the shrinkage upon hardening can hardly be prevented.

Due to their nature, most irreversible hygric movements occur early in a buildings life. Damage typically arises within the first year after construction, although this may depend on prevailing weather conditions. For thermal movement, there is only one event which could lead to irreversible changes: a fire. The extreme temperatures – and temperature gradients – may effectively change a material's composition, comparable to what happens with clay when fired. All other, less extreme temperature ranges only lead to reversible dimensional changes.

The amount of thermal or hygric movement that a building element shows in a certain situation depends on a number of factors. Key concepts in this are the properties of its material, the thermal and hygric conditions to which this element is exposed, and the flexibility of the building in accommodating dimensional changes. The subsections below will each deal with one of these three central concepts, and will explain how they may cause structural damage.

Differences in thermal and/or hygric behaviour between materials

The first factor that influences the extent of thermal or hygric movement is the type of material. Different materials react differently to changes in temperature or moisture content. Damage is most likely to appear where materials with widely divergent properties meet.

For thermal movement, the (relative) extent of dimensional change is expressed in the thermal expansion coefficient α, which is a material property. Clay bricks, limestone and wood have thermal expansion coefficients within a comparable range, which implies that they will behave similarly under similar conditions. Sandstone has a slightly higher coefficient and, thus, shows slightly larger dimensional changes. Nevertheless, problems typically arise when above materials are combined with concrete, calcium silicate or steel, as the latter three materials have coefficients up to twice as high as those of brick, stone and wood. As a result, they are up to two times as much affected by temperature changes.

For the amount of moisture movement, the porosity of a material is essential. The more permeable a material is, the more rapidly it responds to fluctuations in the ambient moisture content [Harris 2001]. Wood is very hygroscopic, and will keep shrinking and swelling as a result of changes in its moisture content. This warping is orthotropic: the movement in radial direction can be 10 times higher than that parallel to the grain. Hence, while the axial behaviour of wood is similar in extent to that of masonry, in perpendicular direction large differences can be observed [Pfefferkorn 1994]. Traditional detailing acknowledges this warping behaviour: mouldings were designed in such a way that they provide suitable locations where a 'shrinkage crack' would hardly be noticed.

On this basis, we can point out one source of structural damage related to differences in material behaviour under thermal and hygric changes. For masonry buildings, typical causes in this genre are:

- Hindered dimensional changes due to differences in reaction to changes in temperature and/or moisture content, between two types of units in masonry;
- Hindered dimensional changes due to differences in reaction to changes in temperature and/or moisture content, between two types of mortar in masonry;
- Hindered dimensional changes due to differences in reaction to changes in temperature and/or moisture content, between masonry and concrete; and
- Hindered dimensional changes due to differences in reaction to changes in temperature and/or moisture content, between masonry and timber.

Differences in thermal and/or hygric conditions

A second factor that influences the extent of thermal and hygric movement is the environment: the physical conditions to which a building component is exposed. These conditions determine in large part the range of temperature and moisture content fluctuations that a component has to undergo.

The temperature of an object can change by radiation, conduction and convection. Radiation is influenced by the exposure of an object to the sun and by the colour its surface. Dark-coloured surfaces heat up more quickly than light ones, but also cool down more rapidly. For convection, air temperature and the exposure of an object to wind are important factors. Besides that, also the texture of the object’s surface plays a role: the rougher this surface is, the larger its actual area is, and the more rapidly convection can lead to temperature changes. Conduction, finally, depends on the thermal capacity of a material, which characterizes the amount of energy (heat) required to change a body's temperature by a given amount, and on the presence of insulating layers.

All three heat transfer processes are governed by differences in temperature. Since indoor temperatures are usually kept fairly constant, the temperature changes through which internal building components go are only limited. External components, however, do often experience large thermal fluctuations.

In this context, it is good to note that the temperature of an object can rise well above that of the ambient air. While in the Netherlands air temperatures can fluctuate up to 25 °C over the course of a day, and more than 55 °C during a year [Koninklijk Nederlands Meteorologisch Instituut 2010; Stichting Bouwresearch 1966; Stichting Bouwresearch 1979], the temperature changes that black surfaces experience may actually be as much as twice as high.

Flat concrete roofs, for example, are notorious for their thermal movement, as they are highly exposed to both sun heating during daytime and radiation cooling to the sky at night. Especially in combination with dark-coloured roofing, this can lead to large diurnal dimensional changes. It is especially these rapid changes in temperature that can lead to damage: on one hand, because it is more likely that differences in temperature between objects will occur; on the other hand, because the building has no time to accommodate the thermal movements.

The moisture content of an object can, first of all, be determined by a direct inflow of moisture from rising damp, leakage, or excessive exposure to heavy precipitation. If no such direct source of inflow is present, the moisture content is dependent on the humidity of the air in combination with the temperature of the object itself.

Diurnal fluctuations in relative outdoor air humidity can be 30 % in the Netherlands. Indoors, the relative humidity shows slightly higher variations: 40 % is not uncommon. Nevertheless, changes in moisture content in materials as a reaction to changes in relative humidity of the air take place much slower than temperature variations do: in months, not hours or days [Stichting Bouwresearch 1979].

From the above, we can conclude that there are two ways in which structural damage in masonry can result from differences in thermal or hygric conditions. The first one is related to gradients occurring within the masonry. The second one has to do with sudden changes in the environmental conditions to which the masonry is exposed. We can summarize the options as follows:

- Hindered dimensional changes due to differences in temperature and/or moisture content, between building parts at the shady and at the sunny side;
- Hindered dimensional changes due to differences in temperature and/or moisture content, between building parts below and above ground;
- Hindered dimensional changes due to differences in temperature and/or moisture content, between building parts in-doors and out-of-doors;
- Hindered dimensional changes due to an abrupt, extreme change in moisture content, after production of unfired artificial stone units, leading to irreversible shrinkage;
- Hindered dimensional changes due to an abrupt, extreme change in moisture content, after production of fired clay bricks, leading to irreversible swelling; and
- Hindered dimensional changes due to an abrupt, extreme change in temperature, due to a fire, leading to irreversible swelling;

Lack of flexibility to accommodate dimensional changes

The third factor that determines the absolute magnitude of thermal or hygric dimensional change is related to the size of the building component. The greater the initial size is, the larger the absolute movement. As a consequence, bigger building components need more space to accommodate movement than smaller ones. At the same time, there are fewer joints to provide this space.

Damage arises when dimensional changes cannot be accommodated by the structure. This is a relatively new problem, which has only been given due attention since the 1960s, as can be deduced from the *Scheuren in woningen* (Cracks in houses) report, published by Stichting Bouwresearch [1966]. The increasing use of concrete and masonry for floors and (internal) walls, of combinations of different types of masonry units, of larger and larger subcomponents and of slender structures with less overcapacity has led it emerge as a frequently occurring problem, though.

Where expansion joints are omitted in long runs of masonry, the expansion and contraction cycle may lead the wall to gradually become lozenge-shaped. The displacement tends to be largest at the upper end, where self-weight and subsoil offer least restraining [Cook and Hinks 1992]. If one side of the wall is effectively constrained, this lozenging may be accompanied by leaning of a perpendicular wall: this effect is commonly referred to as bookending.

Another factor is that stiffer joints in cement mortar do not have the flexibility that once was inherent to the masonry constructed with lime mortar. Also wall ties in cavity walls may hinder movement, especially near corners where displacements will be most apparent. The expansion joints commonly included in modern buildings to accommodate movement are, in fact, designed cracks.

Summarizing, the last option that can cause damage due to hindered thermal or hygric dimensional changes is a lack of flexibility to accommodate such movement. For masonry buildings, this situation typically arises when long, uninterrupted walls lack sufficient expansion joints. From our cases has emerged the following specific cause:

- Hindered dimensional changes due to insufficient capacity to accommodate thermal and/or hygric movement, in a long, continuous wall (e.g. the façade of a row of houses).

4.4.2 Hindered dimensional changes due to frost action

Frost action is the process in which freezing of moisture contained in a porous material leads to damage in this material. Brick, stone and mortar are porous materials. Under normal conditions, they contain moisture in their pores. When the temperature of such a material drops below zero, as a result of a subzero outdoor temperature, this moisture will freeze.

As stated in the previous section, water has its highest density at 4 °C. Thus, when water turns into ice, it expands. The increase in volume can be up to 9 % [Cook and Hinks 1992]. If restrained, it is accompanied by a build-up of hydrostatic pressure on the pore walls of the embracing building material. This, in turn, creates tensile forces in the material.

Damage due to frost action is sometimes mistaken for weathering by water or wind. Weathering, however, only leads to loss of original surface material, not to cracks or deformations. Frost action can.

In buildings, damage due to frost action typically appears near the surface facing the outside. This is where freezing temperatures are most likely to occur, under influence of the outdoor climate. Thermal insulation on the inside of the building component can be a disadvantage here, as it prevents heat leaking to and warming up the building envelope, thereby increasing the likeliness of subzero temperatures in the outside skin.

Another reason why frost damage tends to localize at the outside surface is that this is where moisture tends to accumulate. Only very wet conditions may lead to frost action: the more saturated a material is, the less space it can offer the ice to expand. Especially building elements in direct contact with the ground, or those subject to water run-off or collection are vulnerable. One should note that clay brickwork may require three weeks to dry out fully after exposure to only one day of driving rain [Cook and Hinks 1992]. It goes without saying that a leaking gutter is not a favourable condition. However, also the recent trend of waterproofing façades by water-repellent impregnation should be looked at with some suspicion, because it may hinder the natural evaporation and, in doing so, can keep the moisture content at a high level.

Besides on temperature and on moisture saturation, the extent of the damage caused by frost action depends on a third factor: the pore structure of the material. The proportion of fine pores appears to be a predominant factor in frost resistance. Materials with small pores have a higher water retention capacity. As a result, they are more likely to have a high moisture content during freezing conditions and are, thus, more likely to suffer frost damage. Also fine porous mortars, without air entrainers, may suffer from frost damage rather easily. Hard-fired bricks, on the other hand, are less vulnerable to frost action: they have less fine pores.

Finally, the fourth factor influencing the extent of frost damage is also related to material properties: resistance to freezing expansion also depends on the cohesiveness of the masonry [Richardson 2001]. However, as Hinks and Cook [1997] state, the tensile forces induced by freezing water are generally greater than any porous building material can withstand.

In this context, it is important to note that temperatures oscillating around freezing are more destructive than prolonged severe frosts [Hinks and Cook 1997]. Freeze-thaw cycles can lead to an increase in moisture content due to leaching rain and liquid moisture migration [Douglas and Ransom 2007]. Cracks formed in an earlier cycle will then become filled with moisture, too, and when this water freezes in subsequent cycles, the crack will be wedged wider and wider. Hence, frost action in masonry is usually a progressive phenomenon, which nevertheless can occur quickly. Feilden [2003] states: ‘The actual process of freezing and resultant expansion of ice and subsequent contraction on thawing may occur in the British climate on average between 1.5 and 2 times per day in winter.’’ In the Netherlands, typical frost damaging winters occur on average once every 10 years [van Hees et al. 2001].

Frost action has been summarized with the following statement:

- Hindered dimensional changes due to frost action.

4.4.3 Hindered dimensional changes due to corrosion

Corrosion is the process of oxidation of a metal. In common parlance, the term ‘rusting’ is used more often. Corrosion can lead to structural damage in masonry that is in contact with metal, as it can be accompanied by a substantial increase in volume.

Corrosion is a chemical process. The metal is consumed and new materials, with a different composition, are formed. This differs from a physical change, which is a phase transition of one material.

Basically, there are two types of corrosion: direct oxidation and electrochemical (galvanic) action [Addleson 1989]. Direct oxidation is the reaction that takes place between metal and oxygen when this metal is exposed to air. Galvanic action demands the presence of an electrolyte (electrically conductive liquid) and two dissimilar metals. In both cases, moisture is a precondition. Unfortunately, however, this precondition can hardly be avoided in most situations in buildings.

One way to protect a metal from corroding is applying a solid film on its surface, such as paint. In most non-ferrous metals, the product of direct oxidation may actually form such a protective layer. However, in ferrous metals such as iron and steel, the rust does not bond well to the parent surface. As a result, the corrosion process can proceed until either the reactants have been exhausted or the conditions have become (un)favourable.

Besides wet and oxygenated conditions, there are other circumstances that can affect this type of process. Corrosion can be accelerated by atmospheric pollutants, acids and salts [Watt 2007]. Especially chlorides originating from cement or, in marine areas, from the sea are typically associated with an increased reaction rate. Temperature, too, can influence the pace at which corrosion proceeds.

The effect of corrosion is a substantial volume increase. Rust takes up between 6 and 10 times the volume of the iron it ate away [Beckmann and Bowles 2004]. As shown in Section 4.4.2, freezing water only expands 9 %, and can already lead to quite some damage, so one can imagine that the expansive forces induced by corrosion can be devastating for the surrounding masonry. It often leads to cracking of the material in which the corroding metal is embedded.

Corrosion has been labelled as follows:

- Hindered dimensional changes due to corrosion of an iron or steel element.

4.4.4 Hindered dimensional changes due to salt attack

Salts are compounds in which positively charged ions (cations) are bonded with negatively charged ions (anions). These cations and anions unite in such a way that the product is electrically neutral. Typically, salts are combinations of metal and non-metal ions.

In masonry, salts are, to some amount, omnipresent. Most ordinary clay bricks, for example, contain sulphates of sodium, magnesium or calcium [Douglas and Ransom 2007]. However, salts can also originate from adjacent building materials, from the ground or from groundwater: in solution, they can travel by capillarity into porous materials with which they are in contact. Sea salt (sodium chloride) may be carried inland by wind or by flooding; it can also be found in mortar that was prepared using sea water [Lubelli et al. 2004]. In addition, salts can precipitate from flue gases or industrial pollution, too.

Salts can damage masonry in different ways. As regards hindered dimensional changes, we discern two main types of processes. On one hand, crystallization of a dissolved salt can affect the material on or in which it deposits. The damage processes involved in this are called efflorescence and crypto-florescence. On the other hand, harm can be caused when salt ions induce a chemical reaction with masonry constituents. There, the actual cause of damage is the formation of expansive compounds. Both types of processes require the presence of quite substantial amounts of salt and moisture. More details are given in the subsections below.

Efflorescence and crypto-florescence

Efflorescence and crypto-florescence are processes in which a dissolved salt crystallizes upon evaporation of its solvent (usually water). When this crystallization occurs on the surface of masonry, it shows as a white deposit. Both process and result are, then, called efflorescence [Watt 2007].

Efflorescence is not a structural damage, but crypto-florescence can be. In crypto-florescence, the salt crystals form within the pores of a material, rather than at its surface. Since this crystallization entails an increase in volume, pressure is built up in the pores, which may lead to delamination of the material [Hinks and Cook 1997]. Typical forms of damage are powdering, when crystallization takes place just behind the surface of the material; push out of the pointing, when crystallization occurs in the space between pointing and bedding mortar; and spalling, when crystallization happens behind a layer with a different capillary behaviour, for example a layer of masonry that has been treated with a water repellent. Crypto-florescence may also occur where the evaporation front lies behind the surface, for example at the top zone of rising damp [van Hees and Lubelli 2006].

Crypto-florescence has, as a damaging process, much in common with frost action as discussed in Section 4.4.2. Moisture saturation, pore structure and cohesiveness of the material play a similar role here. They also share cyclicity as an important factor. For crypto-florescence, repeated wetting and drying cycles may result in salt deposition gradually blocking the pores, and crystallization accumulating at increasing depths of wetting [Hinks and Cook 1997].

In this context, it should be mentioned that such similarities in occurrence are likely to lead to similarities in appearance. The damages due to frost action and crypto-florescence are, thus, so-called look-alikes. It may not be possible to discriminate between these causes with a visual inspection of the symptoms alone – unless salt crystals are clearly visible. Determining the chemical composition of the white deposit may be necessary to obtain a decisive answer. This can be done on site, using simple chemical tests.

Swelling salt compounds

The second type of salt attack is the process in which a salt reacts with one or more constituents of mortar, forming an expansive compound [van Hees et al. 2003]. Usually, sulphates are involved, which explains the label sulphate attack that is often used in this respect. Crammond [2002] lists the three minerals that are most commonly seen as a product of sulphate attack: gypsum, ettringite and thaumasite. Gypsum is a calcium sulphate, the latter two result from reactions between sulphate and calcium aluminate hydrates, and sulphate and calcium silicate hydrates, respectively. A fourth mineral associated with this type of damage process is Friedel's salt, which is a product of chloride attack.

The formation of especially ettringite and thaumasite requires large amounts of moisture. This water is incorporated into the compound, which, as a result, has a much larger volume than its reactants did have. The volume increase is substantial: Hinks and Cook [1997] mention, for example, expansions of up to 227 %.

Unlike crypto-florescence, the formation of swelling compounds can lead to forces that exceed the vertical compression of the self-weight of a wall. This can lead to horizontal layering of the mortar, spalling and gridlike cracks [van Hees et al. 2003]. Characteristic is also the differential expansion and subsequent bending of unlined chimney stacks, where the reaction rates of the sulphurous flue gases differs for the exposed and sheltered sides [Watt 2007].

From above explanation, it is clear that the formation of swelling salt compounds requires two conditions: the presence of reactive components and moisture. Unfortunately, these conditions are common in masonry. Sulphates can migrate from the environment into the masonry: it can result from air pollution or rising damp. However, sulphates can also be contained in (low-fired) bricks [van Hees et al. 2003]. Carbonate, calcium silicate and alumina, on the other hand, are present in cement-based mortar and hydraulic lime.

Nevertheless, damage due to swelling compounds is most likely to occur at extremely wet locations with high concentrations of salts. These conditions should have existed for a prolonged period of time, as sulphate attack usually takes at least two years to emerge [Hinks and Cook 1997]. Vulnerable building parts are, therefore, earth-retaining walls, chimneys and parapets, which are severely exposed to precipitation [Eldridge 1976].

Damage due to salt attack is sometimes mistaken for weathering by water or wind. Weathering by water and wind, however, only leads to loss of original surface material, not to cracks or deformations. Salt attack can.

Summarizing, salt attack resulting in structural damage in masonry can occur in two ways. These options are:

- Hindered dimensional changes due to salt attack, due to crypto-florescence; and
- Hindered dimensional changes due to salt attack, due to the formation of swelling compounds, due to a reaction between salt and masonry constituents.

4.5 Conclusions

In this chapter, we have reviewed typical causes of structural damage in masonry. Since our focus is on the Netherlands, settlement has been given ample consideration, while seismic action received less attention. The purpose was to provide insight into which processes can underlie this type of damage. In addition, some clues have already been given on the symptoms and context conditions involved.

Essential part of this chapter is the categorisation of causes that we have proposed and applied. This new categorisation has primarily been based on scale level, in line with the damage mechanism concept presented in Section 3.2.2. This has allowed us to define mutually exclusive categories of causes, which, in addition, share essential characteristics as regards their occurrence and effects. Furthermore, we have analysed the causes from a mechanics point of view, departing from a change in force equilibrium, either in time or in place.

In the previous sections, the different categories of causes have been described. This chapter will end with a visual overview that summarises all these causes. This overview is presented in Figure 4.8.

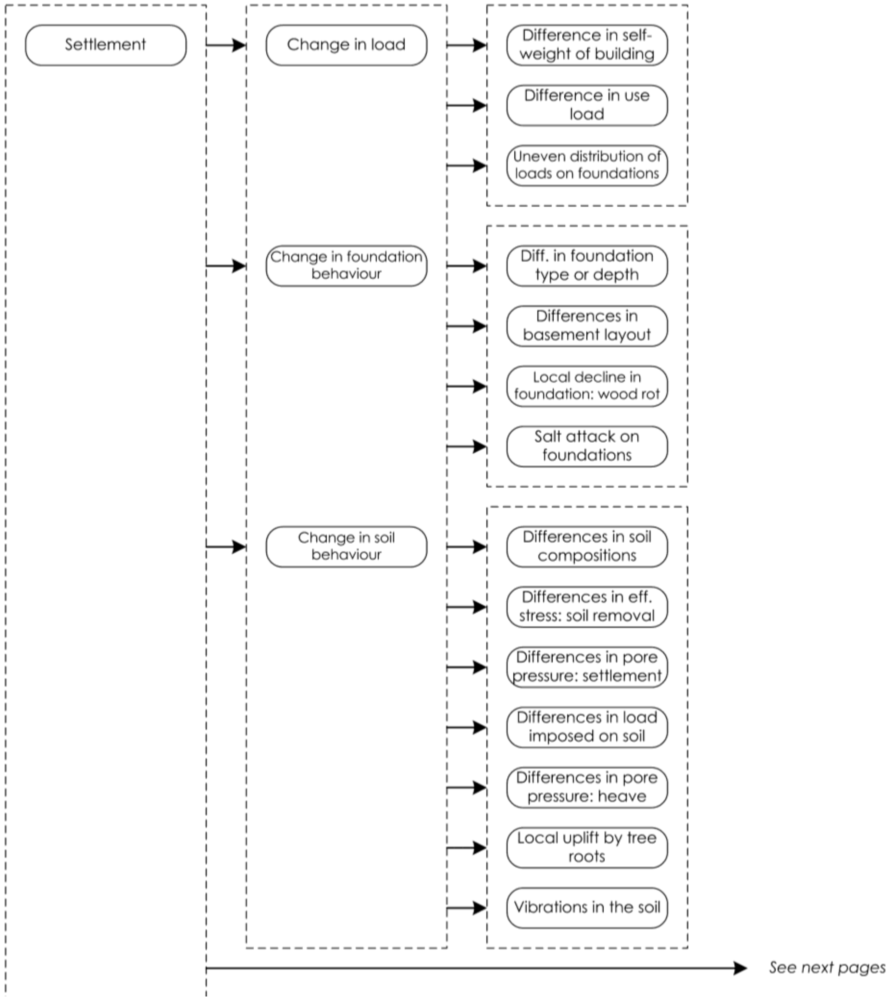


Figure 4.8: Overview of typical causes of structural damage in masonry in the Netherlands.

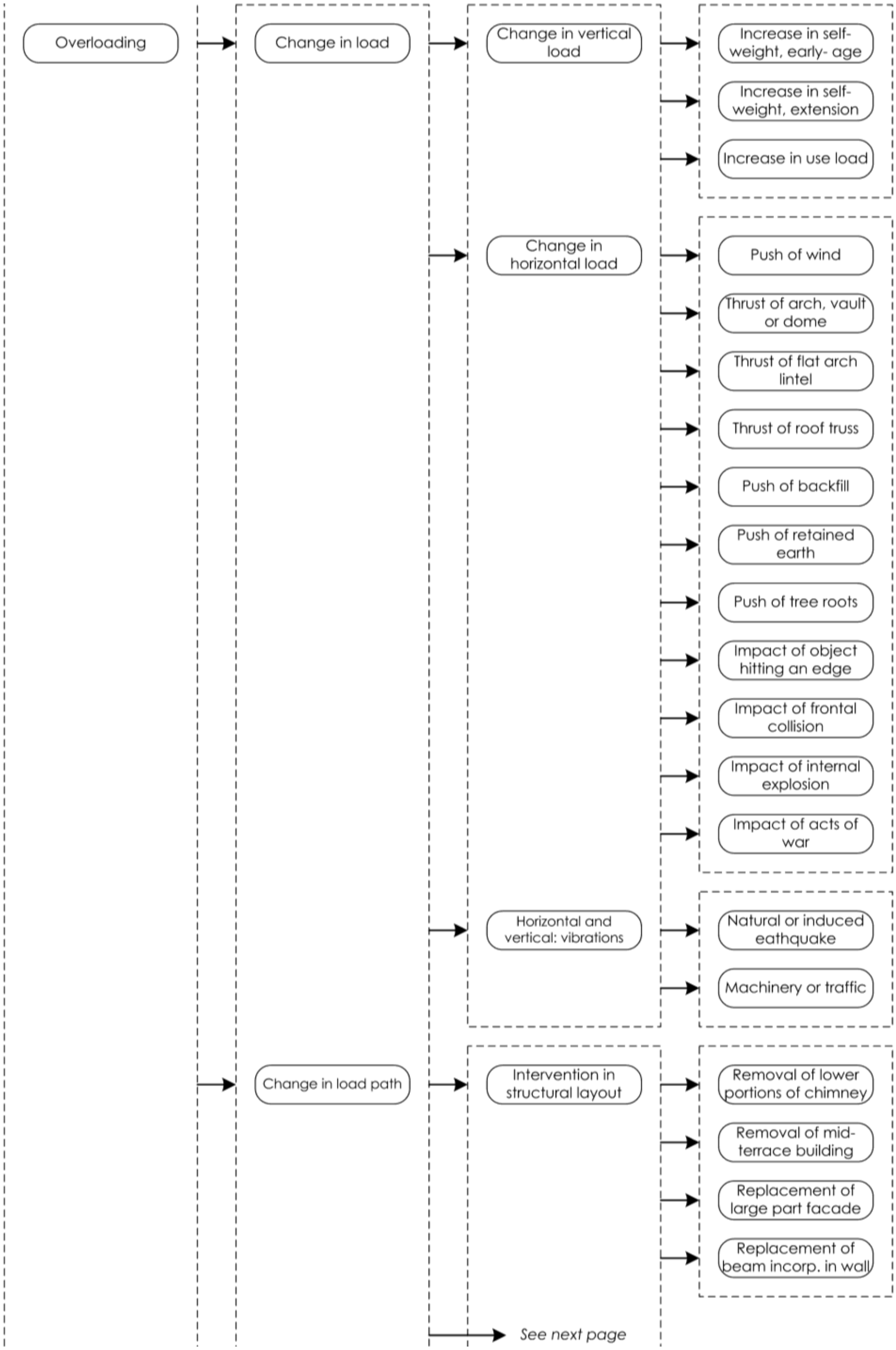


Figure 4.8 (continued): Overview of typical causes of structural damage in masonry in the Netherlands.

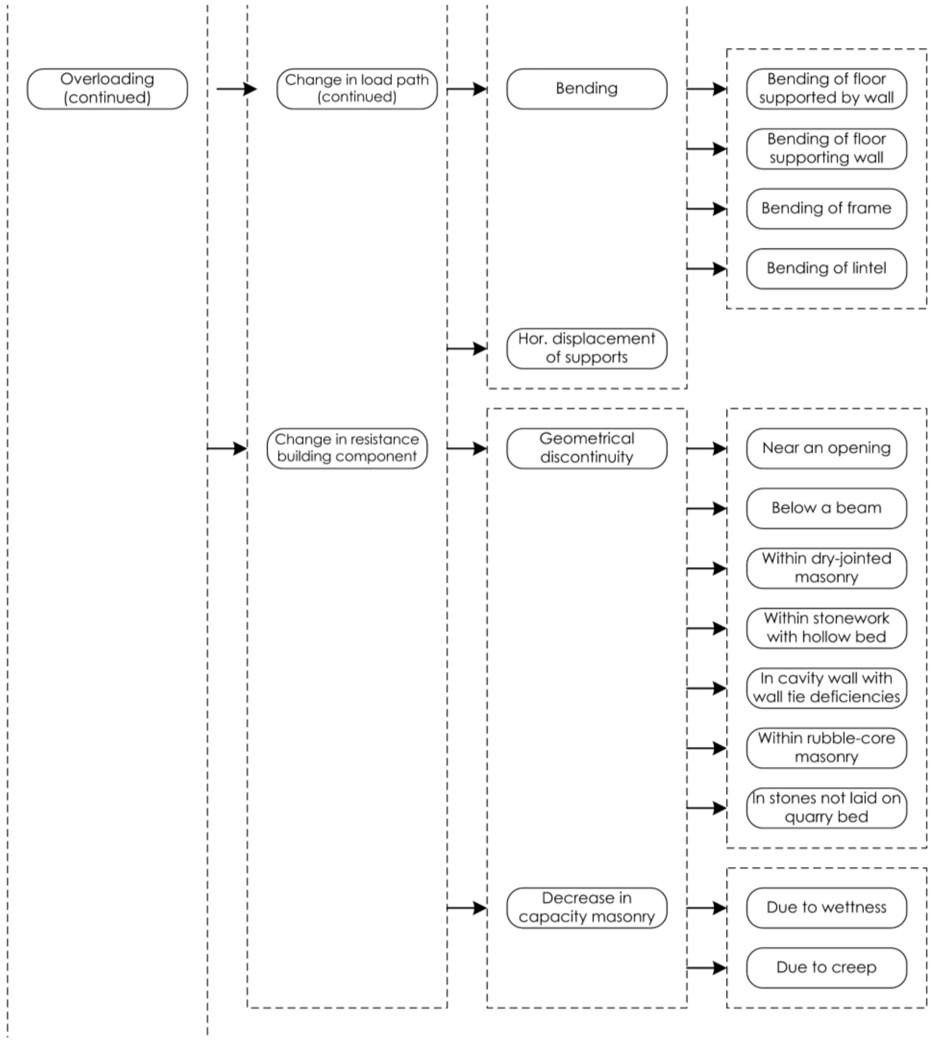


Figure 4.8 (continued): Overview of typical causes of structural damage in masonry in the Netherlands.

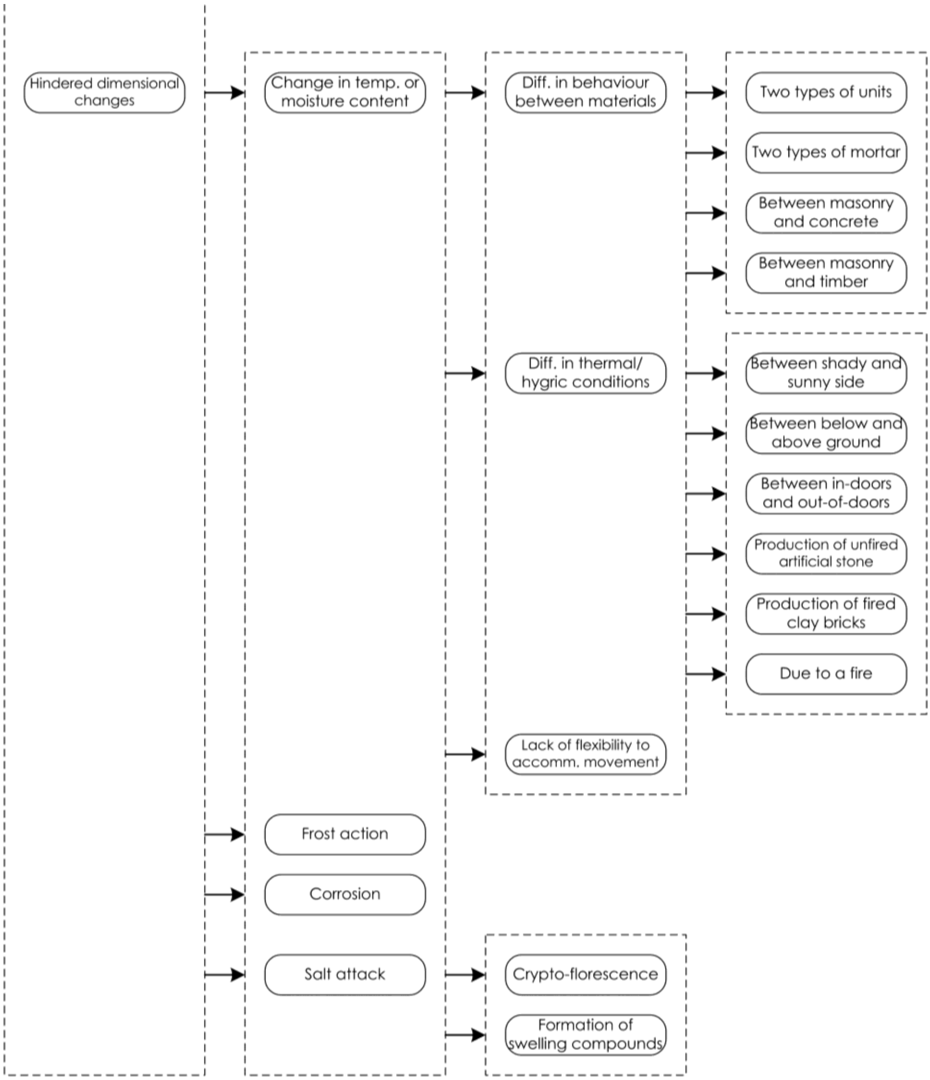


Figure 4.8 (continued): Overview of typical causes of structural damage in masonry in the Netherlands.

Chapter 5
Symptoms of structural damage

To obtain a correct diagnosis, both symptoms and context of a damage need to be interpreted. The present chapter focuses on the symptoms: what are the most important characteristics of a damage, and what do they signal?

Section 5.1 discusses the approach we have followed to identify and describe the most important symptoms of structural damage that can be observed in masonry buildings in the Netherlands. We discern three main types: cracks, deformations and tilts. In the subsequent sections 5.2-5.4, the different symptoms and their interpretation will be discussed in detail. Finally, the last section of this chapter summarizes the main issues in interpreting symptoms of structural damage.

The results of the previous chapter and the current one lay the foundation for Part III. There, we will investigate the relations between symptoms and causes. This investigation should provide insight into how symptoms can be used to distinguish between different causes of structural damage.

5.1 Defining symptoms of structural damage

5.1.1 Looking at structural damage

Structural damage is often complex: it usually has a multitude of characteristics. In many cases, it can be hard to tell what is important to consider, and what not. This can make it difficult to describe and to interpret the damage.

Basic strategy to analyse such situations is to first decompose the damage into separate characteristics: the symptoms. By considering each symptom separately, one should try to find out what clues it gives about its cause. Subsequently, one can combine the results and look for a common denominator: the most probable cause. However, one should always keep in mind that nearby symptoms may well have different origins.

In some situations, above process may be simplified. Certain combinations of symptoms have such a high incidence that they can be regarded as damage patterns. We will return to this subject in Chapter 8.

In this chapter, we will discuss all essential symptoms of structural damage individually. These symptoms have been distilled from the 20 handbooks and additional literature that are under study here. They have been selected on their practicability: to be of use for our diagnostic tool, they should be visually recognizable or easy to assess during an initial inspection.

5.1.2 Assumptions and cautions when looking at structural damage

As has been demonstrated in Chapter 2, the observation of damage is closely related to the expectations one has for a building. Basically, whenever one observes damage, what one actually does is comparing the present state to the original one. A decline in appearance can be considered as an anomaly.

However, in many cases, one does not truly know the original state of the premises. The observation of damage is, then, based on a comparison between the current state and an ideal one. In doing so, one consciously or subconsciously makes assumptions about this ideal state, of which one can only imagine that it once existed.

Most of these assumptions refer to what one holds to be the perfect shape of a building. Especially for refined buildings, people tend to expect that the builders have done their job neatly. In those cases, it is customary to assume that in the original state:

- Edges have once been straight, not curved;
- Angles have once been right, not acute or obtuse;
- Walls have once been vertical, not out-of-plumb; and
- Roofs and floors have once been level, not sloping.

In addition, it is often taken for granted that building plans and elevations were designed with logic in outline and measurements.

Masonry, by its nature, renders a grid that offers convenient ways for checking if a building is affected by local changes of shape. Especially the layers of units, which normally run perfectly horizontally, form a useful frame of reference. By holding a spirit level along the bed joints, vertical deviations can be detected relatively easily. In addition, with the use of slightly more elaborate techniques of measurement, it is possible to relate these relative vertical displacements to a fixed point and monitor their development in the course of time. This is, for example, of great value when dealing with soil settlement.

Although the assumptions explained above are customary and, indeed, very useful when analysing structural damage, one should always be aware that these are only assumptions. They presuppose that the original state of a building did approach the ideal. However, this may not always be the case!

One should always keep in mind that what is now labelled as damage, may have actually been built as such on purpose. For instance, be careful when dealing with leaning façades: in the Netherlands, house fronts have been built with an inclination to reduce rainwater ingress. In Dutch, this is called *op vlucht gebouwd*. Also joints between buildings and extensions may sometimes be misinterpreted as cracks, as is shown in Figure 5.1 (left).

Other signs of damage may actually be earlier repair works instead. For example, in the past split, wedge-shaped bricks (in Dutch: *varkens*) were incorporated in the masonry to correct a settlement that had occurred during construction works (Figure 5.1, middle). Similarly, church towers sometimes show a kink when subsidence was ‘corrected’ by aligning subsequent building phases anew to verticality (Figure 5.1, right). Summarizing, the following cautions should be taken into account when looking at structural damage:

- Ask yourself: Is this damage, or has it been built this way on purpose?
- Ask yourself: Is this damage, or is it evidence of repair?

5.1.3 Interpreting symptoms of structural damage

All structural damage can be described as a deviation in shape that is caused by loading. In fact, to be able to bear a load, structural elements will always undergo a certain deformation. When this deformation is relatively small, it will not even be noticed. However, as soon as it exceeds certain functional or aesthetical limits, people will regard the deviation as damage.

In construction industry, the customary question put to a structural engineer is as follows: will the deviations in this structure be small enough so as not to be regarded as damage? The prevalent approach is, then, to calculate how a building would react to anticipated loads or load combinations. The procedure traditionally taught starts from the load, first calculating internal reaction forces, then determining local stress states at critical points and, finally, ends with ascertaining that these stresses will not lead to local failure or undesired deformations.

In the diagnostic process, this procedure should be reversed. Starting from the failure, the result of an unknown combination of loads, one wants to trace back the cause of this effect. Symptoms need to be interpreted in terms of stress states, and stress states translated into (resultant) loads.

Please note that different loads may well lead to identical stress states and, thus, to identical symptoms. This typically is the case for look-alike damages. When assessing such damages, it is especially important to take alternative hypotheses into account.

In this chapter, we will investigate what each symptom tells about its cause – and what not. This will help us determine which symptoms are essential in the diagnostic

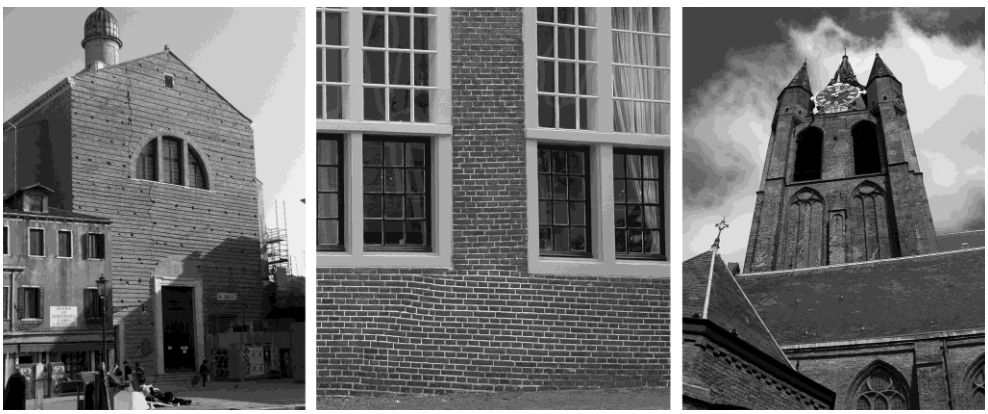


Figure 5.1: Three cases in which assumed structural damage is not damage. From left to right: church in Venice, Italy, where a joint resulting from an intervention may be misinterpreted as a crack (photograph by R.P.J. van Hees); so-called *varkens* to correct subsidence in houses next to the Hooglandse Kerk in Leiden; and kink in the tower of the Oude Kerk in Delft.

process – and need to be included in our tool. Besides being easy to recognize, these symptoms should be as much as possible explanatory, too. In other words, we look for symptoms of which the appearance gives clues on how the damage has occurred.

5.1.4 Organizing symptoms of structural damage

In Section 2.1.3, we have presented the three main symptoms of structural damage. These most distinctive features are:

- Crack development;
- Deformation; and
- Tilt.

Apart from the fact that these main symptoms are easy to recognize visually, they also represent different failure modes. As mentioned in Section 2.1.3, cracks point to a lack of strength, deformations indicate a lack of stiffness, and tilt designates a lack of external stability. We will briefly discuss their general characteristics before examining the more specific, individual symptoms in the next sections.

When dealing with structural damage, the distinction between deformations and cracks appears to be the most important one. Deformations and cracks are both deviations in shape. In applied mechanics, the terms (geometrically) continuous and discontinuous deformations are used in this context. What we call deformations in this thesis are, in this context, continuous deformations, which comply with the so-called compatibility conditions. This means that the coherence between all parts of an element have remained intact: adjacent parts have stayed in contact. Cracks, however, can be regarded as discontinuous deformations. They do not comply with the conditions of compatibility: the crack is a gap that has appeared between adjacent elements.

Which of the above two types of structural damage an element actually shows under a certain load depends on the material of which the element is made. To be more precise: the strength of the material determines the stress level at which the transition from (continuous) deformation to (discontinuous) crack takes place. As long as stresses do not surpass the material strength, deformations occur; however, if stresses increase up to this strength, then the material will fail and a crack will arise. In quasi-brittle materials, like masonry and concrete, this process takes place gradually, starting from microcracks that finally bridge into a macrocrack.

It is useful to look at cracks and deformations in this way, because it clarifies how one cause can lead to seemingly completely different damages. In fact, in pure deformations, the total distortion that an element has undergone is smeared out over a large area, while in cases where a crack has formed this distortion is concentrated and localized at this crack. From this, it follows that the type of damage determines where one should measure relative displacement.

Nevertheless, one should realize that, in practice, the difference between deformations and cracks is not as sharply defined as it may seem. It is more a question of a smooth transition: continuous deformations are often accompanied by multiple, small cracks, while building parts between cracks may show slight deformation as well.

The third main symptom is tilt: the full-body rotation of a building as a whole. Typical signs of tilt are that vertical edges have gone out-of-plumb, and that originally horizontal courses of masonry are not horizontal anymore; however, that these edges and courses have remained straight. Although connections to adjacent components such as service pipes can be affected, tilt is not accompanied by cracks or deformations.

In the following sections, we will examine the symptoms of structural damage in more detail. Our aim is to propose a set of clear, consistent and recognizable basic concepts that allow one to specify structural damage. Please note that the actual damage patterns, most of which are composed of a combination of symptoms and context conditions, will come up for discussion in Chapter 8.

All symptoms presented in this chapter have been deduced from examples in our sample of literature. Before a symptom has been included in our selection, we have evaluated its descriptiveness and its explanatory value. These two criteria are indicators for the two ways in which symptoms can be used in the diagnostic process: either to identify a damage, or to interpret its cause.

The symptoms that are essential within a diagnostic process are not just those that are easy to recognize. Preferably, they should also say something about the cause of damage. To determine which characteristics this involves, we have used basic principles of applied mechanics.

For each symptom defined in this chapter, we will indicate how it can be determined and what it tells about its cause. Complementary to this, Appendix A gives an overview of investigation tools helpful in an on-site inspection.

5.2 Characteristics of deformations

Using basic principles of applied mechanics, both cracks and deformations can be related to stress states. Via these stress states, it is possible to determine the direction of the (resultant) force under which the damage has occurred. For deformations, five basic load situations can be discerned: compression, tension, shearing, bending and torsion. These situations are illustrated in Figure 5.2.

Figure 5.2 illustrates that, under compression, an element is shortened, while under tension it is stretched. These deformations in the direction of the load are accompanied by transverse expansion and contraction, respectively. Shearing leads to a deformation in which parallel cross-sections translate with respect to one another (but remain parallel), whereas bending makes parallel sections rotate with respect to one another. Torsion, to conclude, results in twisting of the element.

As Figure 5.2 shows, deformations tend to follow the direction of the imposed loads. Conversely, it is relatively easy to trace back the load through analysing a deformation. In this context it is good to note that, although the loads have all been presented in pairs in Figure 5.2, similar deformations would result from the combination of an ‘active’ load at one end, and a ‘passive’ reaction delivered by a support on the other end of the element.

5.2.1 Direction of deformation: in-plane or out-of-plane

One important way to characterize a deformation is by relating its displacements to the component's geometry. We discern between:

- Deformation in-plane; and
- Deformation out-of-plane.

As stated before, the direction of displacement of a deformation is usually a reliable indicator for the direction of the (resultant) load under which the structure has deformed. Hence, in cases that show deformations out-of-plane, one should give due consideration to out-of-plane loads. Usual suspects are thrusts from roofs or vaults. Nevertheless, out-of-plane deformations in masonry can also occur when, for instance, differences in thermal or hygric conditions between the sides of a wall lead to hindered dimensional changes.

Furthermore, out-of-plane failure may also result from in-plane overloading. This failure mode is called buckling. Buckling, as Beckmann and Bowles [2004] put it, is the structural phenomenon in which, "at a load level well below that which would cause squashing or splitting of the material, a slender compression member will become laterally unstable and fail to carry (further) load." Hence, in this case the displacement is perpendicular to the direction of loading.

Whether a certain deformation is in-plane or out-of-plane can be determined visually. Oblique lighting can be helpful in this context: it can reveal out-of-plane behaviour by creating shadows, as is illustrated in Figure 5.3.

5.2.2 Direction of in-plane deformation: deviation from horizontal or from vertical

For in-plane deformations, we discern between two options. These are:

- Deviation from horizontal; and
- Deviation from vertical.

The former refers to deformations in which horizontal elements, such as bed joints, are no longer horizontal. It suggests a difference in vertical load between the ends. The latter concerns deformations that have made vertical edges go out-of-plumb, suggesting differences in horizontal loading.

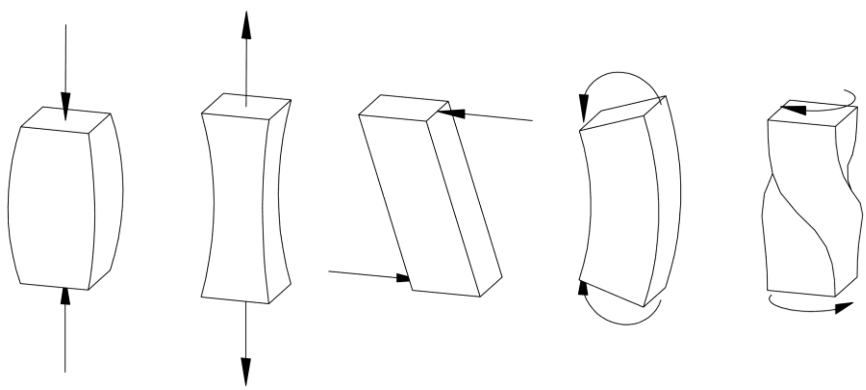


Figure 5.2: Five basic loads and their deformations: compression, tension, shearing, bending and torsion.

Both of these options often occur together, but this is not necessarily the case. To check whether there are any deviations from the horizontal, one can use a spirit level. Vertical deviations can be identified with a plumb line.

5.2.3 Direction of out-of-plane deformation: inward or outward

Out-of-plane deformations can be typified by either inward or outward movements:

- Deformation out-of-plane, inward; or
- Deformation out-of-plane, outward.

Again, the direction of out-of-plane deformation is linked to the direction of loading, but also to the location of supports.

To describe out-of-plane deformations, the terms 'bending' and 'bulging' are frequently used. The difference between these terms lies in the location of the deformation with respect to the building element, rather than in the direction of the displacement. Bending is used for deformations that are largest at one end, for example at the top of an element, while bulging refers to a deformation that has its maximum halfway.

The direction of an out-of-plane displacement can be assessed visually (see the shadow in Figure 5.3). When in doubt, oblique lighting or a plumb line may provide certainty.

5.3 Characteristics of cracks

Cracks are often more difficult to interpret than deformations. We suggest analysing a crack by looking at three main features: the crack direction, the displacement over the crack, and the variation in crack size over the crack length. Each of these three items will be discussed in a separate subsection.

Figure 5.3: Deformation out-of-plane revealed by oblique lighting.

A fourth important characteristic is crack depth. Crack depth can range from superficial to deep. However, unless a crack goes through the full wall thickness and is visible at the opposite face, its actual depth is difficult to measure, at least with simple tools during an initial survey. This is the reason why crack depth will not be included in our tool.

5.3.1 Crack direction

The most convenient way to describe the direction of a crack is by relating it to the geometry of the element in which the crack has appeared. For orthogonal elements such as walls and columns, the terms 'horizontal', 'vertical' and 'diagonal' can be used. This brings us to the following options for cracks in columns or walls:

- Crack direction is diagonal, in one direction;
- Crack direction is horizontal; or
- Crack direction is vertical.

The direction of cracks in arches, vaults and domes, however, can better be described in relation to the span of these elements. For (thick) arches and vaults, these directions can be parallel, perpendicular or diagonal to the span, whereas for domes a distinction can be made between cracks in the meridional or in the hoop direction. The options are, thus:

- Crack direction is parallel to span;
- Crack direction is perpendicular to span;
- Crack direction is diagonal to span;
- Crack direction is meridional; or
- Crack direction is hoop direction.

Please note that it will, thus, be necessary to specify the building component in which the crack shows, before one can apply above terms unambiguously.

Although the direction of a crack is often its most eye-catching characteristic, its explanatory use is less straightforward. Unfortunately, the relation between crack direction and load direction is slightly more complicated than is the case for deformations. This is illustrated in Figure 5.4, which displays the basic crack forms and their source loads analogously to the basic deformations in Figure 5.2.

Figure 5.4 demonstrates that cracks can occur parallel, perpendicular or even diagonal to the direction of loading. The crack direction depends on the distribution of normal tensile and compressive stresses in the element. But it is also governed by the material: masonry.

When analysing crack patterns, one should keep in mind that cracks always appear perpendicular to the largest (principal) tensile stresses. Where a crack arises, the material is locally torn apart. The crack forms a gap in a previously continuous medium.

Hence, under tension, cracks appear perpendicular to the direction of loading. Under bending, cracks will start at the side of the element that is stretched. However, in that case it is not the direction of loading that can be determined from the direction of the crack, but only the direction of the bending moment. Shear forces induce a combination of compressive and tensile stresses that occur at an angle of 45 ° to these forces. As a result, cracks appear diagonal to the imposed load. As Figure 5.4 (right) shows, torsional cracks even spiral around the element [Lilliu 2007].

The most striking crack pattern to emerge from Figure 5.4 is, however, the one at the left side: under compression, cracks appear parallel to the applied load. The physical explanation for this axial splitting lies in the granular structure of masonry and its brittle behaviour [Beranek and Hobbelman 1992]. In addition, it is due to the fact that masonry has a relatively low tensile strength compared to its compressive strength (ratio 1 : 10). In other words, masonry is more vulnerable to tensile stresses than to compressive ones.

Above combination of properties has the effect that a masonry object, held under compression but unrestrained and unsupported in its lateral directions, paradoxically fails in tension. This failure results from tensile stresses that appear perpendicular to the compressive stresses. Hence, in most situations, failure of masonry under compression starts with (tensile) splitting cracks before true (compressive) crushing can occur.

In this context, one should note that above discussion has focused on the global crack direction. The actual crack path can be straight, stepped or toothed; continuous or at intervals. However, the local crack directions along this crack path appear to be less relevant for the diagnostic process. Differences in type of crack path do not necessarily point to differences in causes or even to differences in direction of loading; the crack path merely indicates the ratio in strength between units and joints.

5.3.2 Displacement over crack

A second characteristic of crack development is the type of displacement that becomes apparent at the crack. In fracture mechanics, which deals with discontinuous failure, it is common to distinguish between three modes of failure: mode I, II and III. These three modes are illustrated in Figure 5.5.

Mode I failure is the so-called pure opening mode. It is characterized by a displacement that occurs perpendicular to the crack, and is caused by normal stress. Mode

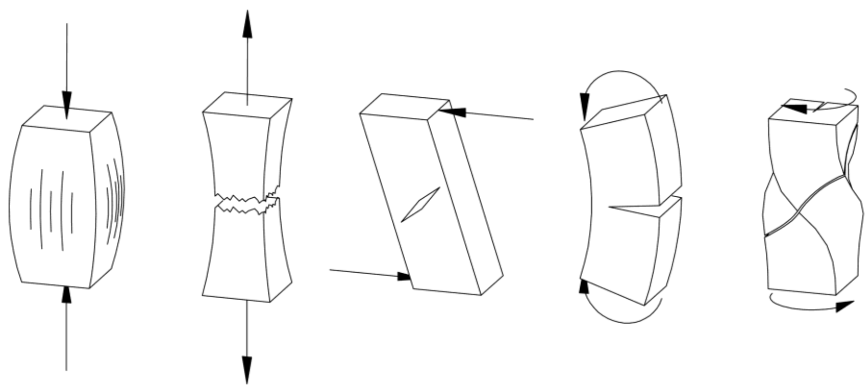


Figure 5.4: Five basic loads and their cracks: compression, tension, shearing, bending and torsion.

II is the shearing mode. It results from in-plane shear stress, and features a displacement parallel to the crack direction. In other words, the parts on either side of the crack slide along one another. Mode III, finally, is the tearing mode. Contrary to the two other modes, it is caused by out-of-plane shear stress, resulting in a displacement that is also out-of-plane.

Hence, the options to describe the displacement over a crack are:

- In-plane displacement, perpendicular to crack;
- In-plane displacement, parallel to crack; and
- Out-of-plane displacement over crack.

The displacement over a crack tells us how the building part at one side of the crack has moved compared to the part at the other side of the crack. One should always keep in mind that this is a relative displacement: in itself, it does not indicate which of the two parts has moved. In fact, it may well be the case that both parts have.

Usually, it is possible to identify the type of displacements over a crack with one look. The masonry itself, if executed in a smooth, regular way, can offer a convenient reference system. A ruler or a spirit level may be of assistance in checking the alignment of the two surfaces on either side of the crack.

5.3.3 Variation in crack size over length

The third important characteristic of a crack is its size, and especially changes in this size along the length of a crack. Average crack size is often used to express the level of damage, as has been discussed in Section 2.1.2. However, distinguishing between hair cracks, cracks up to 10 mm, cracks up to 25 mm, and cracks of 25 mm or more appears to be of little value in the diagnostic process. In fact, it is not so much the size of each crack separately that one should consider: the combination of many thin cracks can be more dangerous than the occurrence of a single wide one, even more so because these finer cracks are usually not observed until they have reached a more critical stage.

Hence, instead of absolute crack size, it is the variation in crack size over length of a crack that is most explanatory. By measuring the crack size at different points along one crack, one can identify whether a crack is tapered or not and, in the former case, if it either is widest at one end and tapers towards zero at the other end, or is widest halfway its

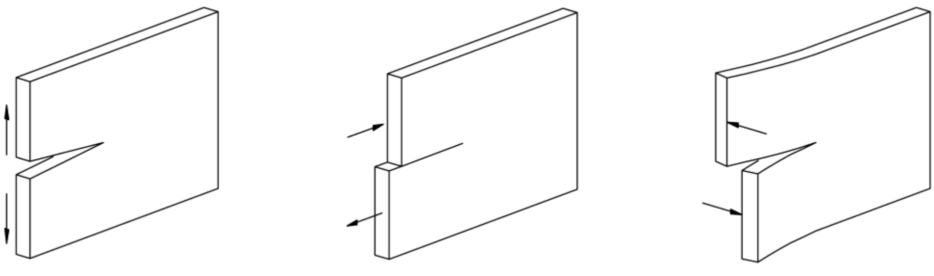


Figure 5.5: From left to right: mode I opening failure, mode II shearing failure and mode III tearing failure.

length. This provides insight into the type of movement, and helps to discern between translations and rotations (compare Figure 5.6 and 5.7): If the crack size is constant along the length, this means that only translations can have taken place; and if it shows an increase to one side, a rotation must have occurred. Tapering towards both ends, finally, points to failure under shear stress.

The options for this symptom are:

- Crack has constant size or is tapered towards both ends; and
- Crack is tapered towards one end.

For the latter option, we can further distinguish between:

- Crack is widest at top, narrowest at bottom; and
- Crack is widest at bottom, narrowest at top.

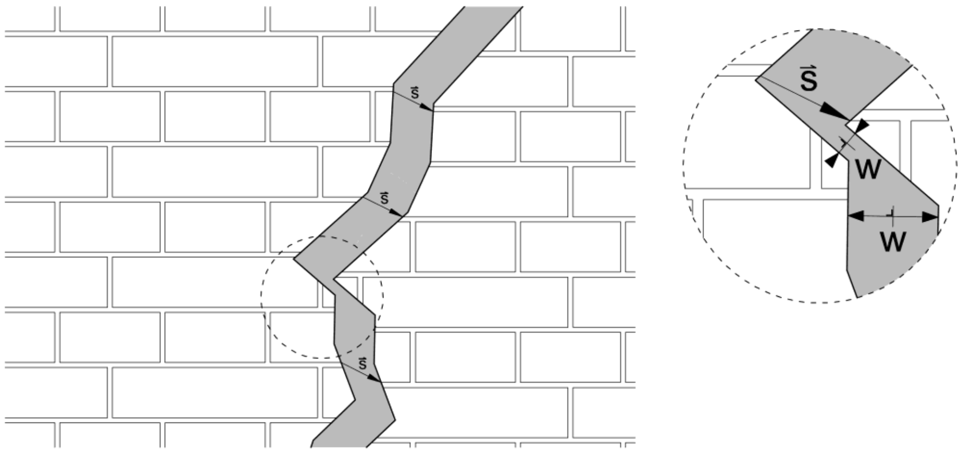


Figure 5.6: Crack size $\vec{s}$ and crack width *w* in case of translation [after Pryke 1983].

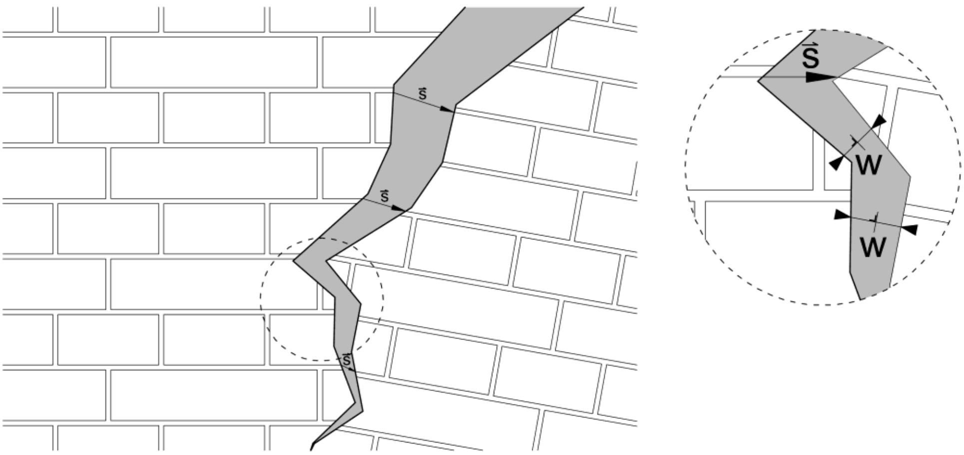


Figure 5.7: Crack size $\vec{s}$ and crack width *w* in case of rotation.

In this context, it is good to note that there is a slight difference between crack size and crack width. This difference and its implications have been pointed out by Pryke [1983], and are here demonstrated in Figure 5.6 and 5.7. As the illustrations make clear, crack width is measured as the shortest distance between the two edges of a crack. As such, this width merely represents a local interval: It depends on and varies with the crack path.

Crack size, on the other hand, stands for the actual displacement that has occurred along the crack. It can be determined by measuring the distance between two marks, one on either side of the crack, that used to be adjacent. Again, the alternation of units and joints, which is so typical for masonry, lends a helping hand in this procedure.

Crack size and crack width are, of course, related variables. The local crack width, for instance, is always smaller than or equal to the crack size at that point. The maximum crack width occurs where the displacement is perpendicular to the direction of the crack. Hence, if crack width equals crack size, that is an indication of pure tensile failure.

Comparing Figure 5.6 and 5.7 makes clear that the proper way to determine the tapering and 'breadth' of a crack is measuring its crack size, and not its crack width. Although crack width may seem easier to assess, only crack size gives reliable information that is independent from the local crack path.

Nevertheless, in practice, the difference between size and width can be very small. One may not even be able to determine it without specific instruments. In such cases, rotation can better be assessed from a change in the direction of the bed joints, which can be verified by stretching a taut (mason's) line between two points, or by using a spirit level.

5.4 Additional symptoms

In the diagnostic process, a few additional symptoms have proven to be useful for describing or interpreting damage. These will be discussed in the subsections below.

5.4.1 Combination of cracks

It is not uncommon for cracks to occur in combinations. An easy way to describe this co-occurrence is by counting the number of cracks. From our analysis of damage examples, we have come to the following options and phrasings:

- One crack appears at / is / of which crack direction is …;
- Two cracks appear at / is / of which crack direction is …;
- Four cracks of which crack direction is …; or
- Multiple cracks.

The number of cracks in itself is not explanatory, but only descriptive.

Combination of cracks with different crack directions

Co-occurring cracks do not always have the same crack direction. Characteristic combinations of cracks with different crack directions are called crack patterns. After having reviewed the damage examples available from literature, we propose the following options for crack patterns (each line representing a crack):

- Crack pattern is # shaped;
- Crack pattern is ⊥ shaped;
- Crack pattern is T shaped;
- Crack pattern is >---< shaped;
- Crack pattern is \---/ shaped;
- Crack pattern is \ |---| / shaped;
- Crack pattern is \ | / shaped;
- Crack pattern is / | \ shaped;
- Crack pattern is | / \ | shaped;
- Crack pattern is | / | shaped;
- Crack pattern is \ / shaped;
- Crack pattern is / \ shaped;
- Crack pattern is X shaped;
- Crack pattern is > shaped; or
- Other combination of crack directions.

Of course, each of these crack patterns can be parsed and labelled with the indicators mentioned in Section 5.3, e.g. 'horizontal plus vertical cracks'.

Combination of cracks with different courses of crack size over length

Instead of using the crack direction, combinations of cracks can also be described in terms of their sequence and tapering. Phrasings resemble the pattern 'one crack is widest at the top, the other one is widest at the bottom'; or 'one crack appears at the intrados, two cracks at the extrados'. Especially for cracks in arches and vaults, in which stability and force equilibrium are crucial, these sequences are very informative: they explain the rotations between the parts that have become separated by the cracks.

5.4.2 Symmetry

Damage can also be labelled by specifying whether it forms a symmetrical or asymmetrical pattern. To do this, the damage is related to a symmetry axis or symmetry plane, usually a vertical one. Symmetry and asymmetry of a damage usually correspond to symmetry and asymmetry in loading, respectively.

For arches, vaults and domes, it is customary to choose the symmetry axis or symmetry plane to run through the top of the component. The options for this symptom are, then:

- Damage is asymmetric with respect to a vertical plane along the crown; or
- Damage is symmetric with respect to a vertical plane along the crown.

For deformations in arches or barrel vaults, one can add:

- Curve of arch is flattened halfway span (arch sag);
- Curve of arch is sharpened to both sides (arch hog); or

- Curve of arch is sharpened to one side, flattened to other side (arch sway).

These options can be assessed visually, when they are pronounced enough. Examples are shown in Figure 5.8.

5.4.3 Layering and staining

Within our diagnostic tool, a few other symptoms may be of use. These symptoms are:

- Layering parallel to quarry bed;
- Rust stains; and/or
- Water stains.

These additional symptoms describe specific damage characteristics, and point to specific damage processes. Rust stains, for example, are a reliable indicator for corrosion-induced hindered dimensional changes. A visual inspection should, in general, suffice to identify them.

5.5 Conclusions

The best approach to analyse damage is by decomposing it into separate symptoms. This chapter has given an overview of the most important symptoms of structural damage in masonry. The various options for these symptoms have been listed, and we have indicated what they tell us – and what not.

As has been demonstrated in the previous sections, the most striking or easy-to-communicate characteristics of damage are not necessarily the most explanatory ones. The main information one can obtain from interpreting symptoms of structural damage is the direction of (relative) movement that a building part has undergone. From this, one may deduce the direction of loading under which the damage must have occurred. It has been explained that deformations and tilts have a more straightforward relation to their loads and are, therefore, generally easier to interpret than cracks.

The symptoms discussed in this chapter will be used in Part III to create a diagnostic tool that is useful in practice situations.

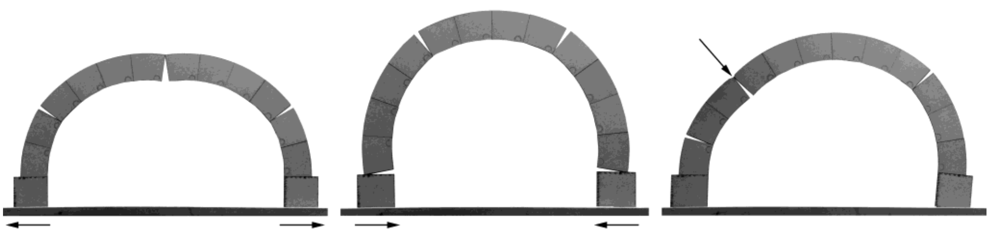


Figure 5.8: Deformations (and cracks) in arches. From left to right: arch sag, arch hog and arch sway.

Chapter 6
Context conditions

In the previous two chapters, we have presented typical causes and symptoms of structural damage in masonry. In this last chapter of Part II, we will now focus on the third component that needs to be considered when diagnosing: the context of a damage. This context is not part of the damage process, but can influence its course or modify its effects.

In Section 6.1, we will discuss our approach to describe the context of structural damage. We propose to distinguish between four categories of context conditions: material, geometrical and environmental factors, which are all related to the scale level on which a damage process takes place; and time, which is connected to sequence and rate of this process. The subsequent sections are each devoted to one of these four types of conditions. General conclusions on the way in which context conditions can be deployed in the first steps of the diagnostic process will be drawn in Section 6.6.

In Part III, the results of the current chapter will be combined with those of the previous two chapters. There, the context conditions will be linked to causes and symptoms of structural damage in masonry, in order to create a diagnostic tool.

6.1 Defining context conditions

If and how damage develops can depend on many factors. Even circumstances that do not have a direct causal connection with the origin of a damage can influence the actual course of a damage process substantially. We term such factors context conditions, and this chapter addresses them.

In Section 3.2.2, we have identified four types of context conditions. Three are related to scale level. These categories comprise material, geometrical and environmental variables. The fourth condition is the factor time. On one hand, it refers to sequence: in which order did the steps of a damage process take place? On the other hand, it is related to rate: how far has a damage process progressed?

The aim of this chapter is to give an overview of those context conditions that are important for diagnosing structural damage in masonry. These conditions have been extracted from the descriptions of representative examples of structural damage that we have collected from literature. To select only conditions that are useful during the initial phase of the diagnostic process, we have evaluated them on two criteria.

First of all, each condition should be relatively easy to assess if it is to be deployed for hypothesizing. In this phase, surveyors do not usually dispose of complicated techniques. A visual inspection or a simple test or investigation should suffice to ascertain the presence or absence of a condition.

Secondly, conditions should also have diagnostic value. As will be shown later in this chapter, there are two ways in which a condition can be distinguishing: it can either be indispensable for describing a certain damage pattern, or have a decisive influence on course or effect of a certain damage process. The absence of such a condition can, then, be used to rule out the presence of a particular damage pattern or a specific hypothesis, respectively.

To synchronize and condense the options, all collected context conditions have been reformulated. The following phrasings have been used:

- Presence of …;
- Absence of …;
- Occurrence of …;
- Damage appears at / in / along / next to / with maximum … (related to place); or
- Damage has appeared in / after / over … (related to time).

The next four sections present context conditions that can be relevant for diagnosing structural damage in masonry. For each type of condition, we have described what role it may play in the occurrence of this damage, or in its manifestation. Furthermore, we have indicated how its presence can be assessed. An overview of investigation tools that come in handy during on-site inspections is given in Appendix A.

6.2 Material conditions

Material conditions can strongly influence damage processes. On one hand, material properties such as strength and stiffness govern the behaviour of a structure under loading. In this way, material is often a determining factor for location and appearance of damage.

On the other hand, material behaviour can also provoke damage processes or even induce loads. Especially differences in behaviour between adjacent materials can lead to structural damage. In this section, three groups of material conditions that are relevant for occurrence or appearance of structural damage in masonry will come up for discussion: the location of damage in relation to the constituent parts of masonry, the type of masonry present, and the presence of other materials.

6.2.1 Location of damage in relation to constituent parts of masonry

One way to characterize structural damage is by describing its location in relation to the constituent parts of masonry. In most cases, structural damage affects masonry as a composite: the combination of units and joints. However, some damages only appear either in the joints or in the units. This restricted extent can be seen as an explicit characteristic of the damage. Terms commonly used to describe damage that we consider to fall in this category include chipping, layering, push-out and spalling.

Damage confined to only the units or only the joint material does not, in general, affect the loadbearing capacity of a structure. However, in some cases it may be (or may be interpreted as) the manifestation of a lack of strength, stiffness or stability, and might then be considered to be structural damage as defined in Chapter 2. Therefore, it has been included in our overview.

The three options for this condition are:

- Damage appears in the composite masonry (default option);
- Damage appears in joints; or
- Damage appears in units.

These options can be verified by visual inspection.

6.2.2 Type of masonry present

Material properties can strongly determine how a component behaves under loading – and what kind of damage may result. For masonry as a composite, this behaviour is governed by the material properties of its constituents: the units and the joints. Below, we will successively discuss the role that unit material and joint material can have in the occurrence of structural damage.

Unit material

Three materials are commonly used for masonry units in the Netherlands: natural stone, fired clay brick and unfired artificial stone. As natural stone is only scarcely available in this country, the blocks used here have usually been imported from abroad, in particular from the German, Belgian and French regions situated upstream. Bricks are made of clay, a commodity that does abound. The winning of clay and the production of the bricks once flourished at many locations on riverbanks, and each river area used to have its own brick sizes and names. The category of artificial stones includes concrete, lightweight concrete and calcium silicate units. A visual inspection is usually enough to ascertain which type of unit is present, although local removal of plaster or wallpaper may be necessary.

The combination of different types of units can induce structural damage. In this context, one may think of thermal expansion. This property, which is expressed in the thermal expansion coefficient α, is different for every (type of) material. And it is this difference that gives rise to damages of which the underlying processes have been described in Section 4.4.1.

In addition, a number of damage processes only develop in certain unit materials. This is, for instance, the case with initial irreversible expansion of fired clay bricks. Similarly, unfired artificial stones may be susceptible to initial shrinkage.

Another thing is that some processes only occur in specific, inferior units. Damage in fired clay brick masonry may, for example, be confined to soft units. These units are underburnt: they have not been fired at high enough temperatures. Underburnt bricks can usually be identified by their colour: according to Eldridge [1976], they may have a pink or salmon colour when occurring in a predominantly red brick wall.

If damage in natural stone is limited to some units, and if large parts of the exposed faces flake off, it is advisable to check whether the affected blocks are laid on their natural quarry bed or not, as this affects their strength. Mahan [1846] has explained it in this way: stones should be given "the same position, in the mass of masonry, that they had in the quarry; as stone is found to offer more resistance to pressure in a direction perpendicular to the quarry-bed, than in any other." He has also indicated how this condition can be examined best: "The directions of the lamina in stratified stones show the position of the quarry-bed."

Summarizing, the options for the condition 'unit material' are:

- Damage appears in natural stone masonry;
- Damage appears in fired clay brick masonry;
- Damage appears in unfired artificial stone masonry;
- Damage appears only in those stones that were not laid on their quarry bed;
- Damage appears along the horizontal edges of units;
- Damage appears at or near connection between two types of units;
- Presence of two types of units; and/or
- Presence of clay bricks that were freshly produced at time of construction.

Except for the condition related to the freshness of clay bricks, all these options can be assessed without difficulty in a visual inspection. If it is plausible that damage has appeared in the first years after construction of the masonry, one should inquire into whether the bricks were freshly produced at the time of construction. This information may be derived from documentation on the supply of building materials, if still available.

Joint material

For masonry, mortar composition, more than type of unit, appears to be the factor that dictates the appearance of structural damage. Especially the extent of deformation that can develop before cracks occur is important in this. This depends on both strength and stiffness.

Masonry with a cement mortar is usually very brittle and cracks easily, while masonry with a lime-based mortar can be quite flexible and may accommodate even considerable deformations without showing much distress. This difference in material context can, thus, lead to a marked difference in damage presentation. Please note, however, that the actual behaviour also depends on time, and especially on rate and duration of loading.

A further factor of influence is the ratio between strength and stiffness of the mortar on one hand, and those of the unit on the other hand. This ratio governs where cracks are most likely to occur: along the joints, or straight through the bricks. Hence, it has a quite substantial influence on the eventual appearance of a damage, too.

Although an understanding of the differences in strength and stiffness between various types of masonry can help to explain differences in damage presentation, these properties as such give no clue about the type of loading under which a structure has failed. They do not allow one to discriminate between damage processes. Therefore, they have not been included into our overview of context conditions.

Apart from its influence on the appearance of a damage, joint material can also induce certain damage processes. For example, lime-based mortar is susceptible to creep effects, while certain combinations of (low-) fired brick and hydraulic lime or cement mortar might, under high water load, lead to the formation of swelling salt compounds (e.g. thaumasite, ettringite) in the bedding mortar, resulting in cracks.

Also the combination of different mortars can lead to damage. This can be the case when joints have been repointed. Nevertheless, also a lack of joint material can be a reason for trouble. In dry-jointed masonry, as an extreme case, some stone might suffer from local stress concentrations. This can lead to damage that is, obviously, limited to the units.

For this condition, the options can be reported as:

- Damage appears in dry-jointed masonry;
- Presence of cement-based mortar in foundations;
- Presence of hydraulic lime mortar in foundations;
- Presence of lime-based mortar; and/or
- Presence of joints that have been repointed.

All of these options can be identified in a visual inspection. To satisfy oneself about the mortar used for the foundations, digging a test pit may be necessary. However, the age of the building may already be a reliable indicator for the type of mortar used, as will be shown in Section 6.2.3.

6.2.3 Presence of other materials

The presence of other materials adjacent to or even embedded in masonry can be a trigger for structural damage. On one hand, this can be due to differences in thermal expansion. Since the relatively small variations in thermal expansion coefficient that exist between various types of units or joint materials can already lead to hindered dimensional changes, one may expect that the much larger differences in behaviour between masonry and concrete, or masonry and timber, have much stronger effects.

On the other hand, other materials may also induce specific damage processes, which, in turn, can affect the masonry. One example is corrosion of embedded iron elements. Another is wood rot, which may lead to local weakening of a structure or foundation.

The combination of two materials in a structure could also lead to unintended load distributions. In concrete frames with masonry infill, this used to be a quite common problem: creep or bending of the concrete could turn the masonry infill into a loadbearing element.

Finally, a last remark on material conditions is on salts. Salt attack is one of the processes in the group of hindered dimensional changes. A prerequisite for its occurrence is, naturally, the presence of certain salts (or ions). Many materials can be a source for salts; unfortunately, masonry is one of them.

In short, the context conditions related to materials other than masonry are:

- Presence of a concrete beam;
- Presence of a concrete floor slab;
- Presence of a concrete frame, with masonry used as infill;
- Presence of a concrete lintel;
- Presence of a concrete roof slab;
- Presence of timber (pile) foundation;
- Presence of timber beam;
- Damage appears at location of iron element;
- Presence of timber window frame; and/or
- Presence of iron element embedded in masonry;
- Presence of source of salt.

A visual inspection usually suffices to assess the presence of above conditions. A decisive answer on the presence of salts can be obtained by relatively simple sampling and testing.

Figure 6.1 sketches the various building materials and different forms of construction used for or in combination with masonry in north-western Europe from 1600 to 2010. It has been based on the work of Beckmann and Bowles [2004] for the situation in the United Kingdom, and on that of Oosterhoff et al. [1988], Haslinghuis and Janse [2005], and Stenvert and van Tussenbroek [2007] for the Dutch, Belgian, German and French situations.

In Figure 6.1, the period of use in the Netherlands has been indicated in dark grey. Where this was preceded by use in the surrounding countries, or where no specific data about the situation in the Netherlands was found, a light grey bar is shown. Although not complete, nor exact, this figure may help one to get a first indication of materials that could be found juxtaposed to damaged masonry, in a building of a certain age.

6.3 Geometrical conditions

Geometrical conditions can be used to describe structural damage and – some – to explain its occurrence. On one hand, the layout of a building offers a convenient reference system that allows one to specify the location of a damage. On the other hand, this layout also determines – together with material properties – where stress concentrations are likely to occur and, thus, where the building may be most vulnerable to structural damage.

In the following subsections, we will first propose a set of options to describe the type of component in which damage occurs. Subsequently, options will be presented with which one can further specify the location of a damage in relation to a building component. Finally, we will discuss some specific conditions in structural layout, the presence or absence of which can trigger certain damage processes.

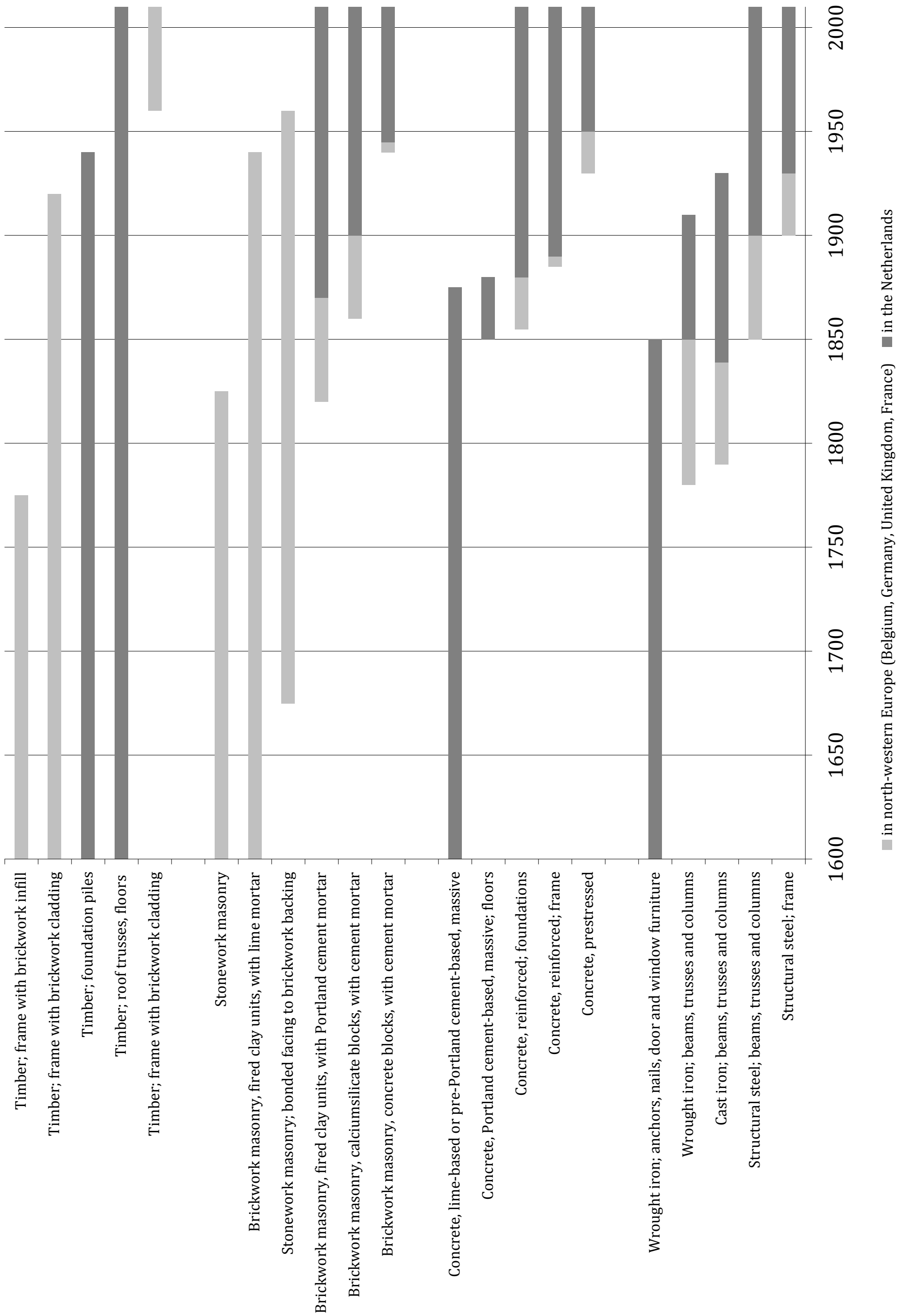


Figure 6.1: Some building materials and techniques used for or in combination with masonry in the Netherlands and north-western Europe (Belgium, Germany, United Kingdom and France) between 1600 and 2010.

6.3.1 Geometry of damaged component

As has been shown in Chapter 5, geometry is used as a reference for describing symptoms of damage. The position of a crack or the direction of a deformation can conveniently be characterized by relating it to the shape of the component in which this damage has occurred. Hence, we will start with defining the options for the geometry of the damaged component.

Every structure can be regarded as composed of a number of basic elements, each with its specific loadbearing function and behaviour. For masonry, which is most effective when used in compression, five basic components are relevant: columns, walls, arches, vaults and domes. These components are illustrated in Figure 6.2.

Each of these five basic geometries is designed to show characteristic loadbearing behaviour. However, for our diagnostic tool especially the distinction between (orthogonal) walls and columns, and (curved) arches, vaults and domes is important. Apart from that, it has also turned out to be useful to divide the latter category further; arches and vaults being singly curved, and domes doubly curved. The options for this condition are, then:

- Damage appears in column or wall;
- Damage appears in arch, vault or dome;
- Damage appears in arch or barrel vault; or
- Damage appears in cross-vault or dome.

Which option is applicable to a certain damage case can easily be established in a visual inspection.

The development of structural damage can be connected to the function a wall may have, and the inherent loading this involves. Also the geometrical layout of the masonry can play a role in damage processes. Both aspects will be explored in the following two subsections.

Wall type

The influence of wall type on structural damage is chiefly based on vulnerability to certain damage processes. A main difference is that between internal and external building components. Only external walls are likely to be affected by erosion, frost action or large temperature fluctuations. External walls are also more probable to be harmed by traffic, by overloading due to wind, or to salt attack. In addition, the push effects of retained earth or

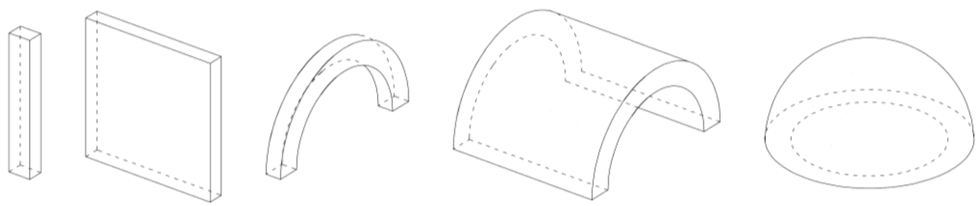


Figure 6.2: Typical masonry components: column, wall, arch, vault and dome.

even tree roots have much more potential to lead to damage in free-standing, unshored garden walls, than in the façade of a house. The options are:

- Damage appears in external building component;
- Damage appears in flank wall of terrace;
- Damage appears in free-standing wall;
- Damage appears in retaining wall;
- Damage appears in roof parapet wall;
- Damage appears in spandrel wall;
- Damage appears in wall that is supported by floor; and/or
- Damage appears in wall that supports the floor.

These conditions can usually be assessed visually. Whether it is the wall that supports the floor or the other way round may be inferred from the internal layout of the building.

Geometrical layout of the masonry

The geometrical layout of masonry may also be a reason for structural damage. Rubble core masonry and stonework with hollow beds can have built-in stress concentrations that may lead to local vertical overloading. Cavity walls, on the other hand, may, in due course, start to suffer from wall tie deficiencies. A loss of connection between the inner and outer leaves might, then, result in overloading as well.

The options for this condition are as follows:

- Damage appears in cavity wall;
- Damage appears in rubble core masonry that has thin shell and high load; and/or
- Damage appears in stones worked with a hollow bed;

Most of these options can be checked in a visual inspection. A borescope may be of help to assess the internal composition of the masonry. There are also even less destructive techniques available (e.g. radar, thermography, sonic pulse velocity), but these may be more complicated to deploy and interpret.

6.3.2 Location of damage in relation to building components

After having determined the type of geometry of the damaged component, a damage can be specified in more detail. This can be done by indicating the direction of displacement, as has been addressed in Chapter 5, but one may also describe the damage by further characterizing its position within the component. For damage in columns or walls, one may, for instance, indicate the vertical or horizontal position, or relate the damage to the position of an opening. A similar set of options can be proposed for arches, vaults and domes. The four subsections below will exemplify these geometrical conditions.

Vertical position of damage in relation to column or wall

The vertical position of damage in columns and walls can be described in terms linked to the height of the element, or by relating it to connections with horizontal elements such as beams, floors or roofs. Some options are only used in a descriptive way, to specify the type of damage. However, relative position can also have direct diagnostic value, when it is implicit to a certain damage process. Overloading due to thrust of a roof or bending of a floor, for instance, are tied to particular areas. Likewise, the effects of creep in masonry typically show in a zone starting from the base and rising up to two-thirds of the height of a (high) wall [Binda et al. 1998]. Also damage caused by hindered dimensional changes tends to be confined to (contact) zones.

The options belonging to vertical position are:

- Damage appears at or just below roof level;
- Damage appears in zone at about two-thirds of the height of the wall;
- Damage appears with maximum at bottom;
- Damage appears with maximum at or just below level of beam;
- Damage appears with maximum at or near a floor level;
- Damage appears with maximum at top;
- Damage appears with maximum halfway between two floors; or
- Damage appears with maximum halfway the height.

The presence or absence of these conditions can be verified in a visual survey.

Horizontal position of damage in relation to column or wall

The considerations applicable to vertical position also hold for the horizontal position of damage. The options belonging to this subcategory are:

- Damage appears at a corner;
- Damage appears at connection between internal and external wall;
- Damage appears at protruding edge; or
- Damage appears with maximum halfway the length.

All can be determined by a visual survey.

Position of damage in relation to wall opening

A third, more specific way to describe a damage is to compare its position to that of a wall opening. Sometimes, the cause of damage is directly related to this opening. This is, for example, the case for overloading due to bending or thrust of a deficient lintel. One can also think of hindered dimensional changes that may take place between the materials of wall and lintel or window frame, especially when the latter are made of a different material.

However, more often this relation between wall opening and cause of damage is less clear. This is due to the fact that openings in a wall form weak spots, which may ‘attract’ damage. Openings interrupt the regular force flow in the structure, thus leading to stress concentrations. Hence, while the damaging load is imposed at some distance, its effects may well concentrate near this opening.

We discern four options for relating the position of structural damage to an opening:

- Damage appears at or just below support of lintel;
- Damage appears below an opening;
- Damage appears near an opening; or

- Damage appears next to and above lintel.

Again, these options can be verified in a visual inspection.

Position of damage in relation to arch, vault or dome

The position of damage in relation to arches, vaults or domes is mainly used to specify the type of damage. As has been indicated in Chapter 5, these curved components ask for labels that differ from those applied to orthogonal columns and walls. Useful concepts are the terms 'intrados' and 'extrados', which indicate the bottom or the top side of a vault web, respectively. Additionally, the position of damage can be linked to characteristic elements such as springings or crown.

Some of the options may also refer to specific causes, and especially to types of overloading. For example, horizontal overloading due to push from backfill usually appears as damage either in the spandrel wall or at the connection of this spandrel wall to the arch ring. Similarly, thrust typically shows as damage at or just below the springings. When displacements of the supports have led to changes in the load distribution and damage in the arch or vault, this displacement should be observable in these supports.

Summarizing, the options for this type of geometrical condition are:

- Damage appears at connection between arch ring and spandrel wall;
- Damage appears at extrados;
- Damage appears at intrados;
- Damage appears at mid span, at or near crown;
- Damage appears at or just below the springings;
- Damage appears in support of arch, vault or dome; and/or
- Damage appears in vault web.

They can be examined in a visual inspection.

6.3.3 Specific conditions in the structural layout

Some damage processes are triggered by specific conditions in the structural layout of a building. We distinguish three categories of geometrical options that can directly be linked to processes: the presence or absence of certain elements; the presence of specific, geometry-related loads; and the occurrence of interventions in the structural layout. These options will be discussed in the subsections below.

Presence or absence of specific structural elements

The presence or absence of specific elements in a structure may give rise to structural problems. In relation to hindered dimensional changes, it is the absence of (sufficient) expansion joints that is a frequent trigger condition. These joints are included in modern buildings to accommodate movement. In fact, they are designed cracks. Where they are not provided sufficiently, damage may arise.

Arches, vaults and domes entail another damage process: they bring about thrust, which can lead to horizontal overloading of adjacent elements. In this context, one should note that flat arch lintels spanning wall openings are arches, too, and that they also induce thrust. Furthermore, the presence of backfill behind spandrel walls in bridges can lead to horizontal push, especially when this backfill is wet and subjected to freezing.

Another set of conditions refers to geometrical properties of the foundations. As one may expect, these conditions are linked to settlement processes. For instance, the presence of a shallow foundation that does not extent below the frost depth of the ground indicates that the building may be affected by frost heave. Alternatively, differences in layout of basement or foundation between adjacent building parts can easily lead to differential settlement. This typically shows as damage at the connection of the building parts in question.

Summarising, the options for this condition are:

- Absence of sufficient expansion joints;
- Presence of arch, vault or dome adjacent to damaged area;
- Presence of backfill behind spandrel wall;
- Presence of flat arch lintel;
- Presence of basement that extends only below part of the damaged building;
- Presence of difference in foundations below damaged and adjacent part of the building; and/or
- Presence of shallow foundation that does not extent below frost depth (ca 600 mm deep).

Most of these conditions can be checked in a visual survey. Other could be inferred from construction drawings. To verify foundation depth and differences in foundation, digging trial pits may be needed.

Presence of specific, geometry-related loads

Specific load conditions can initiate damage processes. The presence of a high (gravity) load, for instance, is associated with creep in masonry. On the other hand, eccentric loads or differences in loading between two, for the remainder equal, building parts may induce differential settlement. We discern the following options:

- Presence of difference in loading between damaged and adjacent part of the building;
- Presence of eccentric load on foundations; and/or
- Presence of high (gravity) load.

Above options may be derived from a visual inspection. However, to assess the presence of an eccentric load on the foundations, trial pits will be necessary.

Occurrence of interventions in the structural layout

Interventions in a previously well-functioning construction can result in structural damage, too. Interventions always bring about a change in the load distribution. Damage occurs if extra load is added, or if a structure is weakened by removal of components. Please note that even temporary removal of an element may suffice to cause structural damage!

The options for this condition are:

- Occurrence of extension built in or on top of existing building;
- Occurrence of removal of lower portions of chimney;
- Occurrence of replacement of beams incorporated in wall; and/or
- Occurrence of replacement of large part of façade.

Usually, these options can be derived from a visual inspection, by comparing floor plans or by comparing the age of building elements. Archive information may render certainty, especially in complex situations.

6.4 Environmental conditions

The third group of context conditions is related to the scale level of the neighbourhood. These environmental conditions encompass circumstances on a broader scale than those linked to the material and geometrical characteristics of the element in which a damage occurs. As a result, environmental conditions are not so much used to describe the appearance of a damage: they can help identify damage processes.

We have divided the environmental conditions into four groups, which will be discussed in succession. These are soil, climate, salts, and interventions and incidents. Options have been selected with a view to the Dutch situation.

6.4.1 Soil

As has been pointed out in Section 4.2, buildings are supported by the ground on which they stand. The amount of support depends on the composition of the soil. In this way, soil is a very influential factor in (especially) settlement processes. The current section distinguishes these soil aspects into a group of soil conditions, and a group of interventions in the soil.

Soil conditions

Soil conditions have a strong influence on both the occurrence of differential settlement and on its extent. The occurrence of differential soil movement can be attributed to the presence of (local) variations in soil properties. Soil is a very inhomogeneous material, if one may consider it as one material at all. Even within the boundaries of one building site, its properties can differ substantially. If such variations are not taken into account in the design of the foundations of a building, they can easily lead to differential settlement and damage. As MacLeod and Abu-El-Magd [1980] have stated:

"… cracking of uniformly loaded buildings founded on uniform soils is uncommon even if the soil is very soft. This is based both on [elastic] analysis and on observation of the real behaviour in buildings. Thus the variability of the soil under the area of the building is probably the most important factor in damage due to differential settlement."

The type of soil that is present below a building typically determines the extent of soil settlement or heave, and also the time it takes before this settlement process nears its completion. The extent of settlement is determined by the compressibility of the soil layers that carry the building, and by the thickness of these layers. The strong time dependency that is characteristic for soil deformations is related to the permeability (and, with that, the saturation) of soils. The more permeable a soil is, the quicker it can react to changes in the ground water balance. As a result, consolidation of sand, which is very permeable, will be completed within a few years from the application of a load, while in clay, which is much less permeable, this process may well continue for two or three decades. Here, too, layer thickness plays a role, since this dictates the drainage length.

In summary, soil conditions that can influence structural damage processes are:

- Presence of clay ground;
- Presence of compressible soil;
- Presence of difference in soil conditions below damaged building;
- Presence of geological fault line; and/or
- Presence of silt, fine sand, or chalk soil.

A general idea of the soil conditions in the Netherlands can be obtained from a set of cone penetration profiles that can be regarded as representative for the Dutch situation [Civieltechnisch Centrum Uitvoering Research en Regelgeving and Heijnen 2005; Stichting Bouwresearch et al. 1977]. More precise information may be found at the Dutch geo-data repository DINOLoket [TNO Geologische Dienst Nederland 2004], which contains, among other things, data from boreholes, cone penetration tests and groundwater levels. Still, if soil conditions seem to play a role in a damage process, it is always advisable to carry out exploratory drillings on site.

Interventions in the soil

Interference in the soil below or in the adjacency of a building may also trigger settlement processes. On one hand, this includes direct interventions in the soil substance. Examples are deep excavations, tunnelling and mining activities.

On the other hand, occurrences that influence the ground water balance can play a role. One may think of changes in the ground water table, or of leakages and floods. However, also growth or removal of trees belong to this category. They may lead to structural damage when occurring close to a building. Especially oaks, poplars, willows, ashes and planes are mentioned in this context [Hinks and Cook 1997; Marshall et al. 2009; Richardson 2001].

Other events that occur in the soil and may be related to structural damage are landslides and seismic events. The options for this condition are, thus:

- Occurrence of deep excavation adjacent to the building;
- Occurrence of flood;
- Occurrence of high ground water table;
- Occurrence of landslide;
- Occurrence of leakage;
- Occurrence of mining;
- Occurrence of seismic event;
- Occurrence of tunnelling;

- Presence of tree adjacent to building, at side of damage; and/or
- Occurrence of removal of tree adjacent to building, at side of damage.

To confirm or refute above options, a visual inspection is usually not sufficient. Changes in the ground water table may be obtained via the DINOLoket [TNO Geologische Dienst Nederland 2004]. To check the occurrences on the scale level of a neighbourhood, such as floods or landslides, one can turn to the archives of (local) newspapers. For leakages and the removal of a tree, one can best inquire from occupants and neighbours.

6.4.2 Climate

Climate can play a role in all three types of structural damage processes: not only in hindered dimensional changes, but also in settlement and overloading. We discern two different factors: temperature and humidity.

Temperature

Temperature fluctuations influence the occurrence of hindered dimensional changes. However, these fluctuations are, in themselves, not distinguishing enough for our diagnostic tool. Due to daily and seasonal cycles, they simply are omnipresent.

Hence, there is no point in distinguishing between whether these temperature variations occur at a certain location or not. Instead, one should examine to what extent a certain building part is exposed to these variations. Based on this, a distinction can be made between components in-door and out-of-doors. This is a geometrical condition, which has been included in Section 6.3.1.

As regards temperature, the only condition that is truly applicable in the initial phase of the diagnostic process is the occurrence of temperatures below freezing point. On one hand, this condition can influence soil behaviour (frost heave), which in Dutch winters can never be ruled out. On the other hand, frost may also act directly in a building component, and cause damage. For external elements, it is inevitable that in winter they will go through temperatures below freezing point. For internal building components, this only occurs when the building has not been heated for some time.

The option for this condition is:

- Occurrence of temperatures below freezing point.

Its presence can be derived from a visual inspection of the location of the building component, perhaps in combination with weather data from the *Koninklijk Nederlands Meteorologisch Instituut* (Royal Netherlands Meteorological Institute (KNMI)).

Humidity

Moisture is a precondition for two important structural damage processes within the group of hindered dimensional changes: frost action and salt attack. Frost leads to damage when moisture contained in a structure (or in the soil) freezes and swells. In salt attack, the role of water depends on the type of process. For the formation of swelling compounds, water is a reactant. Crystallization of salt in the form of crypto-florescence develops in a similar way as frost action. However, the moisture has a different function: it is a means of transport for the salt ions. When this 'vehicle' evaporates, the salt crystallizes – again, the expansion involved is the true cause of damage.

An important source of moisture is precipitation, possibly in combination with leakages, defect or blocked gutters and ineffective detailing of connections. Water may also enter a building component during construction works, or via the ground (capillary rising damp). Furthermore, internal building components receive their amount by the moisture produced by occupants when cooking, washing, showering or just breathing.

Moisture can also lead to changes in soil conditions, as has been discussed in Section 6.4.1. Weather conditions can play a role in this, especially when they differ considerably from the average. In this way, extremely dry or wet weather may lead to soil movement: drying out of the soil leads to compaction, while (re)wetting may invert this process. Apart from this, moisture can play a role in overloading, when wetness of masonry decreases the resistance of the building component.

The options for this condition are as follows:

- Presence of source of moisture;
- Occurrence of extremely dry weather; and/or
- Occurrence of wet weather after extremely dry weather.

The presence of moisture can partly be assessed in a visual inspection, for instance by checking the extent to which building components are exposed to wetting; this depends, for example, on the presence of an overhang. Although objective values of humidity can be obtained with a moisture meter, one should be aware of the fact that a repair may already have removed the immediate cause and traces of wetness alike. Weather conditions may be derived from archives, such as that of the KNMI.

6.4.3 Salts

As indicated in the previous subsection, the presence of moisture is one precondition of heave or hindered dimensional changes due to salt attack. The other precondition is, of course, the presence of salt ions.

- Presence of source of salt

Unfortunately, salts are present almost everywhere. Many building materials are carriers of salts themselves and, unfortunately, (low-fired) bricks and cement mortars are notorious in this respect. Other sources relevant to the Dutch situation are sea-water and sea-wind.

Salt crystals may actually show at the surface of the damaged building component. Still, sampling of material may be necessary to determine the actual amount and types of salt present. Preferably, samples should be taken at different depths along the wall height (see, for example, van Hees et al. [2009].

6.4.4 Interventions and incidents

Interventions and incidents in the environment of a building can activate structural damage processes. They seem particularly able to trigger settlements and overloading. We discern between interventions, which are planned but which may have unanticipated side-effects, and incidents, which are not foreseen.

Interventions

Unfortunate interventions that prompt structural damage come in two types. They can be concrete, such as the construction of a new building close to an existing one, or the removal of another building from the same building block. However, it may also relate to changes in the use of a building that involve changes in use load, or to vibrations from machinery or traffic.

The options belonging to this category are:

- Occurrence of change in use;
- Occurrence of construction of a new building adjacent to the damaged building;
- Occurrence of removal of mid-terrace building; and/or
- Occurrence of vibrations with considerable amplitude, due to machinery or traffic.

They can usually be assessed in a visual inspection, or from archive material.

Incidents

Catastrophic events often bring about damage to structures. One may think of collisions, explosions and acts of war, which may lead to overloading. Fire, on the other hand, leads to extreme temperatures, which may result in hindered dimensional changes.

The options for this condition are:

- Occurrence of collision into the building;
- Occurrence of internal explosion;
- Occurrence of fire; and/or
- Occurrence of war.

Their occurrences can be checked by taking statements from occupants, or by turning to (news) archives.

6.5 Time

The aspect time can be used in different ways during the diagnostic process. As argued in Chapter 5, observing damage is comparing the present state of a building to its original one. This involves, in fact, a comparison between the conditions of one building at various points in time.

In Chapter 4, it has also been explained that damage is the result of changes. These changes start at a certain moment, and they have a certain duration. The factor time, hence, can be used in the diagnostic process either to link the first occurrence of a damage to an incident that activated the damage process, or to relate the development of a damage in time to the course of such a damage process. These two topics will be discussed in the next subsections.

6.5.1 Moment of manifestation of damage in relation to event

In previous sections, various occurrences that can lead to structural damage have been discussed. When diagnosing such damages, one would want to investigate the relation between occurrence and damage. Since cause always precedes effect, a first step could be to examine whether the damage indeed did not show before the event occurred. Unfortunately, it is not that simple.

In many cases, the moment of manifestation of a damage seems to coincide with the occurrence of a certain event. This occurrence is, then, (too) easily considered to have caused the damage. An example is the flood of complaints from people living in an area where large construction works are in progress.

However, the assumed relation between such an event and the perception of a damage may only be causal in the other direction – that is to say: the event did not cause the damage; it only caused the occupants to have a closer look at the condition of their property. In this context, it is good to quote an observation made by Eldridge [1976]:

"… regarding the history of the defect … it must be appreciated that this may only relate to the time when the person first saw the defect and not necessarily to when it actually occurred. … It is surprising for how long cracks can go unnoticed; sometimes for several years. In consequence statements made about the date of occurrence of a crack must be treated with considerable suspicion."

Keeping this in mind, one should be aware that damage may show well after the start of the damage process, at least in the eyes of the observer. Consequently, most true trigger incidents do not catch as much attention as the ones mentioned above. A good example is the removal of a tree growing close to a house. Especially in clay ground, this removal may lead to substantial changes in the water balance in the soil and, hence, to soil movement. However, people just don't see the removal of a tree as a potentially dangerous or harmful event. Similarly, the effects of ill-advised or ill-executed conversions are often underestimated.

There is only one option belonging to this condition:

- Damage has appeared after the following occurrence:

In our diagnostic tool, this option will be used in combination with those environmental or geometrical conditions that are phrased as "occurrence of …". Corresponding environmental conditions can be found in Section 6.4, while the matching geometrical conditions, which are all related to changes in existing load equilibriums, have been mentioned in Section 6.3.3.

6.5.2 Behaviour of damage in time

Damage – usually – changes in time: it takes a while to develop, and only rarely preserves its looks. Roughly, three types of behaviour can take place: the extent of damage can remain constant, unchanged; it can fluctuate on a regular, daily or seasonal basis; or it can increase in time. To determine which option applies to a certain damage, monitoring is needed, preferably spanning a period of more than one year.

Cyclic changes in crack size over time may indicate thermal or moisture movement. However, this does not mean that a crack that shows cyclic changes has indeed originally been caused by thermal or moisture movement. It may simply give evidence of (new) unrestrained movement in the damaged element.

This touches on another aspect: once damage has occurred, it will be a weak spot in the building. It implies that one damage can lead to further damage, by 'attracting' symptoms of other mechanisms.

When interpreting repaired damage, one should also keep in mind that repair work – or inappropriate maintenance – can be the cause of damage, rather than a reaction to it. Building phases can be a cause of damage, as well. Apart from this, building phases can make a damage look incomplete, as the worst areas may have been repaired already. Moreover, they can obscure the origin of a crack, as this origin may have been removed. In all these cases, archive information may be needed to obtain a decisive answer.

Finally, a last remark should be made on time in relation to loading. The rate with which a load is imposed on a structure can be a factor which should not be underestimated. It can determine both the occurrence and the appearance of structural damage. When loads are applied slowly, structures are usually better able to accommodate these changes. This is the way in which lime-based masonry can adjust itself to soil settlements.

Despite this extensive proof of the importance of the factor time in structural damage processes, there are only two options that appear to be sufficiently distinguishing to be of use for our diagnostic tool. These are:

- Damage has appeared gradually, over a considerable period of time; or
- Damage has appeared in the first years after construction.

Both options pronounce upon the occurrence of damage in relation to the time of construction of the building element in which the damage has appeared. Damage that shows in the first years after construction can be linked to early-age loading, or to early-age irreversible dimensional changes. Creep processes, on the other hand, do not take shape until after a sustained period of high loading. By the time cracks start to attract attention, the situation may already be critical and sudden collapse cannot be ruled out [Verstrynge 2010].

Above options may be assessed in a visual inspection, taking the age of the building into consideration. Archive material may help to fix the first observation of the damage. To get an indication of the absolute age of cracks, the sharpness and cleanliness of crack edges can be used as evidence of freshness.

6.6 Conclusions

This chapter has given an overview of context conditions that may be useful when diagnosing structural damage in masonry. We have presented these conditions arranged in four categories. Three are related to scale levels; these are the material, geometrical and environmental conditions. The fourth category refers to the factor time.

Alternative options for each type of condition have been derived from literature. Their selection has been based on two criteria. First of all, they should be relatively easy to assess, either by visual inspection or by means of simple tests or investigations. Secondly, their diagnostic value has been assessed: context conditions only have practical value in the diagnostic process if they are distinguishing, either to describe a damage or to trace back its cause.

For each group of options, we have sketched the role they may have in damage processes. From this, one may deduce their possible role in the diagnostic process. Some conditions turn out to be imperative: without their presence, a damage process cannot occur. For other processes, there are alternative conditions possible. In that case, the absence of one condition has less diagnostic value.

Moreover, one should note that in both situations, the presence of a condition is often not a decisive trigger. In other words, confirming the presence of a certain condition does not immediately imply that a related damage process has taken place (let alone that it has indeed caused the damage in question). In our tool diagnosing will therefore be more a matter of crossing off possibilities than of pointing out the one and only sound hypothesis.

Summarizing, this chapter has pointed out what diagnosing is about. The two main questions one should ask oneself appear to be: Why did the damage occur here, in this material, geometry and environment? And why did it occur now, at this point in time? Combining this information with that of Chapter 4 and 5 leads the way to developing a diagnostic tool. That will be the subject of Part III of this thesis.

Part III
Implementation

In Part II of this thesis, an overview has been given of causes of structural damages, the symptoms to which they may lead, and the context in which they occur. In the following three chapters, the research data on these three components will be turned into an operative diagnostic tool.

Chapter 7 investigates the relations between the three components. What is the influence of each component on a damage process? Numerical and small-scale physical tests are applied to find this out. Subsequently, Chapter 8 combines the conclusions from Chapter 7 with the data obtained in Part II of the thesis. This information is the basis of our diagnostic tool, and Chapter 8 will show the construction of this tool. Finally, the potential benefits and points for improvement of the tool are verified in practice in Chapter 9.

Chapter 7
Testing the relations with experiments

The previous three chapters have described the most important causes, symptoms, and context conditions in connection with structural damage in masonry. In this chapter, we will investigate the correlations between these three components. Aim is to determine the effect that the change of one of four variables has on the occurrence, and especially the appearance, of damage.

Section 7.1 will start by explaining our approach towards testing these relations for settlement. Both numerical and small-scale physical tests have been applied. These tests are presented and discussed in Section 7.2 and 7.3, respectively. The conclusions drawn from them, as summarized in Section 7.4, are the prelude to Chapter 8, allowing us to reinterpret the information collected in Part II of this thesis and translate it into a diagnostic tool.

7.1 Investigating the interaction between causes, symptoms, and context conditions

In Part II of this thesis, we have introduced the separate elements that are important in the occurrence of structural damage in masonry. These are the data out of which our diagnostic tool will be composed. Still, to be able to build this tool, we also need to know how they correlate.

From the descriptions of the causes, symptoms and context conditions, the relations between these elements may already have been perceived. That a certain condition can have a substantial influence on a damage process is often not so hard to envisage; with common sense, many connections can be found in a qualitative sense. However, the actual quantitative influence that one single option has on a specific damage process is much more difficult to determine. With this chapter, we want to assess the consequences of the presence, absence or value of a certain factor, or the actual point of application of an external load on the eventual appearance of structural damage.

To assess the influence of one condition on a process, one needs to let this process develop under well-controlled circumstances. Hence, this is the moment that we shift our attention from the practice-based situations from which the majority of the data in the previous chapters has been deduced, to the more tightly regulated conditions of experiments. Performing a series of tests will allow us to study the effects that isolated changes in load or in context have on the damage process, and the implications this has for the appearance of damage and its interpretation.

We have opted for two types of tests, each with its specific merits. The first approach is numerical; failure of a wall under loading is simulated with a non-linear finite element analysis. The second approach is physical, and puts a small-scale model to test.

In each of the two types of tests, a distinct way of representing masonry is followed. In the numerical tests, masonry will be regarded as homogeneous and isotropic, while in the physical tests units and joints will be represented discretely. With these different strategies, we intend to reproduce the behaviour of different kinds of masonry.

As indicated in Section 1.3, we have chosen to use church buildings as object of study for the tests. Hence, in both approaches (part of) a representative sidewall of a Dutch church building is modelled. Two versions of this wall will be put to test: a blind one, and one with window openings.

As these parameter studies are time-consuming, it would not have been possible for us to study all damage processes that have emerged in Part II. Therefore, we have decided to set an example by focusing on settlement. In the tests, basic settlement troughs will be applied as loads, which distinguish themselves by different trough positions and different trough lengths. This should result in a series of 20 damage presentations, which, by comparison, will allow us study the influence of four factors:

- Trough position;
- Trough length;
- Presence of openings in a wall; and
- Material properties of the masonry.

In the following sections, we will investigate the influence of these four conditions on the occurrence and interpretation of structural damage in masonry.

7.2 Numerical approach

As announced in Chapter 3, we will use the program DIANA 9.3 [TNO DIANA BV 2008b] to model settlement and analyse its effects on a wall. DIANA provides a relatively easy way to assess the effects of different loads on a structure. It uses the finite element method: a numerical technique for finding approximate solutions to complex mechanics problems.

The basic idea of the finite element method is to model an object as consisting of a finite number of parts: the elements. The behaviour of the object as a whole can then be predicted by assembling and connecting the individual elements into a global system. Interaction between the elements, i.e. force transfer, takes place at their connection points, which are called nodes. The nodal displacements are the degrees of freedom of the system. DIANA can determine the element stiffness matrices from the input of material and geometrical properties of the object. Furthermore, it translates external loads into nodal forces to set up the assembled global stiffness matrix and global load vector, and to calculate the nodal displacements from that. Subsequently, these nodal displacements are used to determine strains and stresses in the elements. Since, in our case, the material behaves nonlinearly, the equilibrium equations are solved iteratively.

The use of a finite element program is commonly distinguished into three phases: the preprocesssing, in which the user builds the model; the analysis, in which the finite element program performs calculations on this model; and the postprocessing, in which the user evaluates the results of the calculations. In the following subsection, we will first discuss the input we use in the preprocessing phase to build the model. In addition, we will specify the calculations in the analysis cycle, and the type of results that are to be outputted. The actual results and their evaluation can be found in Sections 7.2.2 and 7.2.3.

Among other publications, DIANA user's manuals [TNO DIANA BV 2002; TNO DIANA BV 2008a] have been consulted for Section 7.2.1.

7.2.1 Outline of the numerical tests

Preprocessing: geometry and mesh

The first step in building a model is defining its geometry. Defining, here, does not only mean recording all dimensions of a structure, but, moreover, determining the best way to represent this structure. In other words, one needs to decide what level of simplification is appropriate.

The first idealization we have made was to opt for a two-dimensional model. This is a reasonable choice, since our model will be loaded in-plane and no out-of-plane displacements are to be expected. Out-of-plane action and restraints by front and rear walls are ignored. Also buttresses are not taken into account, as these hardly influence the in-plane behaviour of the wall.

Although it may seem that three-dimensional models give more accurate results due to their more realistic representation of geometry, this is often not the case, at least not for historical masonry structures. On the contrary, the analysis of 3D models is more complicated than that of 2D ones, which increases the risk of errors [Lourenço 2002]. Furthermore, building, computing and analysing 3D models also requires much more time. In our case, supposed improvements in accuracy of a three-dimensional model cannot outweigh these disadvantages.

As our intention is to simulate a representative Dutch church building, the geometrical parameters of the model are based upon a rough analysis of a sample of 81 church buildings located in the Netherlands. These churches had been brought forward by participants to a questionnaire that we held at the start of this study, in 2006. This inquiry aimed to provide insight into the extent of damage in churches. The participants belonged to various parties involved in the maintenance of churches, such as the *Rijksdienst voor het Cultureel Erfgoed* (Netherlands Cultural Heritage Agency (RCE)), Monument Watch organizations, ecclesiastic real estate departments, parishes and congregations, architectural firms, construction companies and consultancies. The reported 81 churches all suffered from crack development, deformations or both. With their dispersion in location and in building period, they can be regarded as representative for Dutch church buildings.

Table B in Appendix B gives an overview of the data collected for these 81 churches. The data concern, among others, the length, height and width of their sidewalls, and the dimensions of their window openings. Based on these data, we have modelled a non-existing but representative church wall with average values for its geometrical properties. This is in line with the goal of our study: we aim to provide diagnostic support for a variety of buildings, not for one particular church building.

We will analyse two types of walls: one blind wall and one with openings, see Figure 7.1. Both elevations are modelled with plane surfaces. The walls are 10.00 m high and have eight bays, each of which is 4.80 m wide. For the thickness of the (one-leaf) wall, a width of 785 mm is assumed. Despite the two-dimensionality of the model, this thickness should be specified: DIANA needs this information to calculate gravity loads and to compute stresses (as force per area).

Below the wall, a strip of 1.20 m high represents the foundation. The thickness of this foundation strip is set at 1047 mm. This value has been chosen to reproduce the moment of inertia I_z of a stepped foundation (see also Figure 7.4).

The next step is to decompose the model's geometry into a number of finite elements: the mesh. Before this mesh is generated, the user can specify the type of mesh element he prefers and the element size. The choice of a specific element type determines the number

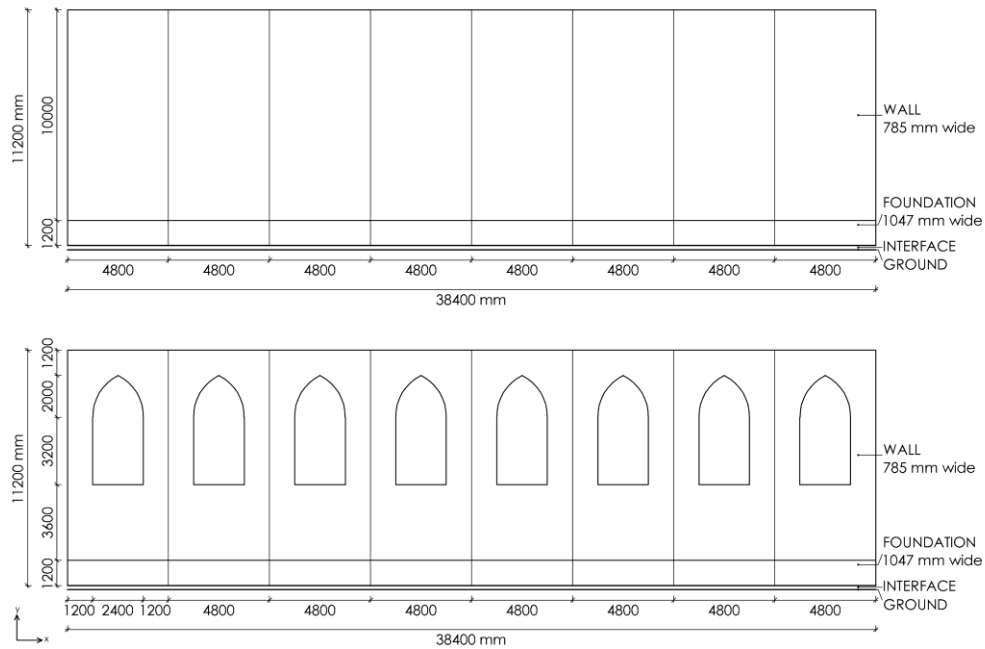


Figure 7.1: Geometries of the blind wall (top) and the wall with openings (bottom), with reference to dimensions.

of nodes per element, the degrees of freedom of the nodes, the basic and the derived variables that can be calculated and the integration scheme applied.

For our model, we have used isoparametric plane stress elements: eight-node curved quadrilateral CQ16M elements for all orthogonal parts and six-node curved triangular CT12M elements for those areas of the wall next to the window arches. Both elements are based on quadratic interpolation, which guarantees a more accurate handling of shear stresses than linear interpolation schemes would. The CQ16M elements are integrated by means of a full three-by-three Gaussian integration scheme. The interface, the concept of which will be discussed in the subsection on boundary conditions, is represented by quadratic, three-plus-three-node curved line interface elements, CL12I.

The requested element side length has been set at 400 mm. This results in meshes that are sufficiently fine to capture individual crack localizations. These meshes are shown in Figure 7.2.

Preprocessing: material model for masonry

The wall we intend to simulate, including its foundation, is made of masonry. Masonry is a composite material: it consists of courses of units (bricks, blocks) laid in and bonded together by mortar. This layout implies that masonry is non-homogeneous and has orthotropic properties that depend on the individual properties of the units and the joints, but also on the pattern in which the units are laid: the bond.

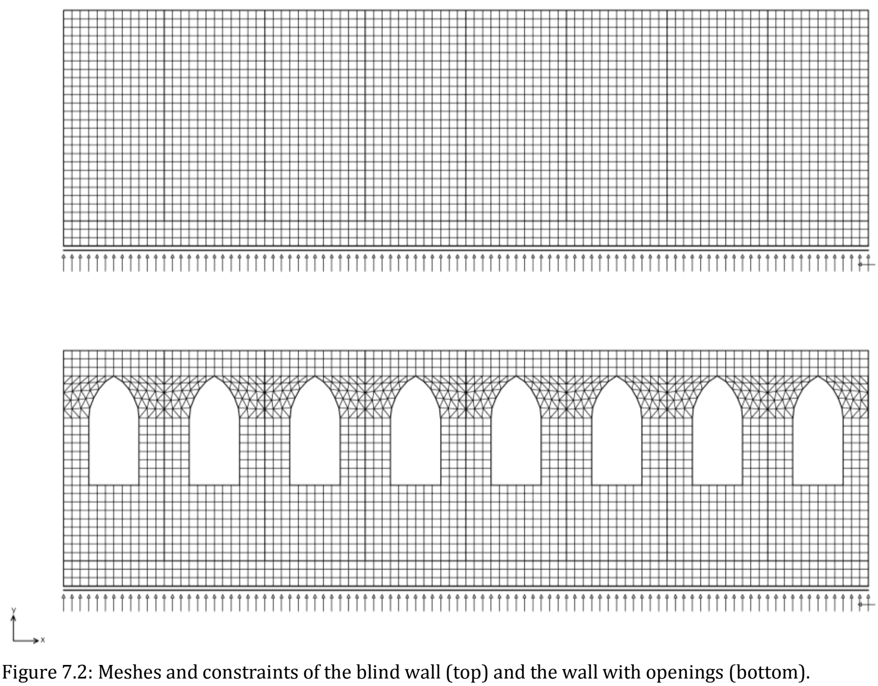


Figure 7.2: Meshes and constraints of the blind wall (top) and the wall with openings (bottom).

One way to represent masonry is to model units and joints individually. Although this approach is possible, it would be virtually unfeasible to use it here because of the large scale of the building compared to the scale of the units. Instead, we consider the masonry as a homogeneous composite material with average properties. Previous studies (e.g. Liu et al. [2000], Lourenço et al. [1998], Rots et al. [1994]) have shown that this is acceptable for predicting global crack paths and crack sizes in walls.

A second issue is that we assume isotropic behaviour. In reality, the elastic constants and strength values of masonry depend on the orientation of stress versus head joints and bed joints. In other words, due to its composition of units and joints, masonry behaves differently in horizontal and vertical direction. Nevertheless, we expect dominant cracks to occur vertically. These cracks will be governed by constants and strength values orthogonal to the crack direction, i.e. horizontally. Hence, horizontal properties have been taken as a starting point for our isotropic material model. This is a reasonable simplification for studying an average, representative wall, as was proven by previous studies (e.g. Boonpichetvong et al. [2005], Douglas et al. [2003], Rots et al. [2006]).

For our study, the most important criterion the material model should fulfil is a good representation of the failure behaviour of masonry. As has been discussed in Section 5.1.4, there are two types of masonry failure: continuous and discontinuous deformations. In line with this, we can distinguish between two options to model masonry failure.

Discrete crack models simulate pure discontinuous deformations. In currently available finite element programs, discrete cracks typically can only occur at and grow along a path of predefined interface elements. In other words, discrete crack models require the user to explicitly model all potential crack paths. For our study, this is a disadvantage: since it is precisely our intention to study the location and direction of the crack path or pattern, we do not want to a-priori determine where failure occurs.

The alternative is to use a continuum model. In the smeared crack approach, quasi-brittle behaviour is modelled by reducing the strength of the material as a function of the strain (softening), while cracking is spread out over the size of a finite element, rather than in a single crack (e.g. Feenstra and Rots [2001]). Upon violation of the failure criterion, e.g. the tensile strength, the initial isotropic stress-strain law switches to an orthotropic law and a smeared crack is formed perpendicular to the major principal stress (e.g. Rots [1988]). Using the smeared crack approach, the crack width (or better: crack size, see Section 5.3.3) cannot be determined as accurately as the discrete approach would allow. However, the smeared crack approach has the important advantage that location and direction of failure are not predefined, but calculated in relation to local stress states.

DIANA offers several smeared crack concepts (e.g. plasticity, decomposed strain, total strain). These models differ in the way they deal with strain parts and with changes in the direction of a crack. The plasticity and decomposed strain models are formulated incrementally, whereas the total strain model adopts a total procedure.

Of these models, the total strain rotating crack model appears to be the most robust one. In this model, the crack orientation is continuously updated with the direction of the major principal stresses [Rots 1988]. The rotating crack concept provides for mode I tensile failure (see Figure 5.5). It avoids the arbitrariness of the shear retention factor for the fixed crack model, and the complexities involved in the multidirectional crack model. As we intend to analyse global crack patterns, the smeared total strain rotating crack concept suits the demands of our parameter study.

Assuming an elastic softening material model in tension, basic material parameters are required for the smeared total strain rotating crack concept. First of all, we have decided to opt for brickwork masonry, since the majority of Dutch buildings, including churches, is made of brick. Consistent with the study of Hendriks et al. [1995], we assume this brick masonry to have a Young's modulus E of 6000 N/mm^2, a Poisson's ratio ν of 0.2, and a tensile strength f_t of 0.30 N/mm^2. Crushing or other nonlinear behaviour of the masonry in compression is ignored. This assumption is justified because the compressive stresses in the cases considered appeared to be low compared to the compressive strength. Tensile failure prevails.

Beyond the tensile peak strength, the masonry is assumed to gradually break and soften down to zero. This mode I tensile softening behaviour is controlled by the fracture energy G^I_f, which is defined as the energy required to create one unit of area of a crack. An average value of G^I_f = 0.05 N.mm/mm^2 is assumed for the masonry.

The fracture energy equals the area under the stress-crack opening diagram for a discrete crack. In our test, we have opted for a smeared crack model. This implies that the crack opening is smeared out to a crack strain over a certain width, the so-called crack band width h (e.g. Rots et al. [1985]). This tensile behaviour has been described with a linear tension-softening curve, see Figure 7.3. The crack band width is calculated by DIANA as the square root of the total area of the element. This leads to a value of h = 400 mm for the quadrilateral elements. The ultimate strain ε_u for the linear softening diagram can be derived from:

$$\varepsilon_u = (2 \cdot G^I_f) / (f_t \cdot h)$$

which for our models leads to a value of $8.3 \cdot 10^{-4}$.

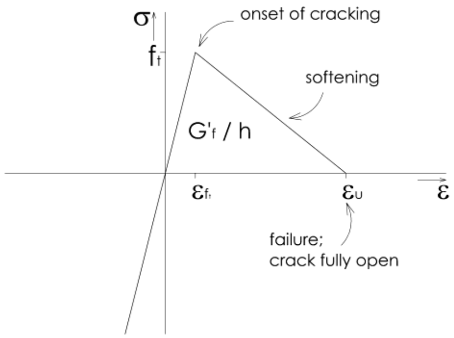


Figure 7.3: Total strain rotating crack model: masonry behaviour under normal stress (tension and compression).

Preprocessing: boundary conditions of interface and constraints

Models can only simulate a part of the real world. Hence, a model has borders and one needs to determine where it ends and 'the rest of the world' begins. Also, one has to specify the way in which model and environment interact at these edges.

For the numerical tests, we have limited the church wall model to eight bays, see Figure 7.1. This is consistent with the average value calculated in Appendix B. The sides of the wall are left unconstrained, which implies that they are free to move. At the upper edge, a real wall would support a roof. While we did not model this roof structure, we will apply its load to the upper edge of the wall. However, we do not define any constraints at this edge, since the roof structure would hardly limit in-plane translations or rotations of the wall.

The lower border of the foundations of the wall would, in the real situation, be supported by soil. Since our focus is on the wall's behaviour and not on that of the ground, we choose to leave this subsoil out of the simulation and opt for a so-called semi-coupled model [Boonpichetvong and Rots 2004]. As a consequence, the lower boundary of our model should reproduce the behaviour of a layer of ground supporting the wall, including the bond between wall and soil.

Buildings are never rigidly connected to the soil on which they stand. Generally, the bond between building and soil is only based on compression and cannot transfer any tensile stresses. Therefore, local settlement of soil does not necessarily lead to equivalent displacements in the structure above it: a gap might open between soil and foundation and sliding might occur. We will model this behaviour with a no-tension interface, see Figure 7.4.

An interface element controls how stresses are transferred between either of its sides. To be more precise, it relates stresses acting on it to relative displacements across it. These relations can be defined separately for the normal and the shear direction, and are

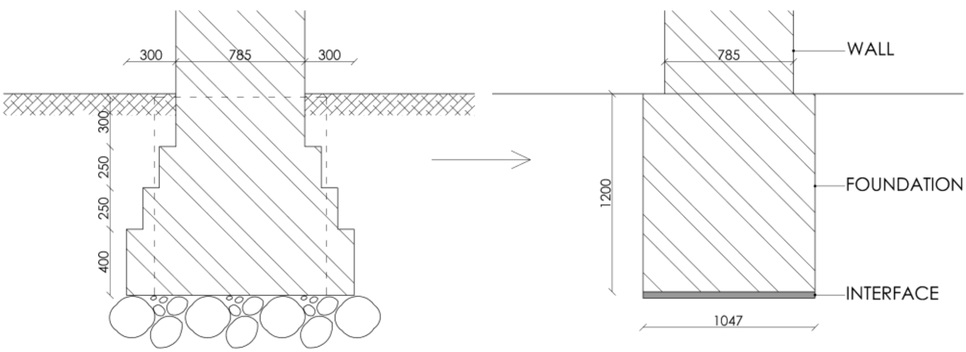


Figure 7.4: Shallow foundation on sand and its representation in our numerical model.

expressed in the normal and shear stiffness, respectively. To correctly represent the connection between building and soil in the normal (vertical) direction, our interface should be stiff under compression and weak under tension. This implies a normal stiffness k_n that is constant in the compressive region and almost zero in the tensile region.

For these analyses, we presume the shallow foundation to be supported by a fairly compact layer of sand. The normal stiffness in compression of the interface has been set at a value of 0.030 N/mm^3. We have eliminated the transfer of tensile stresses by setting the stiffness in tension at 3.10^{-8} N/mm^3. An overview of the interface properties in normal direction is presented in Figure 7.5 (left).

For shearing, i.e. the behaviour in the tangential or horizontal direction, the interface should reproduce the friction between soil and structure and, hence, the transfer of shear stresses. Resulting horizontal movement is largely governed by soil-structure interaction. Although the recent study of Netzel [2009] has demonstrated that the transfer of horizontal strains can substantially influence the effects of settlement, its occurrence is not yet fully understood.

As Netzel has shown, the introduction of horizontal strains at the bottom of a wall can lead to an increase, but also to a decrease in damage, depending on the position of the wall with respect to the settlement trough. Hence, disregarding the transfer of these strains, as we propose to do in our tests, will in some cases lead to underestimating the effects of settlement; in other cases, however, it is a conservative, safe approach.

Since occurrence and effects of horizontal movements are not indisputable, we have chosen to focus on the effects of vertical ground movements only. Possible effects of horizontal ground movement on the building are eliminated by assuming an almost zero value for the tangential interface stiffness k_t = 1.10^{-15} N/mm^3, see Figure 7.5 (right). By doing so, the building can slip and move independently from the soil: horizontal displacements in the ground will not be transferred by this so-called smooth interface.

The actual support offered to the wall is defined at the lower boundary of the interface. For all nodes on this edge, translations along the y-axis have been suppressed. In addition, to prevent inadvertent horizontal displacements, the end node of this edge has also been constrained for translations along the x-axis. The constraints of the wall have been displayed in Figure 7.2.

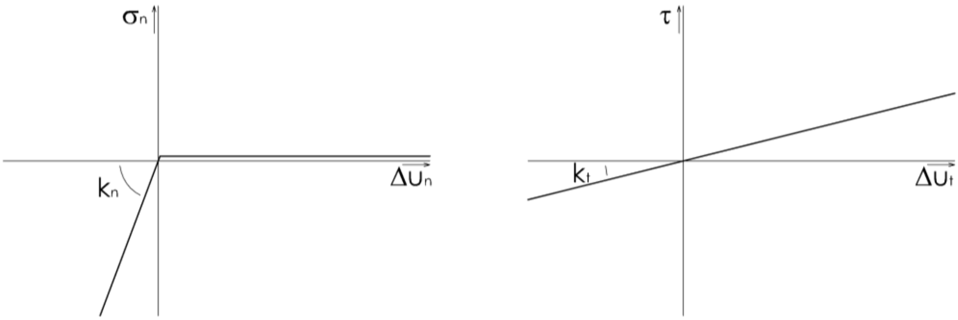


Figure 7.5: Interface properties in normal direction (left) and tangential direction (right).

Preprocessing: applied loads

Our wall models will be loaded with three loads: a gravity load, a line load and a displacement load. The gravity load represents the weight of the wall itself. DIANA automatically derives its magnitude from the model's geometry and the mass density ρ of the masonry, which has been set at $2.0.10^{-6}$ kg/mm^3. For the gravitational acceleration g, a value of 9.81 m/s^2 has been assumed.

A line load imposed on the top edge of the wall corresponds with the weight of ceiling and roof. We assume it to be 11.0 N/mm, which is a representative value for a timber ceiling and a timber roof clad with tiles.

For the simulation of settlement-related processes, we want to focus on the effects they have on a building: to what damage symptoms do they lead? Therefore, we have chosen for a semi-coupled model: instead of simulating damage processes within the soil, we will impose vertical displacement fields to the lower bottom of the interface. Each of the five displacement fields that we have modelled, reproduces the effects of a representative settlement trough, see Figure 7.6. These troughs are described in terms of (parts of) an inverted Gaussian distributed curve [Peck 1969]. Trough A has been described by:

$u_{y;n} = -100 \,.\, \exp[-x_n^2 / 5.00 \,.10^6]$ for $0 \leq x_n \leq 4800$

in which $u_{y;n}$ is the vertical displacement at node n and x_n is the horizontal distance of the node n to the left end of the model. This corresponds with a trough with a maximum (vertical) settlement of 100 mm at the left end of the model and a point of inflection at a horizontal distance of 1581 mm from this maximum. Trough B has been described by:

$u_{y;n} = -100$ for $0 \leq x_n < 18800$

$u_{y;n} = -100 \,.\, \exp[-(x_n-18800)^2 / 5.00 \,.10^6]$ for $18800 \leq x_n \leq 38400$

in which case the settlement trough extends over more than half of the wall. Trough C takes up almost the whole length of the wall, leaving only its utmost right end in place:

$u_{y;n} = -100$ for $0 \leq x_n < 33200$

$u_{y;n} = -100 \,.\, \exp[-(x_n-33200)^2 / 5.00 \,.10^6]$ for $33200 \leq x_n \leq 38400$

Trough D is a complete trough under two bays at the centre of the wall:

$u_{y;n} = -100 \,.\, \exp[-(x_n-19200)^2 / 5.00 \,.10^6]$ for $14400 \leq x_n \leq 24000$

Finally, for curve E the length of the central settlement has been set at four bays, with a point of inflection at a horizontal distance of 3163 mm from the point of maximum settlement. This leads to a shallower trough, described by:

$u_{y;n} = -100 \,.\, \exp[-(x_n-19200)^2 / 2.00 \,.10^7]$ for $9600 \leq x_n \leq 28800$

Horizontal displacements due to settlement have been disregarded in this parameter study. The occurrence of such movements depends to a large extent on the interaction between soil and structure. This soil-structure interaction is still subject of research and it has, so far, not been fully understood. Including its possible effects would only make our study unnecessarily complicated, with a non-hypothetical danger of leading to inaccuracies.

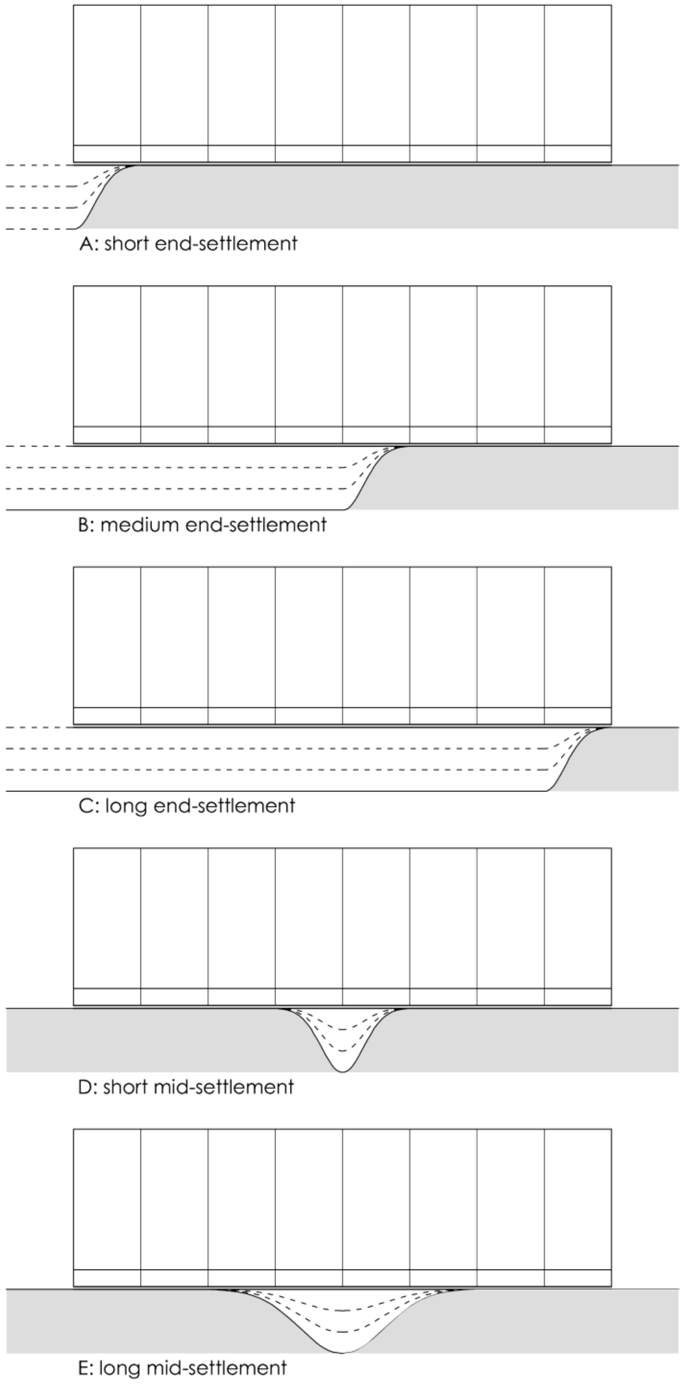


Figure 7.6: Five (exaggerated) displacement fields representing common types of settlement.

Analysis

Our models are now ready to start the actual calculations. Due to the material properties assigned to the masonry and the interface, the models behave physically non-linear: the relation between forces and displacements at a certain moment depends on displacements at earlier stages. To solve these relations and determine the state of equilibrium, an incremental-iterative solution procedure has been adopted. This means that loads are imposed incrementally and that, within each increment, the equilibrium solution is sought iteratively.

For the iteration process, we initially use the Regular Newton-Raphson algorithm, in which the tangential stiffness is evaluated and updated every iteration. Alternatively, in those cases when the regular approach cannot reach convergence, the Modified Newton-Raphson algorithm will be applied. In this algorithm, the tangential stiffness is kept unchanged within each increment. Both Newton-Raphson algorithms are combined with the Line Search algorithm to increase the convergence rate.

The ending of the equilibrium process is governed by energy criteria for convergence and divergence, and by a specified maximum number of iterations. For our models, the result of an iteration will be regarded as satisfactory (i.e. sufficiently accurate) if the relative energy variation has become less than 0.01 times the reference energy norm. If so, the iteration has converged and a next load step will be applied. We set the divergence criterion at 100, which means that divergence is assumed as soon as the relative energy variation exceeds a value of 100 times the reference norm. In that case, the analysis will be aborted. The maximum number of iterations per increment (loadstep) is set at 50. If no convergence is reached within these 50 steps, but also no divergence has occurred, the analysis will be continued with the next increment. However, the results of all steps succeeding a no-convergence step will be considered with reservation.

Using above settings, the three separate loads are applied one after another. First, the own weight is activated, in one step. After equilibrium is found, the line load is applied, also without increments. When equilibrium is reached again, all displacements resulting from self-weight and line load are reset to zero. This has been done for postprocessing reasons: in this way, deformations as shown in the results can be entirely attributed to the imposed settlement. Stresses and strains, however, are kept in the model.

Then, we let DIANA start with incrementally imposing the displacement load. Each displacement increment represents a percentage of the total displacement field. In this way, the shape of the trough is kept constant throughout the analysis, while the amplitude is increased.

We start with 10 steps in which, per step, 0.5 % of the total displacement curve is imposed. After these 10 steps, the maximum vertical displacement in the interface will be 5 mm. Subsequently, the displacements are increased with 5.0 mm steps, up to a vertical nodal displacement of 100 mm.

Postprocessing

Per case, the reliability of the calculation has been verified by checking the following output:

- The vertical displacements of the lower edge of the foundation, compared to the vertical displacements of the lower edge of the interface (i.e. the imposed displacement field), at 100 % of the total settlement imposed;
- The support reactions, defined as the out-of-balance forces, i.e. the difference between the externally applied forces and the internal forces, in the supported nodes, at 100 % of the total settlement imposed;
- The maximum principal (σ_1) stresses in wall and foundation, at 0 %, 50 % and 100 % of the total settlement imposed;
- The minimum principal (σ_2) stresses in wall and foundation, at 0 %, 50 % and 100 % of the total settlement imposed. With maximum values of 4.1 N/mm^2, compressive stresses indeed never exceeded the compressive strength f_c of this type of masonry, which is 8 N/mm^2;
- The deformations of wall and foundation, at 100 % of the total settlement imposed;
- The partial and closed cracks, i.e. those cracks for which the normal crack strain is below the ultimate strain ε_u of the softening branch (see Figure 7.3), in wall and foundation, at 0 %, 50 % and 100 % of the total settlement imposed;
- The full cracks, i.e. those cracks for which the normal crack strain is beyond the ultimate strain ε_u of the softening branch (see Figure 7.3), in wall and foundation, at 0 %, 50 % and 100 % of the total settlement imposed;
- The relative horizontal displacements of both end points of the lower edge of the foundation, the upper edge of the foundation and the upper edge of the wall, with respect to the imposed settlement. This horizontal displacement is equal to the total crack size at these three heights.

For each case, the final crack pattern and deformations have been combined into one picture. These results are presented in Section 7.2.2, followed by a discussion in Section 7.2.3.

7.2.2 Results of the numerical tests

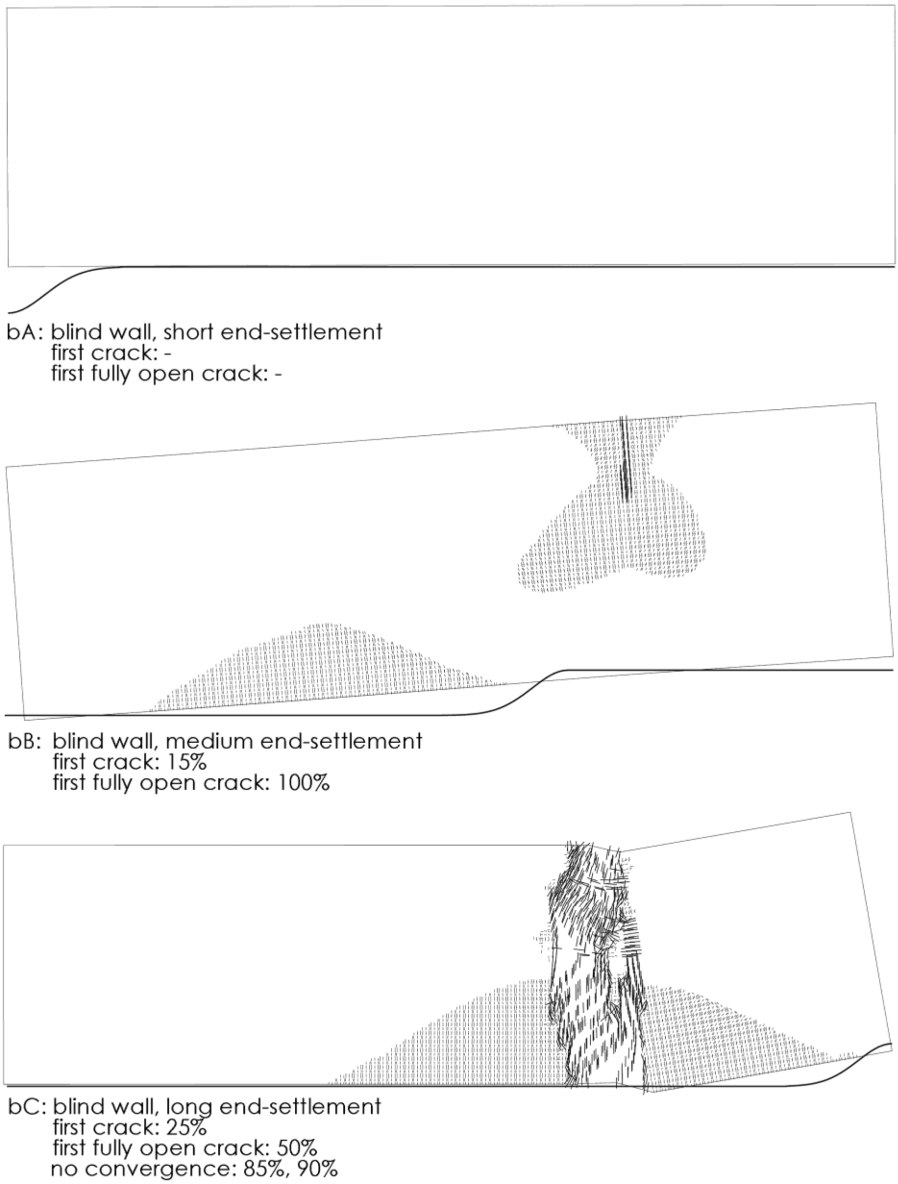


Figure 7.7: Deformations and cracks resulting from different end-settlement troughs, in blind walls, tested in DIANA 9.3. The bold lines at the bottom of each wall indicate the fully imposed vertical displacement. The strong lines within wall and foundation represent fully open cracks, while the thinner lines are partial (hair) cracks. Below each figure, the percentage of imposed displacement at which partially and fully open cracks appeared is indicated. Deformations have been scaled 20 times.

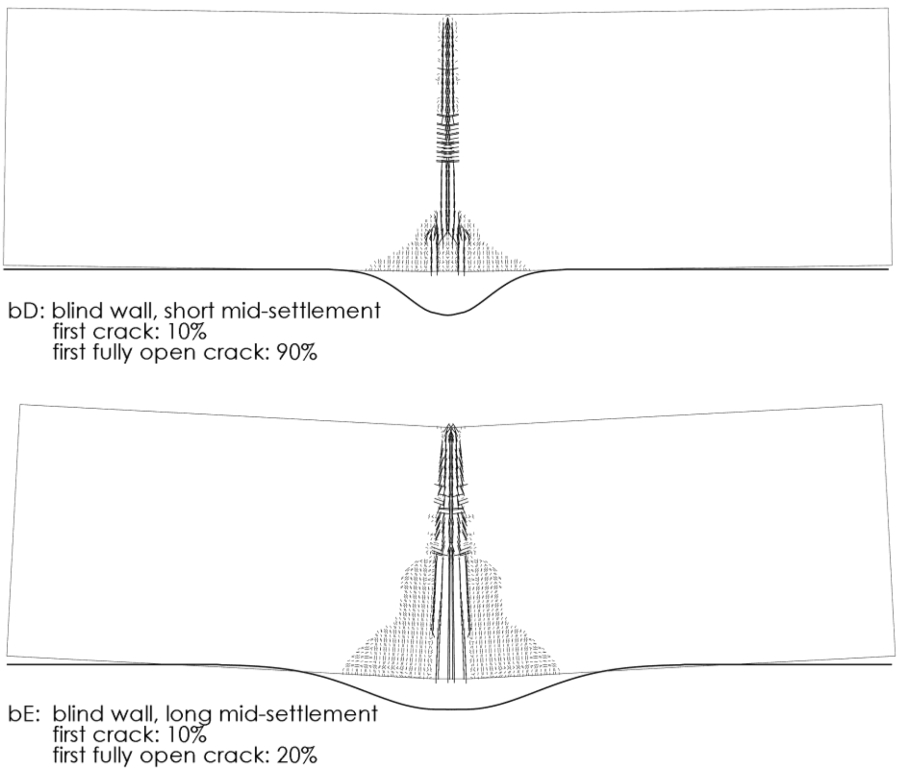


Figure 7.8: Deformations and cracks resulting from different mid-settlement troughs, in blind walls, tested in DIANA 9.3. The bold lines at the bottom of each wall indicate the fully imposed vertical displacement. The strong lines within wall and foundation represent fully open cracks, while the thinner lines are partial (hair) cracks. Below each figure, the percentage of imposed displacement at which partially and fully open cracks appeared is indicated. Deformations have been scaled 20 times.

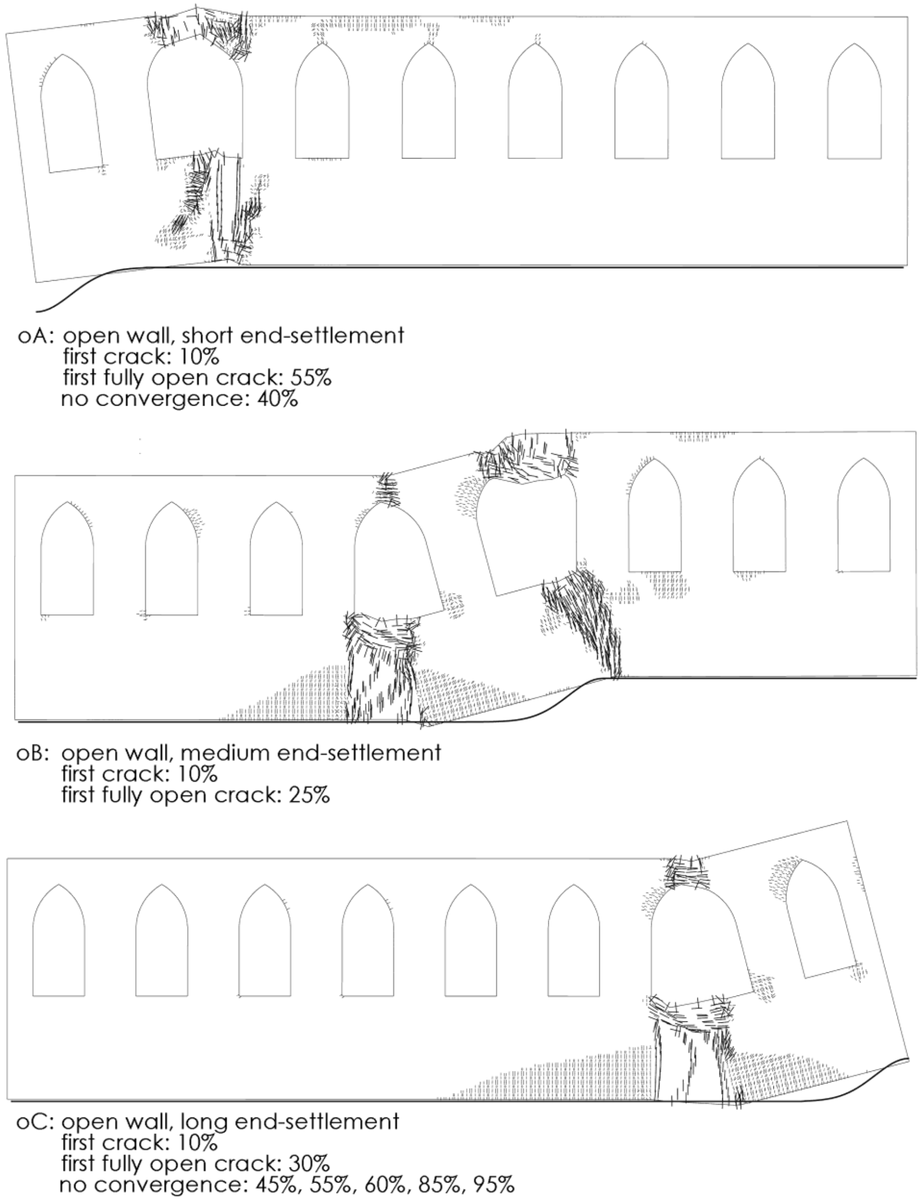


Figure 7.9: Deformations and cracks resulting from different end-settlement troughs, in walls with openings, tested in DIANA 9.3. The bold lines at the bottom of each wall indicate the fully imposed vertical displacement. The strong lines within wall and foundation represent fully open cracks, while the thinner lines are partial (hair) cracks. Below each figure, the percentage of imposed displacement at which partially and fully open cracks appeared is indicated. Deformations have been scaled 20 times.

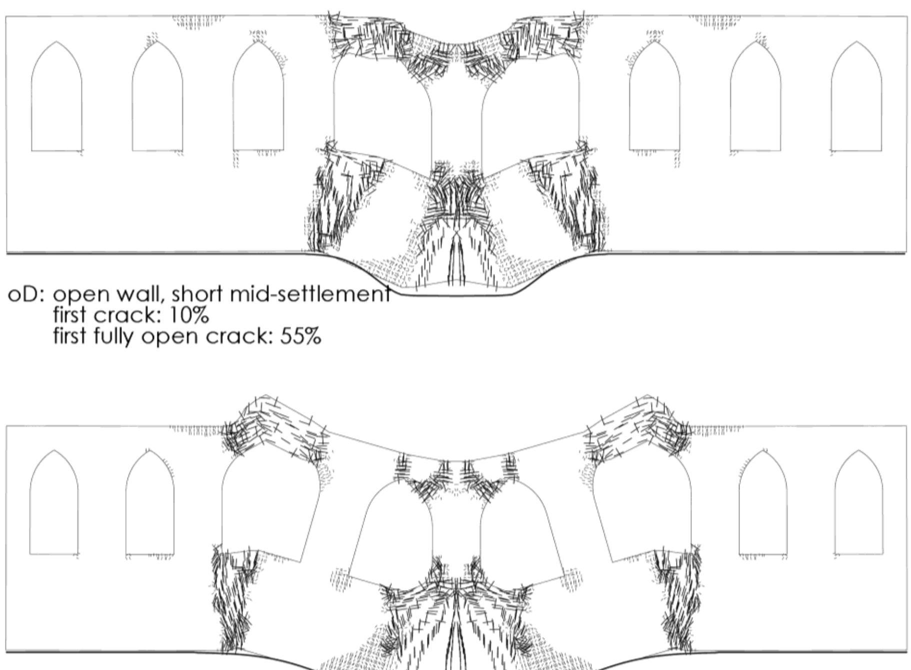


Figure 7.10: Deformations and cracks resulting from different mid-settlement troughs, in walls with openings, tested in DIANA 9.3. The bold lines at the bottom of each wall indicate the fully imposed vertical displacement. The strong lines within wall and foundation represent fully open cracks, while the thinner lines are partial (hair) cracks. Below each figure, the percentage of imposed displacement at which partially and fully open cracks appeared is indicated. Deformations have been scaled 20 times.

7.2.3 Discussion of the numerical results

The results presented in the previous section concentrate on the damage resulting from the imposed vertical displacements. Figures 7.7-7.10 show, first of all, the resulting deformations. For the sake of clarity, these deformations are shown in an exaggerated form: they have been scaled twenty times with respect to the original, overall geometry. As all displacements caused by the gravity load and the line load have been reset to zero during the analysis, the resulting displacement can be entirely attributed to the imposed settlement.

The bold lines at the bottom of each model indicate the imposed settlement trough. As one can see, this line differs from the bottom of the foundation: at some points, a gap has formed between wall and support. These gaps prove that the interface functions in the correct way. Its no-tension properties guarantee that the imposed displacements have not been transferred directly to the wall, but, instead, have led to a loss of support.

Another phenomenon is that at other points the wall appears to have sunk slightly below the supporting interface. This, of course, does not represent a real situation, but is a visual consequence of the interface. It does not have any physical meaning or consequence for the behaviour of the wall.

In addition to the deformations, Figures 7.7-7.10 also display the final crack patterns at the moment that 100 % of the vertical displacement has been imposed. Within these crack patterns, a distinction has been made between cracks that are fully open, and those that are only partially open or have closed during the settlement process. This distinction should be viewed in the light of the normal crack behaviour of masonry, as defined in Figure 7.3. There, it was shown that for strains below ε_{ft} masonry behaves linear elastically. Above that value, that is after the tensile stress in an element has exceeded the tensile strength of the material, a crack will start to develop. First, while in the softening branch of Figure 7.3, partial cracks arise. Then, as soon as in one of the elements the ultimate crack strain ε_u has been reached, at that point the partial crack evolves into a fully open crack. At this stage, failure tends to localize in one zone: a band of fully open cracks. The remaining partial cracks usually close. This strain localization into a crack band and unloading behaviour at either side of the crack band is typical for (unreinforced) elastic-softening materials such as masonry. For each load-model combination, the time of occurrence of both partially and fully open cracks has been indicated below the resulting damage, expressed in a percentage of the total vertical displacement imposed.

By comparing the results of the ten load-model combinations, it is possible to study the effects that location and relative size of a settlement trough have on the eventual damage. The following paragraphs will discuss these effects. In addition, the comparison also provides information on the differences in failure behaviour between walls with and without openings. This influence of openings on settlement processes, and the influence of material properties, will be dealt with in Section 7.3.

Effects of trough position

Five different displacement troughs (A-E) have been imposed on the wall models. These five troughs can be subdivided into two categories: end-settlements, in which one of the ends of the wall is left unsupported, while the other end remains in place; and mid-settlement, in which the settlement trough reaches neither end, but takes place under the centre of the wall. Hence, troughs A, B and C belong to the former category, while D and E go with the latter.

When considering the damage caused by mid-settlement, it is apparent that there is a strong relation between the position of the trough and the position of the damage. In all four cases, the fully open cracks have appeared directly above the trough. Furthermore, each damage presentation is symmetrical to the centre of the corresponding trough.

For end-settlement, the opposite is true. Here, cracks tend to occur slightly away from the onset of the displacement and the damages are, just as the troughs themselves, asymmetrical. From this we can conclude that a symmetrical damage presentation is a reliable indicator for mid-settlement troughs, while an asymmetrical presentation points to end-settlement.

Effects of trough length

Apart from their position, the imposed displacement fields A-E also differ in their length ℓ. For end-settlement, we have tested a short (ℓ = 4800 mm) (A), a medium (ℓ = 24000 mm) (B) and a long (ℓ = 38400 mm) (C) trough. For mid-settlement, the two variants consisted of a short one (ℓ = 9600 mm) (D) and a long one (ℓ = 19200 mm) (E). When considering the damage resulting from these different troughs, the effect of trough length on the damage becomes evident.

Especially for end-settlement, it is clear to see that the response of the walls changes with a change in trough length. When the short end-settlement is applied, the wall undergoes a negative bending moment: the upper edge of the wall is put under tension, which causes it to elongate. Such a convex type of settlement profile is called 'hogging'. The bending crack associated with this profile starts at the top of the wall, where the tensile stresses are highest. The resulting crack opening is widest at this top edge.

Under medium end-settlement, the initial behaviour of the wall is identical and the first crack again develops at the top of the wall. However, in this case the broken-off end of the wall is longer, which implies that a small rotation of this part can be enough to allow it to regain support at its far end. The blind wall under medium end-settlement (bB in Figure 7.7) shows this behaviour and demonstrates that this regaining of support can bring the first crack to a halt: it tapers to zero halfway the wall height. Nevertheless, the emergence of hair cracks in the lower zone of the left part of the wall already indicates how the bending mechanism would have developed had we taken the displacements a little further.

The wall with openings under medium end-settlement (oB in Figure 7.9) shows this next step. After regaining support at the broken-off end, further displacements have caused the separated part of the wall at the left hand to bend downwards in the middle. This so-called sagging leads to a second crack, which is widest at the bottom of the wall.

In the third variant of end-settlement, the displacement we imposed was almost as long as the wall itself (bC, oC). Only its utmost right end was left supported and in place. In that case, most of the wall just subsided with the settlement and damage occurred near the place that was fixed at the original level. The sagging mode, hence, led to a crack that started at and is widest at the bottom of the wall.

It appears that, for all three end-settlement troughs, the location of the damage does not correspond closely to the location of the settlement trough. Especially for the blind walls, which are rather stiff, the cracks occur at some distance from the onset of the displacements. Thus, one should be careful in using the location of a crack to trace back the position of this onset.

When looking at the results for the wall with openings under mid-settlement (Figure 7.10), one can recognize the double bending mechanism that was also shown for medium end-settlement. The order in which the cracks occur is, however, opposite. The first crack arises due to sagging, starting at the bottom of the wall directly over the largest displacement. This crack, then, snaps towards the two central windows and, subsequently, to the top of the wall. Because of this, the wall is in effect split into two separate parts, which can each be regarded as being subject to a short end-settlement. This implies that further displacements lead to the two symmetrical cracks that are widest at the top.

As Figure 7.8 shows, the blind wall reacts much stiffer to the mid-settlements than the wall with openings does. As a consequence, the damage is limited to a sagging crack at the centre of the wall. The separated wall parts lean towards each other, but no hogging cracks occur. This is in line with the results of case bA (Figure 7.7): the blind wall is sufficiently strong to be able to cantilever over a short end-settlement, without showing any sign of damage.

However, one may have expected a different behaviour under mid-settlement. In reality, masonry structures tend to bridge such gaps in their supports by arching. The masonry below the arch would follow the vertical displacement, while the masonry above it would transfer its loads towards the sides.

It appears that this arching behaviour did not occur in our numerical tests. The reason for this lies in the properties of the interface. As explained in Section 7.2.1, we assumed an almost zero value for the tangential interface stiffness k_t, thus eliminating the influence of horizontal ground movement on the wall. This choice for a smooth interface does, however, influence the crack development in our model: due to a lack of friction, wall and interface can move independently from each other in the horizontal direction. This implies that the horizontal thrust that arching produces cannot be accommodated at the supports. Instead, it had to be delivered by the lower masonry rows, which explains the crack pattern.

Apart from the difference in crack pattern, another consequence of this choice for a smooth interface is that it has probably resulted in relatively heavier damage for the sagging type of settlement. In reality, the soil would provide some lateral restraint to the foundations. This has a positive compressive effect in the lower zone of the wall that, in our model, is susceptible to crack initiation [Burland and Wroth 1974]. Our damage presentations for sagging can, therefore, be regarded as conservative.

Contrarily, the smooth interface may have led to an underestimation of the damage caused by hogging, as Netzel [2009] has demonstrated. In that case, horizontal displacements of the soil can lead to additional tensile strains on a building. It is important to state that, although quantitative comparisons on the severity of damage resulting from the different settlement troughs should not be made on the basis of the results of our study, the damage presentations that we have found are representative.

Based on this comparison of the effects of relative trough length, the importance of the tapering of a crack has been highlighted. This tapering indicates the rotation that has occurred between wall parts on each side of a crack. Of course, one should consider this rotation as a relative one: tapering in itself does only indicate the direction of bending, not the direction of vertical movement. In other words, the crack pattern of bC can result from a long settlement trough at the left side, but also from a short heave at the right side. The latter variant has, indeed, been analysed and gave an almost 100 % match in results with case bC. Summarizing, we can state that for the interpretation of a crack, its tapering is the most important characteristic to identify the underlying settlement trough from the damage, and not the exact location of this crack.

7.3 Physical approach

Supplementary to the numerical tests, small-scale physical tests have been carried out to further study the effects of settlement on the sidewall of a representative Dutch church building. A comparison between the results of both types of tests provides insight into the influence that wall openings and material properties have on the eventual damage presentation. But before we present these results, we will first discuss the outlines of the physical tests.

7.3.1 Outline of the physical tests

Simple models can sometimes provide refreshing insights into complex matters. This is certainly the case for masonry. Although masonry is one of the oldest materials used for construction, modern world seems to have forgotten how to deal (and design) with it. Masonry differs from other, modern structural materials in the sense that simplifications such as homogeneity, isotropy and linear elasticity are not adequate to fully understand its behaviour. Because of its composition, masonry must work in compression, and stability is a more crucial requirement than strength.

The idea for the series of tests that we will discuss here has been derived from Huerta [2005]. Huerta advocates the use of simple, physical models for studying the structural behaviour of masonry. He especially proposes a pragmatic approach for studying the effects of in-plane loading on masonry. The method consists of building a model out of individual blocks that represent masonry units, then placing this model on an inclined surface, and simulating settlement by moving the model's supports.

Major advantage of this test set-up is that it enables the use of a two-dimensional model rather than a three-dimensional one. By placing this model on an inclined plane, it is subjected to reduced self-weight, without a risk of out-of-plane collapse. Huerta explains:

"The physical principle involved is evident. The weight of each block acts vertically. As the block is supported by the inclined surface …, this force may be resolved into two other forces: one normal to the surface … and the other contained within its surface. When the inclination … is well above the angle of friction …, all blocks tend to slide downwards and these forces are proportional to the gravity forces." [Huerta 2005].

Slanting the model, thus, ensures that all blocks are pressed against each other, so that the separate units together form the tight fabric of dry stone masonry. The masonry will react to any small movement of its supports by the formation of cracks, the blocks seeking a new equilibrium by hinging. In this way, these small-scale physical tests offer an excellent way to study the occurrence of cracks and deformations.

Geometry and mesh

The geometry of the model is the first matter that needs to be defined. As mentioned before, a two-dimensional model is sufficient here: only in-plane loads and in-plane displacements are investigated. This allows us to let the model parts be cut out of sheet material, by means of a laser cutter.

We will test two types of walls: one blind wall and one with openings. The geometrical parameters are kept in line with those used in the numerical tests. All dimensions have been based on a study of sidewalls of 81 Dutch church buildings, as has been discussed in Section 7.2.2 and elaborated in Table B in Appendix B. The models are built on a scale of 1 : 25. For practical reasons, they are limited to four, instead of eight bays: the results of the numerical tests have shown that deformations and true, fully open cracks tend to concentrate within the four bays that are closest to the applied troughs. Each bay is 400 mm high and 192 mm long, and below it is a foundation strip of 48 mm high. This makes the overall size of the physical models 448 mm high by 768 mm long.

To allow the models to crack and deform, each wall is composed of individual blocks. For the standard blocks, a size of 16 by 32 mm (scale 1 : 25) has been opted, which corresponds to masonry units of 400 x 800 mm in reality (1 : 1). All blocks, both for the wall and for the foundation strip, have been (laser-) cut out of 3 mm medium density fibreboard (MDF). The geometries of the two models, including the way they are divided into blocks, are shown in Figure 7.11.

Material model for masonry

This type of test entails a discrete representation of masonry, with separate blocks representing the individual units. No mortar (or glue) is used between the blocks; the joints are left open. This implies dry friction, without cohesion. The failure behaviour of our models, thus, depends on the properties of the blocks and their interaction.

All blocks have been made of 3 mm MDF. Compared to the imposed loads, the compressive strength of each MDF block is virtually infinite. However, the lack of joint material implies that, under tension, the models will fail at the connection between the blocks: although the joints are rough enough to prevent the units from sliding, they cannot withstand any tensile stress and gapping will occur.

With this simulation of masonry failure behaviour, our models closely fit in with the three simplifying assumptions that are generally applied to traditional masonry, as formulated by Heyman [1995]:

- Masonry has no tensile strength;
- Stresses are so low that masonry has effectively an unlimited compressive strength; and
- Sliding failure does not occur.

Boundary conditions and constraints

Since a model, by nature, can only partly represent a real situation, it is necessary to define its limits. Not only does this mean that one must determine where a model ends, it also implies that one has to decide on the properties of the edges. These properties should closely simulate how a real structure would interact with its environment.

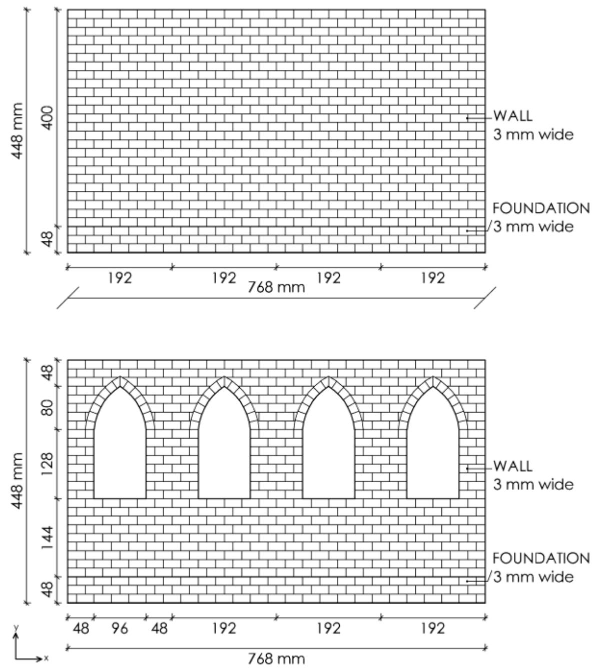


Figure 7.11: Geometries and meshes of the blind wall (top) and the wall with openings (bottom).

We have limited our models of the walls and their foundations to four bays, see Figure 7.11. Subsoil is not modelled in detail. Instead, the lower edges of the foundations are supported by 4 mm thick MDF strips. The joint between foundation and support strip is left open, i.e. no mortar is used, so that tensile stresses cannot be transferred. This is consistent with the real situation, in which the load transfer between building and subsoil only takes place in compression.

In the horizontal direction, friction between model and support may cause slight transfer of horizontal displacements. To prevent excessive movement in the base of the models, pins are used to constrain each end of the bottom row of units horizontally. Along the rest of their height, the left and right side of the model are free to move. Also the upper edge of the wall is left unconstrained. As out-of-plane behaviour is not taken into account in the tests, these boundary conditions are considered to be appropriate.

Applied loads

The models will be loaded with two types of load: a gravity load and a displacement load. The gravity load results from the reduced self-weight that acts on a model when the background panel is inclined. Its exact value is, of course, dependent on the model's geometry and mass density and on the angle of inclination of the background panel.

With these tests, we want to focus on the effects that settlement can have on a building, rather than trying to reproduce such processes within the soil. Five representative settlement troughs will be simulated by moving parts of the support strip. These troughs are illustrated in Figure 7.12.

Two types of troughs are used. Troughs A and C follow curved paths, which are similar to the Gaussian curves used in the numerical tests (see Section 7.2.1). Both are composed of four elements, which together taper off from 0 to 40 mm in height and have a horizontal length of 212 mm.

For trough A, the displacement will be applied by laterally pulling out the curved elements, one by one, from below the model, see Figure 7.13 (top). This leads to a short end-settlement at the left side of the model, with a trough length of 212 mm. The maximum vertical displacement is 40 mm.

Trough C represents a long end-settlement that takes up almost the whole length of the wall, leaving only its utmost end in place. For practical reasons, this trough is simulated by applying a short heave trough at the right hand. We have verified with numerical tests that this approach gives correct results: both troughs lead to identical differential displacements. Hence, trough C is realized by inserting the curved elements at the right side of the model, effectively leading to a trough length of almost 768 mm and a maximum vertical displacement of 40 mm.

Troughs B, D and E are formed by combining wedge-shaped elements. Each displacement load will be applied by slowly spreading the lateral supports of the middle wedge-shaped element, as is illustrated in Figure 7.13 (bottom). They all lead to a maximum vertical displacement of 40 mm, but their trough length varies. For B, the final

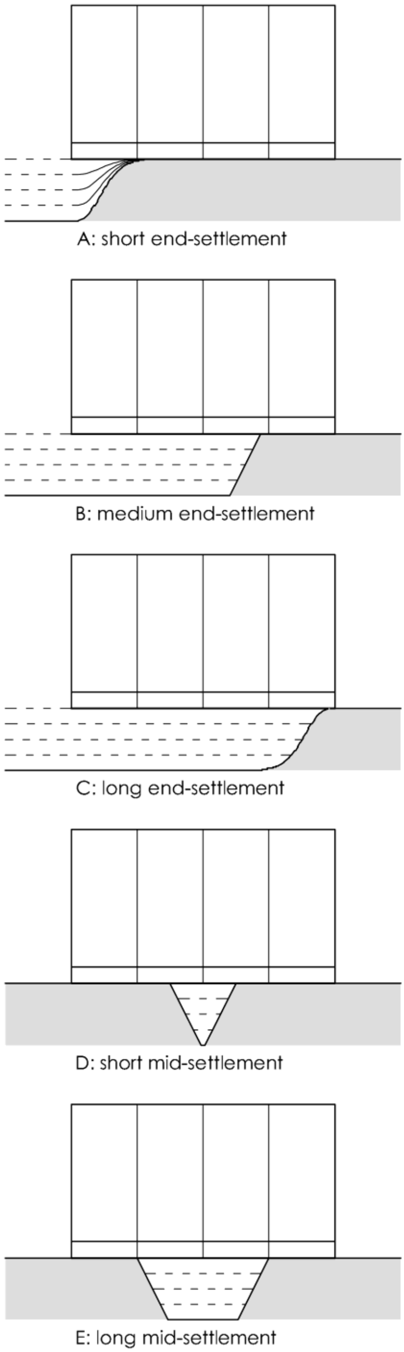


Figure 7.12: Five (exaggerated) displacement fields representing common types of settlement.

trough is 576 mm long, which corresponds to the length of three bays. D results in a trough of 192 mm (one bay), while E is 384 mm long (two bays).

Test procedure

Figure 7.14 gives an overview of the test set-up. At the start of each test, the block model is built on a flat, smooth and contrasting background panel. The panel has a protruding brim on one of its edges and two trapeziums mounted to its underside. With the model completed, the whole panel can be raised and slanted to an inclination of approximately 45 °.

All displacements are imposed incrementally. Two alternative approaches are followed. Initially, the displacements are increased continuously, by hand, while at the same time a series of photographs is taken. However, in some cases horizontal friction

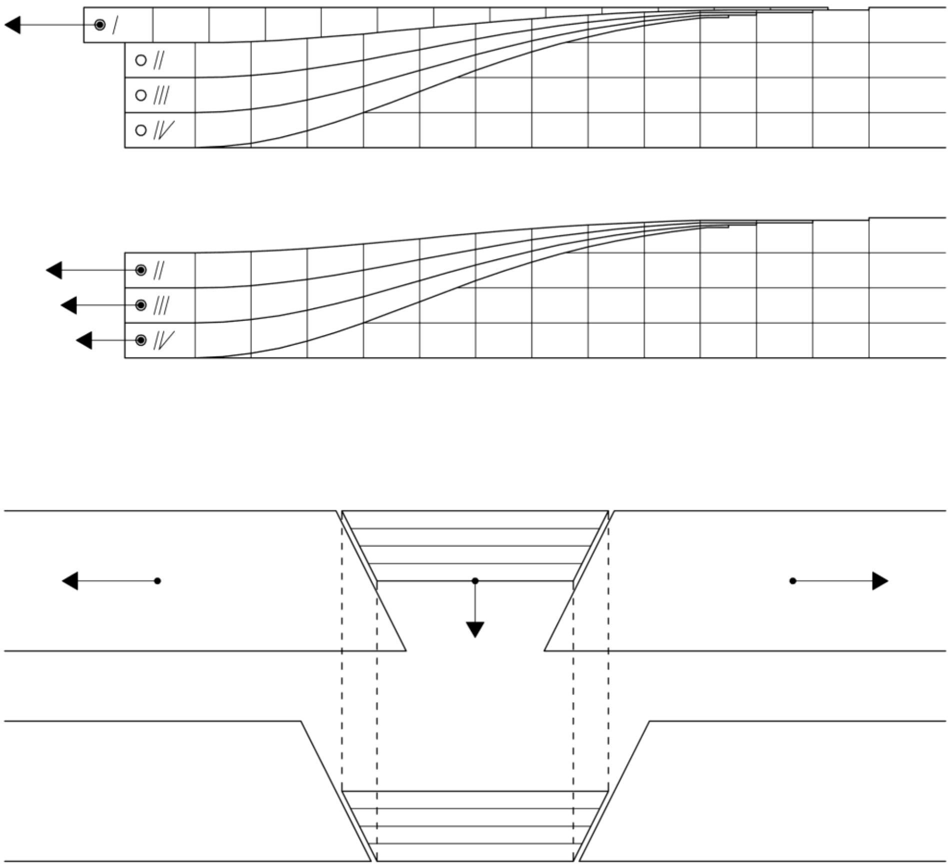


Figure 7.13: Method of imposing troughs A and C (top); method of imposing troughs B, D and E (bottom).

between model and support may lead to excessive deformations and premature (sometimes even out-of-plane) failure. For those cases, the displacement will be increased stepwise by placing the model in horizontal position while moving its supports. After each step, the model will be raised and the new equilibrium situation will be photographed.

For each load-model combination, the photographs of the final crack pattern and deformations are presented in Section 7.3.2.

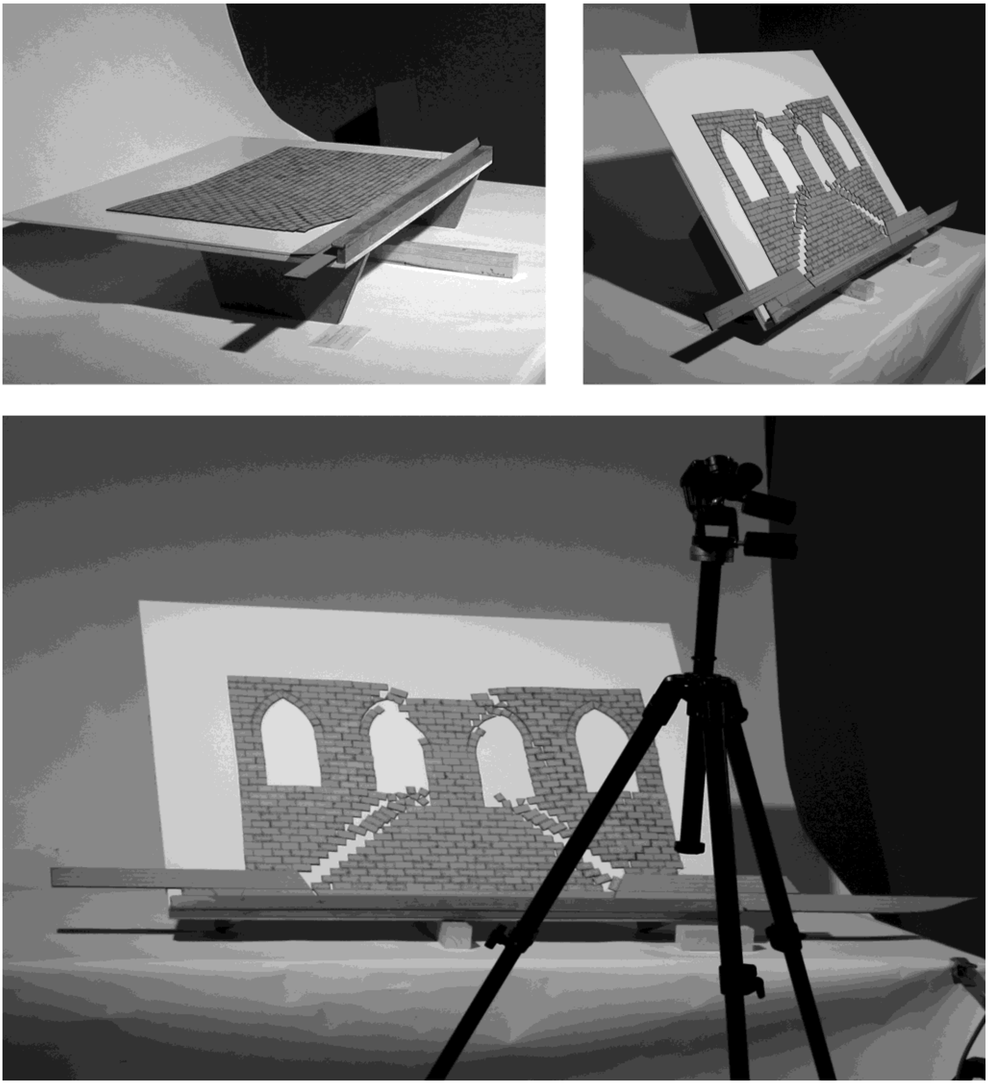


Figure 7.14: Test set-up.

7.3.2 Results of the physical tests

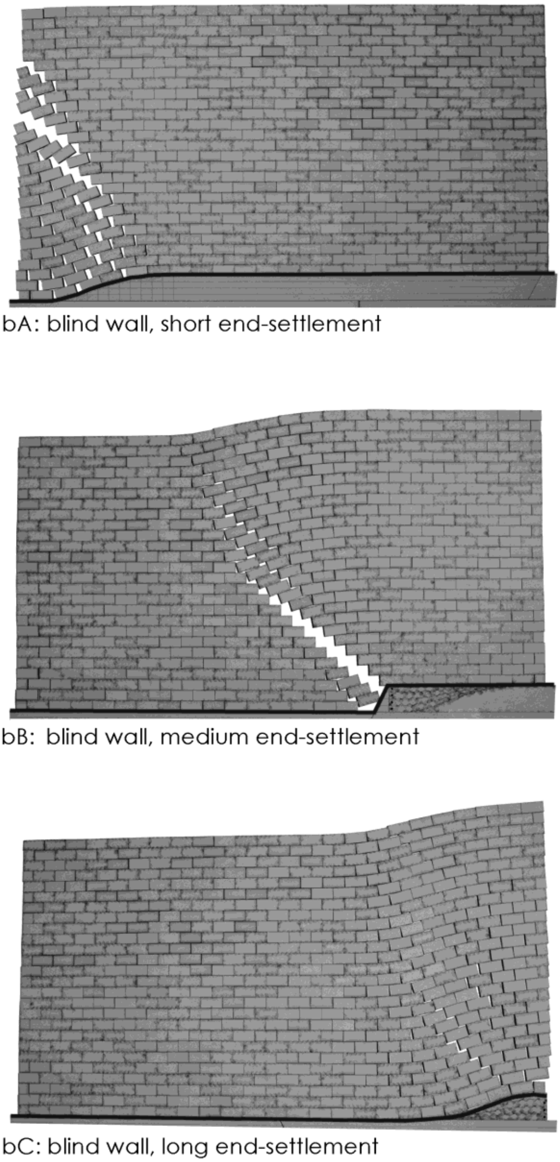
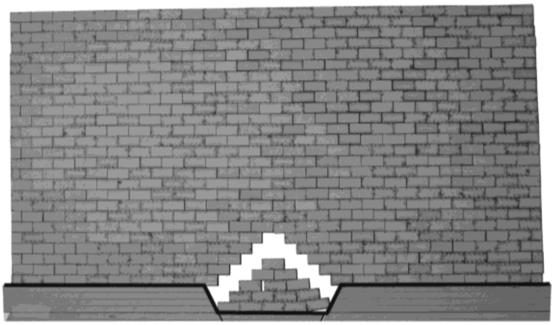
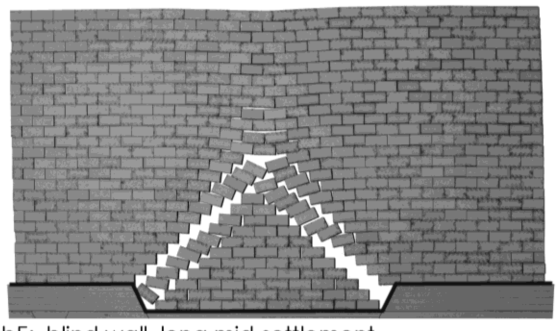


Figure 7.15: Deformations and cracks resulting from different end-settlement troughs, in blind walls, tested with a small-scale physical model. The bold lines at the bottom of each wall indicate the fully imposed vertical displacement.

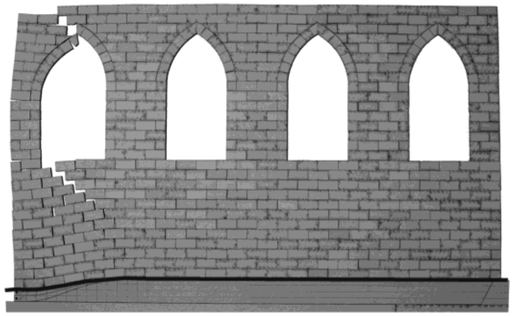


bD: blind wall, short mid-settlement

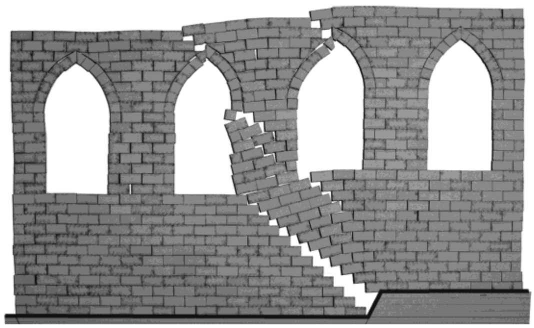


bE: blind wall, long mid-settlement

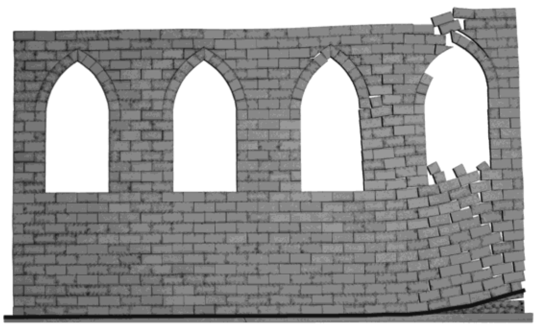
Figure 7.16: Deformations and cracks resulting from different mid-settlement troughs, in blind walls, tested with a small-scale physical model. The bold lines at the bottom of each wall indicate the fully imposed vertical displacement.



oA: open wall, short end-settlement



oB: open wall, medium end-settlement



oC: open wall, long end-settlement

Figure 7.17: Deformations and cracks resulting from different end-settlement troughs, in walls with openings, tested with a small-scale physical model. The bold lines at the bottom of each wall indicate the fully imposed vertical displacement. Please note that for oA and oC results are shown for 50 % of the intended displacement.

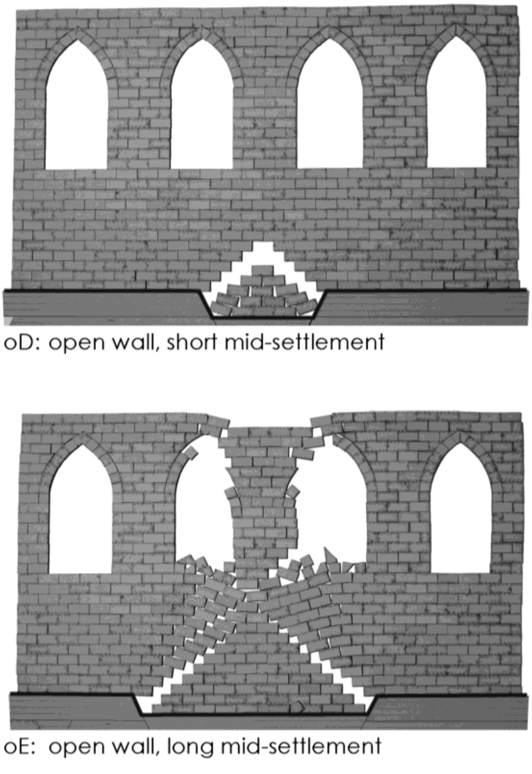


Figure 7.18: Deformations and cracks resulting from different mid-settlement troughs, in walls with openings, tested with a small-scale physical model. The bold lines at the bottom of each wall indicate the fully imposed vertical displacement.

7.3.3 Discussion of the physical results and comparison with numerical tests

The previous section has presented ten damage presentations, which result from imposing five displacement loads on two physical models. The photographs shown in Figures 7.15-7.18 give an overview of the cracks, deformations and displacements that have occurred within the walls. Clearly visible are the gaps that have opened between some of the blocks, which demonstrate that our models comply with the simplifying assumption that masonry has no tensile strength.

The bold lines at the bottom of each model indicate the imposed settlement profile. The maximum vertical displacement that was imposed measured 40 mm. However, for models oA and oC (in Figure 7.17) intermediary results are shown, as further increasing the settlement in these open walls led to partial collapse of the models.

The physical tests presented here constitute a supplement to the numerical tests that have been described in Section 7.2. The two types of test are quite dissimilar. Not only are their methods fundamentally different, they have also partly been based on contrasting suppositions. For the sake of clarity, we have summarized the most important assumptions in Table 7.1.

As Table 7.1 shows, some of the assumptions that we applied in the numerical tests have been adapted to fit the physical tests. These adaptations concern the number of bays, the material model for masonry, the horizontal (tangential) interface behaviour and the smoothness of inclination of the imposed settlement troughs. It is clear that, because of these differences, the results of the two types of tests can only be compared in a relative, qualitative way. For our study, this is not a problem: we are not interested in absolute values, but in basic damage characteristics, which we can derive from the final damage presentations.

Taking the results from the physical tests together with those from the numerical tests, one can examine the behaviour of four different models under five types of settlement troughs. By comparing the twenty damage presentations resulting from both tests, it is now possible to study the influence that two factors have on the occurrence of damage due to settlement processes: the presence or absence of openings in a wall and the material properties of the masonry of a wall. But before discussing these influences, it is first important to check whether the conclusions drawn from the numerical test results are confirmed by the physical test results.

Effects of trough position reconsidered

A study of the effects that trough position has on the eventual damage in the numerical models led to the conclusion that a symmetrical damage is a reliable indicator for mid-settlement troughs, while an asymmetrical presentation points to end-settlement (see Section 7.2.3.). When looking at the results from the physical tests, it is obvious that they affirm this conclusion. Under mid-settlement (bD and bE in Figure 7.16, oD and oE in Figure 7.18), the damage is virtually symmetrical, with only small deviations where the trough did not leave an equal part of a unit supported at each of its sides (bE) or where the symmetry line of the trough did not correspond with the symmetry line of the wall model (oE). Similarly, end-settlement led to asymmetrical damage, as was the case in the numerical tests. Hence, the physical test results accord with those of the numerical tests with regard to the effects of trough position.

Effects of trough length reconsidered

In Section 7.2.3, a comparison based on trough length has shown the relation between this length and the bending mechanism that governed the response of a wall. It has led us to the conclusion that the tapering of a crack is its most important characteristic for identifying the underlying settlement trough, as this tapering indicates the relative rotation. The physical test results partly agree with this statement. For short end-settlement, the physical models bA and oA (in Figures 7.15 and 7.17) display the same

Table 7.1: Comparison of essential assumptions for numerical versus physical tests

Description	Numerical tests	Physical tests
Geometry and mesh		
	Two-dimensional	Two-dimensional
	Eight bays	Four bays
- Model size	38.4 x 11.2 m at scale 1:1	19.8 x 11.2 m at scale 1:25
- Standard element size	400 x 400 mm at scale 1:1	400 x 800 mm at scale 1:25
Material model for masonry		
- Masonry representation	Continuum model	Discrete elements
	Homogeneous	Heterogeneous
	Isotropic	Orthotropic
	Smeared cracking	Discrete cracking
- Masonry properties	Low tensile strength	Zero tensile strength at joints
Boundary conditions, constraints		
- Interface	No-tension interface	No-tension interface
	Zero transfer of horizontal displacements	Low transfer of horizontal displacements
Applied loads		
	Self weight	Reduced self weight
	Line load	No line load
	Five settlement troughs	Five settlement troughs
	Five gradually inclined curves	Two gradually inclined curves
		Three abrupt, steeply inclined curves
Analysis / Test procedure		
	Incrementally imposed displacements	Incrementally imposed displacements
	Numerical calculation	Physical test
Post-processing / Results		
	Deformations	Deformations
	Cracks	Cracks
	Displacements	Displacements
	Stresses	
	Support reactions	

behaviour as the numerical ones: the walls undergo a negative bending moment and show cracks that start at and are widest at the top edge or at the upper part of the side edge.

Under medium and long end-settlement, the cracks start at and are widest at the bottom, which would indicate a positive bending moment. A transitional mechanism, as oB in Figure 7.9 showed, did not occur in the physical models, although that was anticipated. For a part, this could be attributed to the differences in ratio between trough length and wall height, which were not identical in both tests. Nevertheless, the true reason why under medium end-settlement (bB in Figure 7.15 and oB in Figure 7.17) the cracks are widest at the bottom most probably lies in the steepness of settlement trough B, which is a consequence of the test procedure. Unlike the short and long end-settlements, the medium end-settlement has been formed using wedge-shaped elements, as was illustrated in Figure 7.13. These wedges made the onset of the trough rather acute. In combination with the lack of cohesion between the separate wall units, this meant that the bottom edge of the wall did not deform due to bending, but failed under shear. While a smooth curve would allow for smearing out of the vertical displacement over a large wall area, the abrupt onset initiated a crack that opened almost purely vertically. This discontinuity remained localized in a small strip, thereby overemphasizing the effects of shearing, and outshining deformations due to a negative bending moment at the top. From this we can conclude that the tapering of a crack should always be seen in relation to its boundary conditions, and that it is necessary to make a clear distinction between bending and shear cracks.

For mid-settlement, the steepness of the trough onset also affected the appearance of the cracks and their tapering. More noteworthy is, however, that in the physical model the typical arching behaviour does occur. For the numerical models it was mentioned (in Section 7.2.3) that arching did not occur because of a lack of horizontal friction provided by the interface. In the physical models, the interaction between wall and 'soil' could take place, because the surfaces of both were rougher. As a result, the masonry of the wall was able to transfer its loads towards the sides and bridge the trough. This difference in behaviour can, thus, be entirely explained by the difference in horizontal interface properties.

Influence of openings

Both in the physical and in the numerical experiments, a blind wall (b) and a wall with openings (o) have been modelled and tested under settlement. When comparing the results, the general expectation is confirmed that openings make a wall more vulnerable to settlement damage. Not only are the resulting deformations and cracks larger for the walls with openings, cracks also occurred earlier and grew quicker to fully open cracks. This becomes evident when one compares, for example, the results for short end-settlement. In the numerical tests, the wall with openings (oA in Figure 7.9) shows a large, fully open crack, along with considerable deformations, while in the blind wall (bA in Figure 7.7) at this stage not even one partial crack has appeared.

In the physical tests, the difference in behaviour between the walls with and without openings may, at first, seem less pronounced. However, one should keep in mind that the damage displayed for the wall with openings (oA in Figure 7.17) has occurred at a vertical displacement that was only half the displacement imposed on the blind wall (bA in Figure 7.15). When we continued the test on the wall with openings, stability was lost and part of the model collapsed. Since, in collapsed state, cracks and deformations could no longer be traced, photographs of the situation just before failure have been selected. Actually, when taking a closer look at the results for physical model oA, the eventual failure mechanism is already apparent: the voussoirs at the top of the window are on the verge of collapsing, while the pier at the left side also shows some hinging.

The presence of openings in a wall is not necessarily a disadvantage. Openings reduce the effective height and, thus, the stiffness of a wall substantially, allowing it to adjust to a settlement trough more easily and to regain support. While walls with openings may show cracks and deformations, it is quite possible that they have already reached a stable situation; whereas, for walls without openings, the fact that they are undamaged is no guarantee that damage may not appear suddenly and, then, immediately lead to a dangerous situation.

Not only are walls with openings more susceptible to settlement damage than blind walls, they also fail in a different way. Under identical loads, the walls with and without openings initially showed a comparable overall behaviour. But where, in the blind walls, damage tended to remain localized in one crack, in the walls with openings cracks snapped towards the windows and then spread. As a consequence, the damage presentation in a wall with openings may differ substantially from that in a blind wall.

This difference in damage presentation is especially clear in a comparison of the results for long mid-settlement (bE and oE). In the physical tests, the blind wall (bE in Figure 7.16) is able to bridge the settlement by arching. The masonry below the arch follows the vertical displacement of its support, while the masonry above the arch transfers its loads towards the sides. In the wall with openings (oE in Figure 7.18), a similar arch is formed initially. However, the weight of the pier above it, which acts as a point load on the top of the arch, cannot be carried off sideways. As a result, the arch fails and the pier drops.

In the numerical tests, the damages of the blind and the open walls under long mid-settlement are even more dissimilar. The wall with openings (oE in Figure 7.10) fails under double bending, with one sagging crack in the middle and two hogging cracks at the sides. The blind wall (bE in Figure 7.8) reacts much stiffer and only shows one sagging crack at the centre of the wall. Arching does not occur. This difference should, however, be attributed to the properties of the interface; an issue that has been expounded in Section 7.2.3. In this respect, the physical model does give a better impression of the difference in response between masonry walls with and without openings.

It is important to note that the effects of openings depend on their size, position and distribution. Especially the reduction in effective height to which openings lead should be seen in relation to the length of the imposed settlement trough. As long as a wall has enough height below its windows, compared to the trough length, the wall may not even 'notice' the impairment. This becomes apparent in the physical models bD and oD (Figures 7.16 and 7.18). There, the presence of openings does not make any difference: the base of the wall is stiff enough to bridge the trough.

We can conclude that openings do have a substantial influence on the appearance of settlement damage. This should be taken into account when interpreting damage. However, since it is not always obvious how openings change a damage pattern, studies aiming to provide more insight into this topic would be beneficial for surveyors.

Influence of material properties

The most essential difference between the numerical and physical tests is the way the masonry has been modelled. In the numerical model, the masonry has been regarded as a homogeneous, isotropic material: no distinction has been made between unit and joint. This option was chosen to limit the number of presumptions. It allowed us to describe the behaviour of masonry as a composite material (in terms of Young's modulus, tensile strength, fracture energy, etc) instead of having to estimate the properties of its separate components and their interaction.

Alternatively, in the physical tests, we did model each individual unit. This had the practical implication that we had to build the model on scale and to limit it to four bays. The masonry behaviour was not established by the input of values for Young's modulus and strength, but has been captured in the physical discontinuity of the model: the use of separate blocks without bonding automatically replicated the standard simplifications of zero tensile strength, infinite compressive strength and no sliding, as discussed in Section 7.3.1.

A comparison between the damages resulting from both types of tests shows that these differences in material properties lead to differences in damage characteristics. In the numerical models, cracks tend to proceed in a straight, mostly vertical line, while in the physical tests the cracks are mainly stepped and diagonal. Case oB is a clear example of this. In both the physical and the numerical model, a crack started above one of the windows, snapped to the top of the window arch, and then proceeded from one of the lower window corners towards the ground. In the numerical model for oB, presented in Figure 7.9, the cracks are almost vertical and seem to take the shortest path. In the physical model, the cracks start at similar positions, but their progress is determined by the position of joints, which forces them to follow a diagonal path.

We can conclude that the material properties of a wall have a substantial influence on the characteristics of settlement damage that occurs in this wall. Cracks simply occur wherever the tensile stress exceeds the tensile strength – and when units and joints have a comparable tensile strength, as is the case in our numerical model, the cracks appear irrespective of the mesh. However, when the bond between units is much weaker under tension than the units themselves are, as in the physical model, cracking will localize in the joints, leading to diagonal or stepped cracks.

In the latter case, failure is probably more a matter of stability than of strength. This can be seen in physical model oC (Figure 7.17), where part of the right window arch has collapsed. At the same time, a low tensile strength in the joints may also allow a wall to deform more easily. For example, the blind wall under a long end-settlement (bC in Figures 7.7 and 7.15) could spread the imposed displacement over a larger area in the physical model (Figure 7.15) than in the numerical model (Figure 7.7), so that in the physical model the damage is less pronounced.

In reality, the properties of masonry are between these two extremes. The physical model may resemble the behaviour of a masonry wall that was built with lime mortar: it does show signs of settlement, but its flexibility allows it to deform and adapt to a new support profile. The numerical model reproduces cement-based masonry, which, as a composite, is stronger but also much more brittle and more isotropic: cracks tend to follow the joints. The actual failure behaviour of a Dutch church wall will lie somewhere in the middle, depending on, especially, the type of mortar used. Since the use of lime versus cement is related to building periods (see Table 6.1), the time of construction of a building can be used as a fairly reliable indicator for the type of failure behaviour.

7.4 Conclusions

In this chapter, we have conducted numerical and small-scale physical tests to investigate how trough position, trough length, the presence of openings in a wall, and material properties of masonry can influence the presentation of damage. Determining the extent of influence of these factors is important, because it affects the information a damage can give us about its occurrence. The stronger the influence of the cause on the eventual presentation is, the easier it generally is to read this cause from the damage. However, if the context plays a more influential role in the appearance of damage, this role needs to be recognized within the diagnostic process in order to obtain a sound diagnosis.

A comparison of the test results has led us to the following conclusions for damages caused by settlement of the soil:

- A symmetrical damage presentation is a reliable indicator for mid-settlement, with the centre of the damage usually corresponding with the centre of the trough;
- An asymmetrical damage presentation points to end-settlement, but the location of the damage does not necessarily coincide with the exact location of the trough;
- It is the tapering of a crack that is the most important characteristic for its interpretation, not its precise location or direction;
- Considering the tapering of a crack allows one to distinguish between cracks caused by bending, and cracks caused by shearing;
- For cracks caused by bending, the tapering indicates the relative rotation that has occurred between two wall parts, but does not tell whether one part has moved downwards, or the other upwards;
- The tapering of a crack is influenced by the acuteness of the settlement trough;

- Openings make a wall more vulnerable to settlement damage: damage occurs earlier and grows quicker;
- Openings make a wall more 'flexible', allowing it to adjust more easily to a settlement trough;
- Openings usually form the weak spots in a structure. As such, they have a substantial effect on the eventual damage. Size, position, and distribution of openings should be taken into account in the interpretation of (complex) damage presentations;
- Whether a crack occurs, or a deformation, depends on masonry properties, and not on the cause of damage;
- Whether a crack occurs straight or stepped depends on masonry properties, and not on the cause of damage.

Above conclusions may put the information obtained from literature and presented in Part II of this thesis in a different light. The options presented there, and their relations, will be re-evaluated and reinterpreted. This will be discussed in the next chapter.

Chapter 8
Constructing the diagnostic tool

The previous chapter has provided us with a sense of how part of the data that have been collected in Part II of this thesis correlate. Now it is time to specify all relations conclusively and translate them into an operative diagnostic system. That is what this chapter is about.

Three aspects come up for discussion. In Section 8.1, we will explain how we have laid down the relations between all component options in an explicit way. Subsequently, Section 8.2 will pursue our approach towards creating a decision support tool based on these relations. Finally, Section 8.3 will consider the pros and cons of a paper version of a diagnostic tool against those of a computerized system.

This chapter ends with conclusions on our expectations for the tool. Whether it lives up to these expectations will be tested in Chapter 9. There, our diagnostic tool is put into practice.

8.1 Determining the relations between the components

In this section, we will describe the procedure by which we have determined how all components as defined in Part II of this thesis are related. This procedure consists of three steps. First, damage patterns are composed using the most recognizable and informative symptoms and context conditions. Next, these patterns are linked to causes that can underlie them. Finally, essential context conditions are associated with these causes, and we will investigate which context conditions may be of help in distinguishing between different causes. These three steps are elaborated in the subsections below.

8.1.1 Relating symptoms to context conditions: damage patterns

Our diagnostic tool should support surveyors in interpreting structural damage in masonry. To be able to do this, our tool needs to present a clear categorization of typical, frequently occurring damage presentations. Our first task in constructing the tool is to determine which features characterize certain damages. For this, we will use the component options as defined in Chapter 5 and 6.

Structural damages can hardly be characterized with one single feature. More often than not, they display a combination of symptoms. In Chapter 5, the separate basic symptoms have been discussed.

In addition, Chapter 6 has shown that, to truly be able to characterize a damage, one often needs to refer to its context, too. For a concise and compact description of damage, especially geometrical indications have proven indispensable. In this way, by relating symptoms to context conditions, we will define damage patterns: the presentations of damages in their context.

Our set of damage patterns has been based upon over 500 cases that we collected from the literature sample (see Section 3.3). To begin with, these cases are assigned to broad groups. This categorization is based purely on the appearance of the damages, leaving underlying causes aside.

Next, all cases are labelled. For this, we primarily use the symptoms as defined in Chapter 5. Context conditions are added where they help in describing the visual aspects of the damage. In essence, this concerns options that indicate the location of a damage in relation to the masonry or to the building components. These have been phrased in Chapter 6 as "damage appears at / in / along / next to / with maximum …". While we attribute these labels, the categorization of cases is further refined.

Subsequently, we make sketches of the general appearance of each category. The labels of the corresponding cases are used as a reference in this stage, to make sure that the crux of the matter is captured. At the same time, they allow us to evaluate if a case is actually covered by the category to which it is attributed.

Finally, we rank the categories on visibility and informativeness of the labels. In doing so, the conclusions of Chapter 7 are used to weigh how explanatory each label would be in relation to the underlying failure mechanism. In this way, this phase cumulates in a first proposal for a tree diagram structuring our damage patterns.

8.1.2 Relating damage patterns to causes

To support the formulation of hypotheses, our tool should, of course, indicate those causes that possibly underlie the damage patterns. Users should be able to learn as much as possible about the occurrence of a damage just by analysing its appearance with the assistance of the tool. Therefore, the next phase consists of establishing the connections between damage patterns on one hand, and typical causes of structural damage on the other.

The first step in this is to collect, for all cases, the descriptions of their causes from the original literature sources. These cause descriptions are synchronized by rewriting them using the phrases proposed in Chapter 4. This clears the way for step two: comparing some of the cases.

To further improve the tree diagram of damage patterns, some cases are compared. First and foremost, cases of which the appearances have been described with exactly the same set of labels, but which turn out to be caused by different processes are reconsidered: Do their appearances provide further clues which would allow one to distinguish between these causes? If so, the pattern to which both examples belong is split into two variants, each bearing a more precise label; if not, both causes are included in the list of hypotheses for the original pattern.

Conversely, a second comparison focuses on those cases that share all except one label, and that are attributed to the same cause. For these cases, we check what the deviant labels tell about the underlying failure mechanism. Could these two cases be identical in occurrence? If so, the two are merged into one general pattern, thereby removing the deviant labels; if not, they are kept apart.

The third step is, then, to translate the concrete causes originating from the practice examples into abstract load combinations. Per damage pattern, we schematize the underlying failure mechanism by indicating in which directions (resultant) loads must have acted. In this, we follow a retrospective approach: starting from the result, the damage, we thoroughly examine in what way and under what circumstances it must have occurred. To do this, basic principles of mechanics are used, such as the relations between forces and deformations, as illustrated in Figure 5.2, and between forces and cracks, as shown in Figure 5.4.

Each abstract load combination is marked in the sketch representing the matching damage pattern. These representations are important, for they will allow users of our tool to better understand and evaluate the hypotheses proposed. Furthermore, they will also help them to invent other, not explicitly mentioned causes in addition to the ones on the list.

The load sketches emphasize one important aspect regarding the interpretation of damages due to settlement. They confirm that for settlement processes, there is no direct connection between the exact cause and the eventual failure mechanism: it is not so much the source of this process that determines the damage appearance, but its effects in terms of position and size of the settlement trough with respect to the building. We have, in fact, already applied this insight in Chapter 7, by testing different settlement troughs instead of simulating specific causes. We will elaborate on this point in Section 8.2.4, as it has consequences for the outline of our tool.

8.1.3 Relating causes to context conditions

The last phase is to link causes to context conditions. Aim of this phase is to find distinguishing conditions that allow one to discriminate between different causes of structural damage. These are the essential and sufficient conditions that can be used to confirm or refute the possibility of a certain hypothesis when appraising a damage in practice.

Many of the context conditions that can be used to distinguish among causes refer to circumstances that are indispensable for the inception and continuation of a damage process. These are pure cause-condition links. However, there are also conditions that describe the effect of a specific cause. On one hand, these may stipulate the exact location of damage; on the other hand, they can fix the relation between the time of manifestation of a damage and the occurrence of a particular event.

The links between context conditions and causes of structural damage are inferred from three sources. Some are deduced from the original description of our collection of damage cases. Others are based on the detailed discussions of typical damage processes as published in our literature sample. The remainder is prompted by common sense, and is merely made explicit here.

8.2 Setting up a diagnostic tool

In the previous section, we have described how we have established all relations between causes, symptoms and context conditions. With this, the content part of our tool has been completed. The next step is to make these data accessible by translating them into an operative tool.

One factor that is critical for the success of a diagnostic decision support system is that it should be tailored to the users' workflow (see Section 3.1.3). This certainly applies to the manner in which information contained in the system is unlocked. We want to structure our data in a convenient way, so that each user can find what is relevant for him.

Our aim is to create a decision support system that, by offering relevant information at the proper moment, stimulates and helps surveyors in consciously working through the initial stages of the diagnostic process. Starting point of a diagnostic process is always the damage. Hence, we propose to take the appearance of damage as point of departure for our tool. In Section 8.2.1, we will substantiate this proposal.

Subsequently, Sections 8.2.2 – 8.2.4 will address our approach to designing the tool. Three topics will be considered. First, we will explain how we have created a decision tree to allow users to identify the damage pattern that corresponds best with the damage they have under investigation. Next, we will discuss how we have outlined the information that is to be presented per pattern. Finally, Section 8.2.4 will explain why the conditions related to settlement processes have been dealt with in a slightly different way.

8.2.1 Using the appearance of damage as organizing principle

The single most important choice in the design of our tool is on how to create access to all data. In Section 2.1.2, we have already studied the various approaches that diagnostic handbooks use to structure their information on damage in buildings. Their main organizing principle turned out to be the cause of damage. Location of the damage, either in terms of material or of geometry, was also commonly used. Only a few handbooks based their categorization based on the appearance of damage.

To determine which organizing principle would best suit our diagnostic tool, we have again passed these options in review. We can conclude that starting from the cause would not be a logical choice for an easy-reference work that should help in determining the most likely hypothesis. It would ask for premature assumptions on the diagnosis, and pave the way to confirmation bias, which is exactly what we want to avoid.

Departing from the location would seem to be more practical. However, we have already argued in Chapter 2 that an overview arranged by location may still hamper the user in interrelating similar manifestations of damage. Indeed, as was shown in Chapter 7, material and geometry do influence extent and occurrence of damage, but these conditions are not at the base of the relation between cause and damage. In other words, material and geometrical conditions are not the most distinguishing characteristics for diagnosing. On that account, this option has been rejected, too.

Taking the above into consideration, we have decided to follow the less-used organizing principle based on the appearance of damage. Supported by our analysis of symptoms in Chapter 5, we take the view that the damage in itself is the most reliable source to provide clues about underlying processes. Moreover, this type of categorization most closely fits in with the workflow in a diagnostic process: both start from the observation of damage. Hence, we think that using the appearance of damage as organizing principle offers the best opportunities for diagnostic support.

8.2.2 Creating a decision tree to discern between damage patterns

In the previous subsection, we have come to the conclusion that we want to use the appearance of damage as key, as primary means of access to our tool. To accomplish this, damages need to be assigned to categories. We have already made a start with this in Section 8.1, where frequently occurring damage appearances have been captured in damage patterns. We intend to make all data accessible via these patterns. Hence, when starting our tool, the first thing a user would have to do is to determine which damage pattern corresponds best with the practice situation he has under investigation.

Our tool should, of course, ease this process and assist the user with discerning between these damage patterns. We propose to provide this assistance in the form of a decision tree: a set of consecutive questions or statements, and fixed, mutually exclusive answers or options to choose from. Every possible combination of answers in this decision tree stands, in principle, for a discrete damage type.

Since every outcome of the decision tree points to a separate damage pattern, one can say that the definition of each damage type is implied in the sequence of answers. In order to lead to useful categories, these definitions should always be based on those characteristics that are most relevant (i.e. most explanatory) for the eventual diagnosis. The most distinguishing characteristic should come up first.

The decision tree has been based on the tree diagram of damage patterns as developed in Section 8.1. By adding brief statements to groups of options, this tree diagram has been finalized. After two last checks on the logic of the sequence of statements and on the visibility (and surveyability) of the options, the damage patterns have been established definitively. The outline of the decision tree is sketched in Figure 8.1.

In total, 60 damage patterns have been defined. About one-third of these patterns truly are distinctive presentations of specific defects: each one of them is linked to exactly one possible cause. Another third has two or three hypotheses attached. For the remainder, the list of hypotheses is longer.

Indexing damage patterns via a decision tree is beneficial for both user and developer. For users, the advantage is that similarly looking patterns are juxtaposed. Both resemblances and differences between such patterns are explicated, which allows the user to confidently decide which option would best match his case.

For us as developers, the benefit lies in the (almost complete) ruling out of overlaps and inconsistencies. Structuring all damage patterns in a decision tree guarantees that

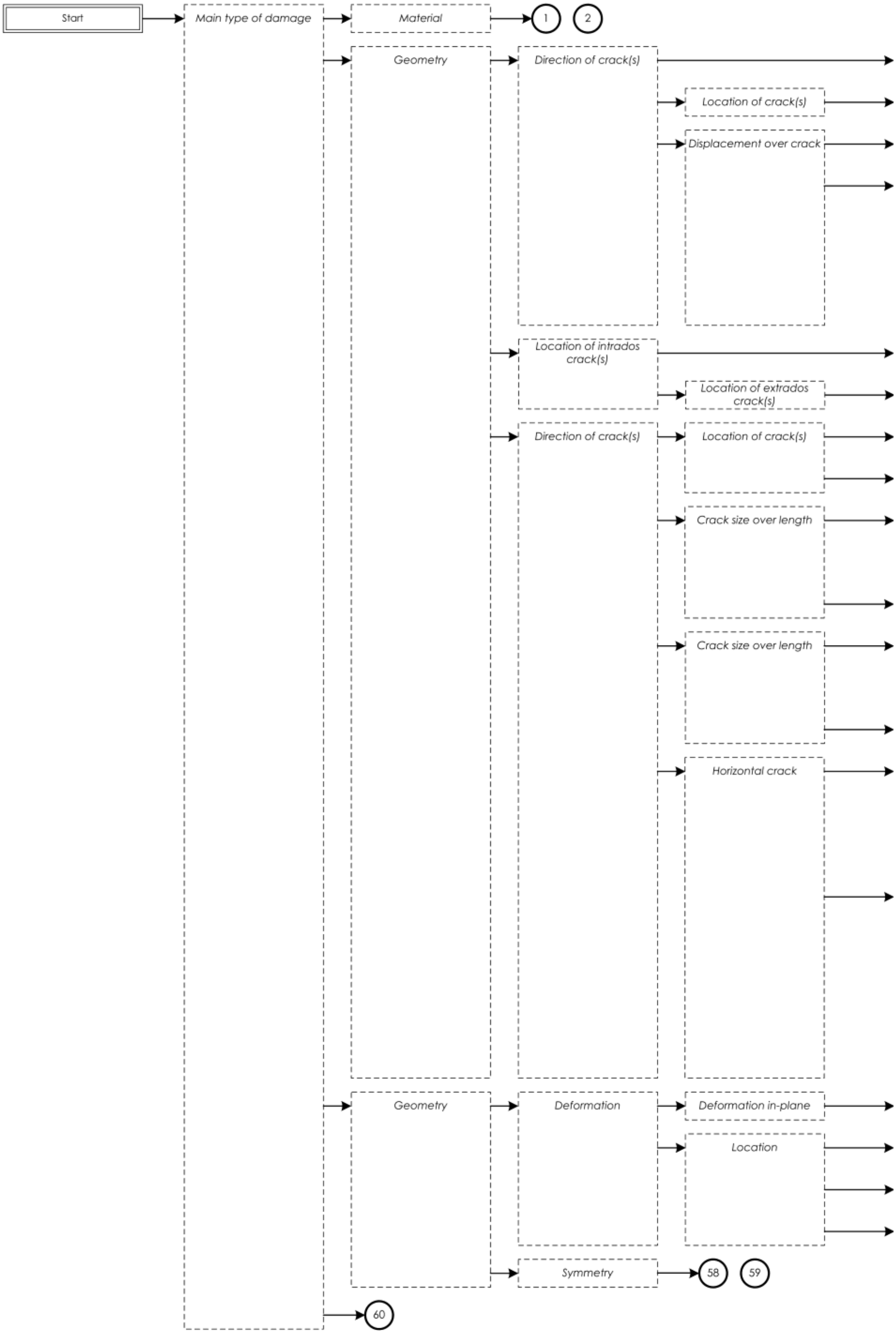


Figure 8.1: Outline of the decision tree.

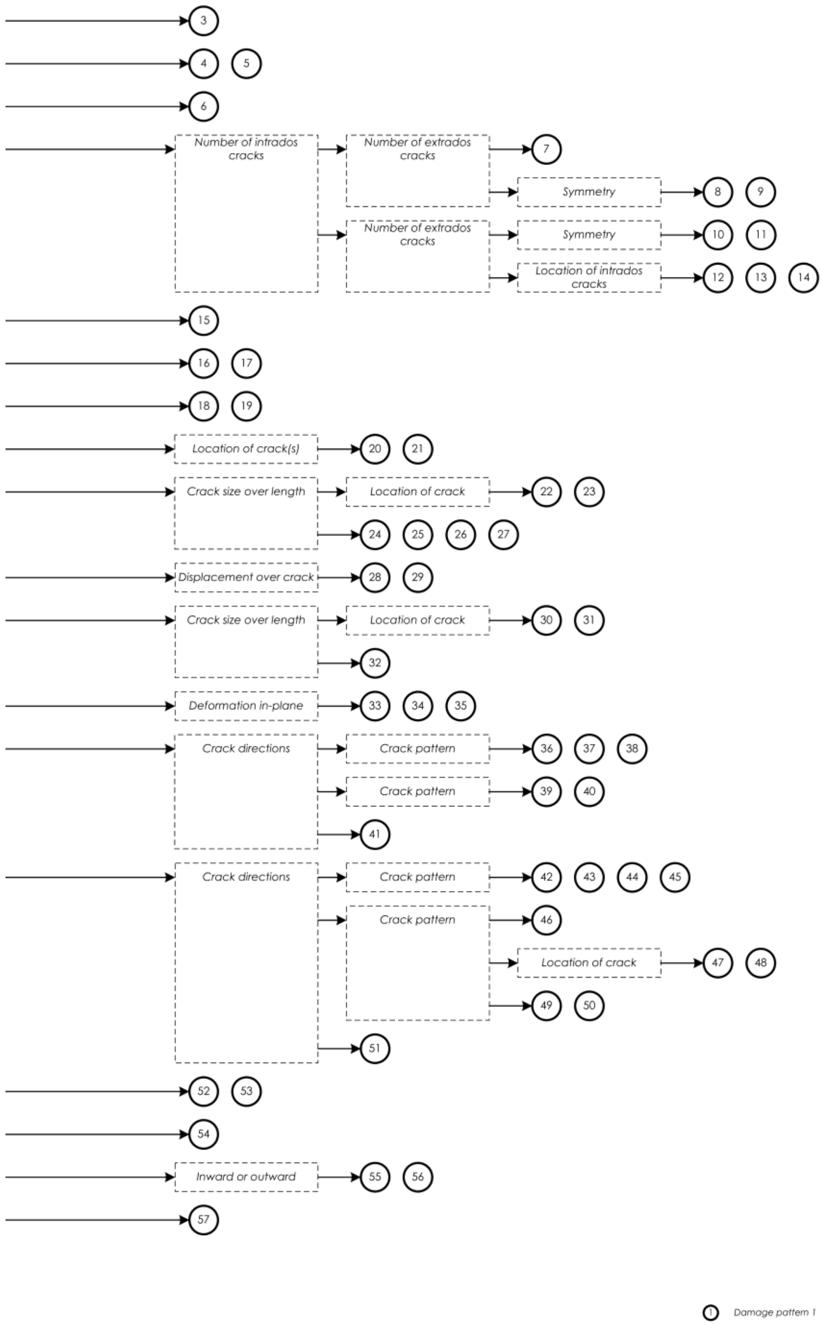


Figure 8.1 (continued).

each of these patterns has a unique, unambiguous set of characteristics. As long as all options in the tree are defined clearly and distinctly, the patterns cannot but be mutually exclusive. This unambiguity is an important improvement compared to the existing handbooks.

8.2.3 Setting up a well-organized layout for the information per pattern

Through the help of the decision tree, each user of our tool is guided to the damage pattern that corresponds best with the case he is investigating. This approach allows us to provide every user with information that is specifically geared to the damage pattern he has selected. This information has been established in Section 8.1.2 and 8.1.3, where the damage patterns have been related to causes, and the causes to conditions.

With our tool, we intend to stimulate attentiveness and carefulness in the attitude of surveyors during the initial steps of the diagnostic process. We characterize these steps as follows. Firstly, the damage is to be identified, including the (general) failure mechanism that underlies it. Secondly, the potential causes need to be recognized, resulting in a list of hypotheses. And thirdly, the probability of these hypotheses should be investigated; a process for which we propose to use the essential conditions.

To let our tool support users in following these three steps with care and concern, the information provided per pattern will be presented accordingly, in a tripartite layout. The subsections below each deal with one of these three parts.

Part A: the damage pattern

After having determined the damage pattern via the decision tree, the user is first of all encouraged to reflect on this outcome. Does the damage pattern indeed match the practice situation? Each damage pattern description starts with three types of information against which the user can test his choice:

- A list of characteristics (both symptoms and context conditions) that define the damage pattern;
- An illustration of the pattern, depicting these characteristics; and
- Some examples of how this pattern can show in practice: photographs or drawings quoted from our literature sample.

If this information confirms the user in his choice, he can proceed with the next part; if not, the match may be incorrect, and the user is advised to try and find a better one by returning to the decision tree.

Part B: hypotheses

In Part B of the description of each damage pattern, the user will find a list of possible causes that are associated with the pattern in question. These causes have been organized according to the categorization put forward in Chapter 4. Please note that the order in which they are listed does not pronounce upon the probability of these hypotheses. In this way, the user is stimulated to study all options with equal care.

The lists of hypotheses are finite and should rather be seen as indications of the range of causes to which one should pay attention. In the illustrations of the damage patterns, under A, we have added arrows to point out the forces that underlie the failure mechanisms. This should help users to appreciate the occurrence of damage and to conceive variants not explicitly mentioned in our tool.

Part C: essential conditions

The third part of each damage pattern description is dedicated to the conditions that are essential for the occurrence of damage processes. Five types of conditions are used. Beside symptoms, these are the context conditions related to material, geometry, environment and time.

The conditions are presented in tables, in which each column represents a hypothesis and every row gives a condition. One by one, the user should verify if a condition is, or could have been, present in the case he has under investigation. If for all conditions belonging to a certain hypothesis the answer is yes, this hypothesis may be the cause.

One should, in this respect, note that evidence of the presence of these conditions does not mean that the corresponding damage process must have taken place. Their presence is merely a precondition, albeit an essential one. Hence, these conditions can only be used to refute hypotheses. In other words, excluding a condition – and a single one suffices – means excluding a hypothesis; but confirming this condition only means confirming the possibility, and gives no decisive answer about the actual cause.

For settlement, to conclude, there is a series of possible causes plus essential conditions that is exactly the same for all associated damage patterns. To avoid repetition and keep the tool compact, we have brought these conditions together in a separate part at the end of the tool. The background of this will be explained in more detail in Section 8.2.4.

By following above procedure, our tool will assist the user in drawing up a list of hypotheses for the damage he is investigating. It does expressly not lead to an instant, cut-and-dried diagnosis, because we think that no tool can ever cover all situations one can come across in practice. Hence, to determine the ultimate cause, further tests or inspections may be necessary. We anticipate that our tool can put the user on the right track and help him decide which surveys would provide the most relevant, discriminating information.

8.2.4 Reason to keep settlement apart

For settlement, the precise hypotheses and accompanying essential conditions are presented at the end of our tool, detached from the 60 damage patterns. The reason for this is that for settlement the 'cause behind the cause' is more important and at the same time less outspoken than for other processes. Consequently, the damage pattern alone does usually not provide sufficient clues to distinguish between the processes underlying settlement.

What damage caused by settlement does tell, however, is the relative movement that the building has undergone. From this relative movement, one may infer location and, possibly, length of the settlement trough. This, in turn, may indicate where to search for the cause of the settlement process. In continuation to our conclusions in Chapter 7, we will now briefly outline how settlement damage can be interpreted.

Settlement damage tends to be strongly influenced by the behaviour of the building. An important factor in this appears to be the ratio in stiffness of the building part below which settlement takes place, and that of adjacent building parts. This ratio determines the extent to which these building parts constrain each other and, as such, their reaction to settlement.

For a purely vertical displacement, three basic responses can be discerned, see Figure 8.2. If the building part on which vertical displacements are imposed is relatively stiff and free to move, a displacement at one side will lead to a rotation. The resulting damage is tilting: vertical edges are no longer vertical and horizontal edges are no longer horizontal, but straight lines remain straight and square angles remain square.

If, however, one end of this wall is kept in place, for example by its connection to a perpendicular wall that is not affected by the settlement, bending is more likely to occur. Under bending, all angles between the edges of a wall remain at 90 °, but two of these edges curve. It may lead to cracks that start at the curved edge that is stretched the most. A bending crack is widest where it reaches this edge, while it tapers to zero at the other end. It is usually vertical.

The third option is shearing. This response takes place when both ends of a wall are firmly constrained and kept upright. In that case, the distortion will consist of skewing: all edges remain straight, but the angles between these edges change. This can eventually lead to a crack in the middle of the plane, which is widest in the middle and tapers to zero at both ends. Usually, the direction of this crack is diagonal.

Above explanation makes clear that the symptoms indicated in Figure 8.2 should be interpreted in relation to the context of the damage. The type of basic response that has

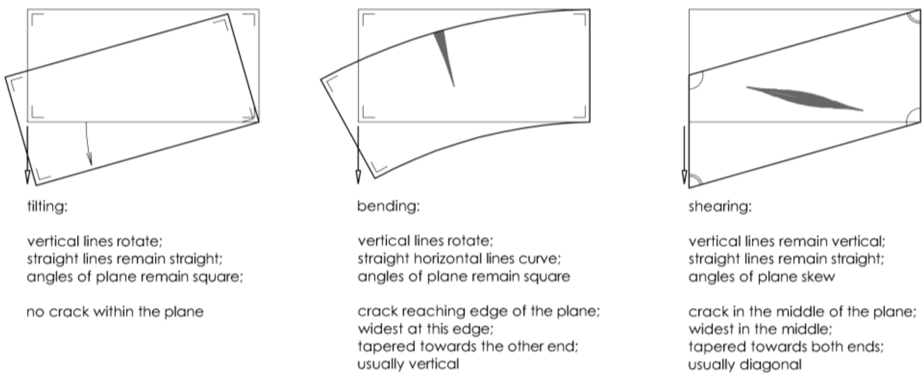


Figure 8.2: Basic forms of settlement damage: tilting, bending and shearing.

occurred in a certain case does not provide any direct clue about the cause of settlement. Nevertheless, all three responses allow one to deduce the relative displacement over the building part. From this, one may infer the location of the settlement trough.

From Figure 8.2, one may already have inferred that there is a second important factor that influences the appearance of settlement damage. Which of the three basic forms of settlement occurs does not only depend on the stiffness of the building, but also on the length over which the settlement trough extends below this building. After all, this length determines which part of the building is directly affected by the settlement, and which part only functions as a constraint.

In the case of tilt, it is quite clear: tilt only takes place if a settlement trough extends beyond the centre of gravity of the (rigid) building. If the trough covers a smaller part of the building, bending or shearing may occur. In which of these two ways a wall fails appears to depend on the ratio between relative height of the wall H (i.e. uninterrupted by openings) and the length L of that part of the settlement trough that extends below the building.

Mastrodicasa [1993] has, by equating the formulas for normal and shear stress, deduced values for this length to height ratio L / H at which the turn from shearing to bending takes place. In Figure 8.3, we have combined three L / H ratios (low, medium and high) with three characteristic positions of settlement troughs (below one end, below both ends or below the centre of a wall). Figure 8.3, thus, presents nine variants of damage due to settlement. It makes clear how one can infer location and length of a settlement trough from crack patterns or deformations in a wall.

When considering Figures 8.2 and 8.3, one should be aware that the damage characteristics only indicate relative displacements, and not the absolute directions of this

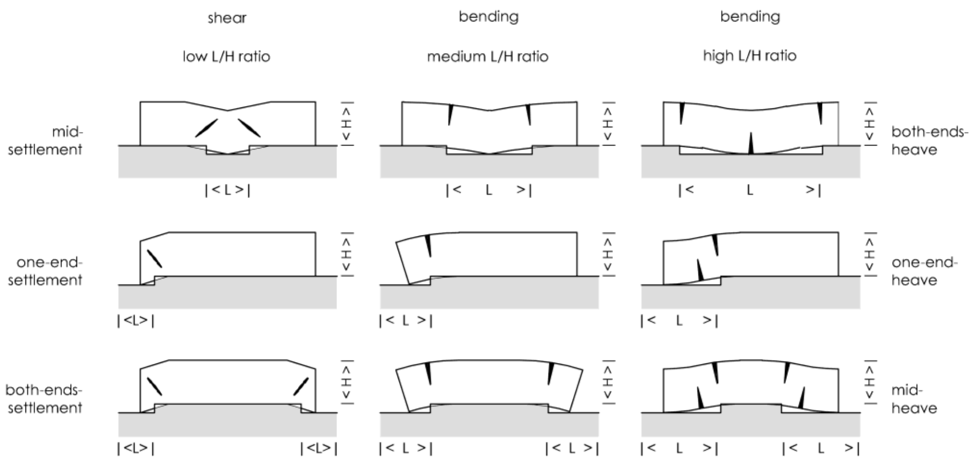


Figure 8.3: Inference of trough location and length from settlement damage.

displacement. Hence, the tilting and shearing as presented in Figure 8.2 can result either from settlement at the left hand or from heave at the right. Similarly, in case of bending, settlement of the right side would lead to an almost identical damage pattern as the one presented in Figure 8.2; only it would be the other vertical edge that rotated.

This line of reasoning also applies to Figure 8.3. Settlement below the centre of a building can lead to similar damage as heave below both ends. At the left side of the figure, the alternatives for settlement have been indicated, at the right side the ones for heave.

Consequently, the damage patterns in our tool have also been given the double labels as hypotheses. These are:

- Vertical settlement: mid-settlement / both-ends-heave;
- Vertical settlement: one-end-settlement / one-end-heave;
- Vertical settlement: both-ends-settlement / mid-heave; and
- Horizontal soil movement.

By examining damage in adjacent walls in combination, it should be possible to get a three-dimensional picture of the settlement trough. We distinguish between uniform, inclined and differential displacements. As has been discussed in Section 4.2, uniform settlement hardly affects a structure. Inclined and differential settlement are more likely to lead to damage, and from the location of this damage, one may infer which type of trough is involved.

Figure 8.4 indicates how damage in parallel or perpendicular walls can be related to vertical movements of the base. Figure 8.4 (middle) shows how inclined settlement generally leads to damage in two opposite walls that are both connected to the settled wall. Differential settlement of a corner (Figure 8.4, right), on the other hand, affects the two orthogonal walls that converge at this corner. In both cases, the damage pattern in these two affected walls will be almost identical (although reflected): the overall damage pattern is symmetrical with respect to the middle of the settled wall or to the corner, respectively.

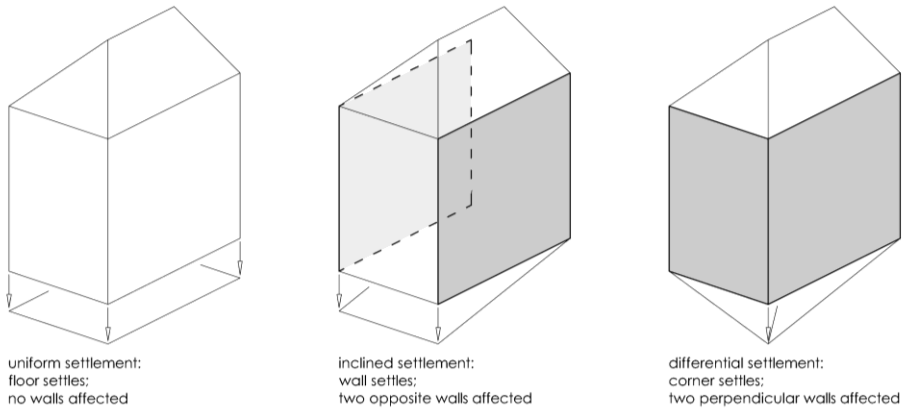


Figure 8.4: Three-dimensional interpretation of settlement damage.

From the above, one can infer that the appearance of a settlement damage is not so much determined by the source of a settlement process, as by the position and size of its trough with respect to the building. This implies that the two lists of hypotheses, one related to vertical movement, the other to horizontal movement, cannot be further differentiated and will be the same for all damage patterns associated with them. The tables with essential conditions corresponding to these hypotheses will be identical, too. To save space and keep our tool compact, we have decided to present these hypotheses and conditions in a separate part of the tool. In the descriptions of the damage patterns in question, the hypothesis indicates the position of a possible settlement trough, while we have added a reference to this separate part for more details on hypotheses and conditions.

8.3 Paper versus computerized version of diagnostic tool

With above procedure implemented, our diagnostic tool has now been finalized. It is a paper version. As has been stated in Section 3.1.3, a computerized adaptation may open up some additional advantages, especially by providing more options to retrieve data. All things considered, we think that a computerized variant could improve the current version of our tool in the following areas.

First of all, a computer system would allow us to make the decision tree for damage patterns interactive. More specifically speaking, the fixed sequence of questions could be circumvented. This would enable users to first answer those questions they are certain about, leaving others open for the time being. In this way, the system would be able to truly adapt to the user's workflow, while at the same time being able to suggest what further information would be useful to the diagnostic process.

Secondly, the computerized version would clear the way to juxtapose images of those damage patterns that meet the characteristics the user has entered so far. This would help the user to visualize how the translation from loose characteristics to a compound damage pattern takes place. Furthermore, it would make it easier for him to evaluate if his input is actually correct – he could immediately see which damage patterns still meet his input after a certain choice, and which ones not.

Thirdly, the use of hyperlinks within our tool would make it possible to provide background information on demand. This would be especially helpful to explain the terms used in the tool, which are now defined and illustrated in this thesis. Hyperlinks could unlock the information contained in the thesis to users of the tool in a more direct way.

Fourthly, within a computer system, the tables presenting essential conditions could be translated in interactive lists of questions. As with the decision tree, it would be possible to answer or leave open a certain question, depending on what the user has already found out on the damage he is investigating. Having filled in what he knows, the user can then be presented with a list of hypotheses that is tailored to his case.

Fifthly, a digital version would make the separate part on settlement processes redundant: these hypotheses and conditions can then be incorporated into the normal information flow per damage pattern. A digital tool does not become any thicker by doing so.

Summarizing, we can state that a computerized version would allow us to supply the user with more information that, at the same time, is better dosed.

In Section 3.3.4, it was already stated that developing a computerized system falls outside the scope of this PhD research; however, that we intended to present all data in such a way that a translation is feasible. Especially implementation of our work in the Monument Damage Diagnostic System (MDDS, as discussed in Section 2.2.2 and 3.1.3) would be a logical next step. While MDDS provides detailed diagnostic support on damages related to moisture, salt and frost, its information on other structural damages needs further development. The contents of our work would complement that of MDDS well, while our tool would certainly benefit from the experiences of MDDS in setting up a digital diagnostic system.

Despite this, one should bear in mind that a paper version certainly has benefits, too. Its features may even make it preferable to a digital system when used on site. For instance, a booklet still occupies less space and weighs less than an average laptop computer – although e-book readers, smartphones and the like are about to nullify this advantage.

Another benefit of a paper version is that it invites users to leaf through its pages. This gives them a better overview of the content of the tool: all information is offered at a glance. In addition, turning over the leaves, to and fro, allows users to casually encounter hypotheses or conditions they were not aware of.

A last advantage of a paper tool is that it allows users to easily add comments. This option should certainly be made available in the computer system. Ideally, different users should be asked to submit their notes and views, so that these can be shared and discussed, and the tool can keep up with developments in the field of building pathology.

All in all, both a paper and a computerized tool have pros and cons. In our user test, in Chapter 9, we will put the question to potential users and ask them which version they would prefer. Whether a digital edition is to be developed will also depend on their reactions.

8.4 Conclusions

Our tool is now ready for use. It has been appended to this thesis as a separate booklet. We expect:

- That the tool is easy to use;
- That it provides information that is clear, relevant and correct; and
- That it is an instructive and effective help in hypothesizing structural damage in masonry.

In Chapter 9, we will see whether the tool lives up to these expectations.

Chapter 9
Diagnostic decision support tool in practice

The previous chapter has resulted in a diagnostic tool that is ready for use. The next step is now to test whether this tool indeed offers support in the diagnosis of structural damage in masonry. This asks for a usability test in practice, the outline and results of which will be discussed in this chapter.

The chapter consists of five sections. In the first one, we will list what we want to find out. On that basis, we will decide how the test should be organized. The practical details of the test set-up are addressed in Section 9.2. Subsequently, the test results are presented in Section 9.3, and evaluated in Section 9.4. Finally, the fifth section sums up the conclusions that we can draw from the user test, including recommendations for improving the tool.

The conclusions presented in Section 9.5 refer to the qualities and disadvantages that the participants of the user test have reported after their first use of our product: the diagnostic decision support tool. The implications of our study as a whole are discussed in the succeeding and final chapter, 10. There, we will evaluate the scientific and societal relevance of this research project.

9.1 Aims and outline of the user test

In Chapter 8, we have created a workable diagnostic decision support tool out of our research data. In line with the aim of this PhD project, the tool is intended to offer support in the diagnosis of structural damage in masonry. More specifically, it should encourage an unbiased formulation and ranking of hypotheses. Now it is time to examine if our tool truly serves this purpose.

What we want to know is whether our tool can improve the diagnosis of structural damage in masonry. Does it facilitate a more consistent interpretation of the symptoms and context of this type of damage? Does it give the user insight into damage processes? Does it offer him alternative explanations? And does it help him reach a sound, well-founded hypothesis?

Summarizing, we want to know if our tool is useful. This main question can be divided into three subquestions, which correspond with the expectations as formulated in Section 8.4:

- Is the tool easy to use?
- Is the information provided by the tool valid? and
- Is the tool helpful in the diagnostic process?

It is evident that we cannot directly answer above questions ourselves: we are not objective; we are biased towards our tool. Hence, a usability test involving independent reviewers is needed to test and evaluate the tool. In the following subsections, the outline of this test is discussed.

9.1.1 General approach

To examine the usability of our tool, a user test needs to be developed. For each of the three subquestions mentioned previously, we will consider which approach is most suitable to find an adequate answer. On that basis, we will decide on the course to be pursued.

The first question, on ease of use, inquires after a personal opinion that is well-nigh impossible to measure objectively. As a perception, this opinion will strongly depend on what the testee is accustomed to, and what his preferences are. In addition, it may also be influenced by the situation in which the test is performed.

To find a reliable answer to this question, the tool needs to be tested in a situation that resembles as close as possible the usual, day-to-day practice. This practice may differ for different types of potential users. Both the test situation(s) and the testees themselves should preferably reflect these differences.

The second subquestion is about the quality of the tool's content. To find a way to judge this content, we have first of all looked at how the medical profession deals with this. There, correctness and completeness of a diagnostic decision support system are typically assessed by entering the data of a sample of real-life cases into such a system. Thereupon, the system's output is compared to human-generated diagnoses as established in practice (see, for example, the work of Berner et al. [1994], as Section 3.1.3 has touched on).

Unfortunately, we cannot adopt above approach here. In the field of building pathology, there is no set of cases which have been accepted by common consent to serve as a 'golden standard' or litmus test. All clear and diagnosed cases that we have come across have been incorporated into our tool, which makes them by definition unsuitable for verification. Hence, we had to look for an alternative approach.

Our proposal is to have experts directly evaluate the plausibility of the content. This requires reviewers with sufficient experience and reputation in damage assessment. It would be ideal to have a number of experts critically appraising the correctness of all information provided in the tool. However, since this group is rather limited, each participant would have to appraise a substantial part of the tool. This would be too much to ask of volunteers. Instead, we suggest letting participants review a random selection. This selection could be based on a practice situation that is chosen by the testee himself.

The third question relates to the effect our tool has on the diagnostic process. Helpfulness actually turns out to be the most difficult value to measure. Ideally, one would want to assess this helpfulness by letting two separate groups assess the same cases: a test group that uses our tool, and a control group that does not have this tool at its disposal. A comparison between the hypotheses of both groups and the 'true', stipulated diagnosis would give an indication of the effect that using our tool has. Unfortunately, this would again require a set of cases for which the diagnosis has been established conclusively, but that have not been used to develop the tool. Moreover, the participants should not yet know these cases. As have already been concluded previously, we do not have such a set of cases available.

Another option would be to determine improvements in the soundness of users' hypotheses by asking participants to first establish a hypothesis without using our tool, and then with. Here, the problem arises that, at the moment the testees start using the tool, they are already biased by their diagnosis established without support. This can make them less open to the alternatives that the tool offers.

As an alternative to above two options, we have decided to rely on the perception of our testees. We think that the best approach is to directly ask their feedback on this matter, using both open and closed questions, and to explicitly appeal for their suggestions. We are, however, aware that this means that we, in fact, ask participants to judge their own bias, which is, of course, hard to accomplish. Hence, the results with regard to this question may not say so much on the actual effect that using our tool has on the soundness of a diagnosis, as that it reflects the users' feeling of being supported. Nevertheless, this may well be a dependable indicator of one's willingness to use our tool at a regular basis in practice.

Considering the combined requirements ensuing from the three subquestions, we propose to organize the user test in such a way that participants can test our tool in a setting of their choice. We anticipate that this will give us optimal insight into how our tool fits in with their day-to-day workflow, which is an important success factor for diagnostic decision support systems (see Section 3.1.3). Furthermore, we expect that this set-up will lead to a large variety of cases to which the tool is applied. This increases the probability that the content of different sections of the tool will be appraised. Finally, diversity in cases is also desirable for evaluating helpfulness. Letting participants choose their cases for themselves rules out our own bias: it prevents us from providing them with damages of which we know in advance how the tool should be applied.

We consider this test set-up as the most realistic, feasible option. It is most convenient for the participants, while it also lets the tool be confronted with real practice difficulties. We hope this resembles best the situations for which our tool has been developed.

9.1.2 Four groups of potential users

With the user test, we want to examine whether our tool is suitable for use in practice. But what does this practice look like? As stated in Section 1.3, our diagnostic decision support tool addresses a wide range of masonry structures, although specific attention has been paid to historical buildings. The target groups we have in mind are parties professionally involved in the maintenance of (historical) masonry buildings. We expect that our tool will especially appeal to four types of potential users:

- Monument Watch inspectors;
- Engineers involved in the structural appraisal of existing masonry buildings;
- Researchers in the field of maintenance of historical buildings; and
- Students in the field of conservation of buildings.

Above four groups of potential users differ in experience in and knowledge of the subject of structural damage, and they probably also have different expectations for a diagnostic decision support tool. Consequently, some aspects of our tool may appeal more to a certain user group than to others. In broad lines, we expect that for Monument Watch inspectors, our tool should especially facilitate their function as general practitioners for buildings. In other words, the tool should help them decide whether a specialist advisor, for instance a structural engineer, should be called in.

Engineers involved in structural appraisal and researchers in the field, on the other hand, may rather look for support or a second opinion on their diagnosis. Especially the lists of hypotheses are expected to be valuable for them. These may bring to mind alternative, maybe for them less obvious causes, such as salt attack.

Students, finally, may most of all benefit from the structured approach that is offered. This should help them make themselves familiar with the field of surveying in general, and the interpretation of structural damage in particular. Above all, our tool will especially support them in identifying the essential characteristics of structural damage and provide them with an easy-reference manual for the possible causes.

A group of potential users that will not be considered here is formed by restoration architects. We assume that their experience, knowledge and workflow vary between that of above four groups. In addition, their use of the tool will closely resemble that of (architecture) students and Monument Watch inspectors. Hence, since we expect that their part will be covered sufficiently by the other target groups, restoration architects have not been invited as a separate group.

Please note that we do not consider loss adjusters or assessors working in insurance-related industries among our target audience. Our tool has not been designed to serve as legal evidence in answering questions of guilt, nor to estimate financial losses or repair costs. This is a completely different discipline, from which we explicitly distance our thesis and tool.

To obtain reliable results from the user test, it is important to have our tool evaluated by representatives of the full range of potential users. Hence, we will invite people from each of the four target groups to participate. By asking the participants to test the tool on a case from their practice, we can also ensure that the necessary variety of workflows will be considered.

To prevent prejudice with regard to the effects or contents of the tool, one additional stipulation is expressed: testees should have sufficient distance to this research project. This implies that they should not be involved in the development of the tool, nor should they belong to the sources of information on which the tool has been based. To avoid even the semblance of partiality, we have decided that they should also not be part of the doctoral examination committee that is to appraise the manuscript of this thesis.

9.2 Implementation of the user test

In the previous section, we have explicated:

- That we plan to have the merits of our product evaluated in a user test;
- That representatives of the four groups of potential users will be invited to participate in this test; and
- That these participants will be asked to use our tool in a case originating from their own practice.

In this section, we will address the practical details: the implementation of the user test. Questionnaire, procedure and response will successively come up for discussion.

9.2.1 Questionnaire

For the third time within this PhD project, we will use a questionnaire to consult external parties and obtain their opinions. This user test serves to find an answer to the research questions as formulated in Section 9.1. Central themes for the queries contained in the inquiry form are, thus, ease of use, validity of content, and helpfulness of our tool.

The theme ease of use has been covered by queries on the following topics:

- Clearness of explanation;
- Clearness of structure (outline);
- Simplicity of putting instructions of use into practice; and
- Preference for digital or paper version of the tool.

The questions related to the theme validity of content have been arranged by the subjects:

- Clearness of provided information (in text and illustration);
- Relevance of provided information; and
- Completeness of provided information.

For the theme helpfulness, we have drawn up the issues mentioned below:

- Support offered by the structure of the tool;
- Instructiveness of the tool;
- Effectiveness of the tool as regards bias and confidence; and
- Participant's interest in using the tool further.

Apart from above themes, we will also ask about the participant's background and the setting in which he has tested our tool. We suspect that both circumstances will influence a participant's opinion on the tool. Regarding his background, the level of experience of a respondent may determine how reliable his remarks as regards content of the tool will be. On the other hand, this experience can also influence the extent to which he will perceive the tool as helpful.

A growing confidence in personal knowledge may well lessen the need for a decision support tool. This, though, does not mean that our tool could not be of service to an expert: we think it would, by reducing the adverse effects of bias. However, as has been mentioned before, the outline of this user test only allows us to ascertain the participants' views on this helpfulness, not the actual effects.

We will determine the level of experience through two questions. One question concerns the work experience in the field of damage appraisal or inspection. The other regards how often one is professionally confronted with damage to buildings. Please note that we do not directly ask participants to indicate the target group to which they belong. We will infer this from their current position and the company they are associated with.

As a second influencing factor we consider the situation in which the user test is performed. Participants are asked to use our tool in a case originating from their practice, supplementary to their usual approach. Of course, we would prefer them to use the tool in a real-life setting. However, since some participants may not have a suitable project in hand at the time of the inquiry, we leave open the possibility that respondents apply the tool to photographs of a case they have settled earlier.

The latter case may have two disadvantages. First of all, an established diagnosis will almost automatically lead to (confirmation) bias while using the tool. Secondly, it will also be difficult to come to fresh conclusions on the basis of photographs. After all, photographs are usually taken to illustrate certain reasoning. As such, they are good to call things to mind, but are usually not suitable to collect new data. If a symptom or context condition has not been noticed on site, it is highly unlikely that this will happen later on while studying a photograph. In fact, this is one of the reasons why it was so difficult for the experts participating in the questionnaire discussed in Section 2.3 to analyse the damage cases!

To be able to examine the influence of the test situation, we have included two questions. The first one concerns the situation in which the tool has been used, distinguishing between the options ‘on site, during an inspection of the damage case’, ‘by means of photographs, within four weeks after inspection of the damage case’ and ‘by means of photographs, more than four weeks after inspection of the damage case’. The second question inquires whether a diagnosis had already been established before the tool was used, or not.

In total, the questionnaire consists of 55 questions. Both open and closed queries have been formulated. The majority of the closed questions use a so-called five-point Likert scale. This means that respondents are asked to specify their level of agreement to a statement by choosing between five options: strongly disagree (- -), disagree (-), neither agree nor disagree (0), agree (+) and strongly agree (+ +).

The questions have been arranged in 10 clusters. These clusters follow the steps that participants are instructed to pass through while using the tool. In this way, we hope to get specific feedback on the separate features of our tool.

In line with this, we explicitly ask respondents to indicate which damage patterns, hypotheses and conditions they have used and assessed. Here, too, we hope to obtain specific feedback. With the help of especially the more experienced participants, we may be able to eliminate omissions and further improve the tool’s content.

In Table 9.1, we have outlined the queries composing the questionnaire. For each query, the type of question (i.e. Likert-type, open or closed) has been indicated. Furthermore, we have pointed out to which theme each one belongs.

One final comment is to be made in this context. As will be shown in the next subsection, three students have tested our tool in an earlier stage than the other participants. They filled out a preliminary version of the inquiry form, in which some aspects were not yet covered sufficiently. The far-right column in Table 9.1 indicates the topics that the preliminary form did include.

9.2.2 Procedure

For each of four target groups, we are interested to find out whether our diagnostic tool will be appreciated as a positive contribution to their work or education. We have investigated this by inviting members of these groups to participate in our user test. A slightly different procedure has been adopted for students versus professionals.

Students have been selected through their enrolment in the MSc course Building Conservation Assessment taught at the Faculty of Architecture of Delft University of Technology. Those working on an assignment about structural damage in masonry were invited to participate in our user test. After a brief introduction, these students used the tool for surveying a church building.

The user test has been distributed in two subsequent semesters. The first group of students (A) reviewed our tool a few weeks before it was rolled out to the professionals. As a reaction to the students' comments, already some improvements to the tool could be made, especially regarding the instructions of use. At the same time, we decided to further extend the inquiry form (see the remarks in Section 9.2.1). In the second semester, tool and questionnaire as distributed to students' group D were identical to the ones dispersed among the professionals.

One student-respondent was not involved in the above-mentioned course; she was working on her MSc graduation project. She was contacted via the Chair of Conservation Techniques. Except for the invitation, her user test followed the procedure and time path set up for professionals, as will be discussed below.

The professionals we invited are employed in engineering consultancies (7 persons), Monument Watch organizations (3) or research (3). With most of them, we have come acquainted in the course of this research project. Some participated in our 2006 questionnaire brought forward in Sections 1.3 and 7.2.1. Others have been approached on the basis of projects in which they had been involved.

Since the user test aims not just to weigh the translation of obtained data into a tool, but also the validity and up-to-dateness of the compiled data themselves, we had intended to only target experts who have not been cited in our tool. Nevertheless, in the end we did invite one author to participate, since we could not find anyone else to replace his specific expertise.

Table 9.1: Outline of the questionnaire of the user test

	Theme: Ease of use	**Type**	
Clearness of explanation			
1.a	The explanation of how the tool should be used is formulated in a clear way.	Likert	*
Clearness of structure			
1.b	The outline of the tool in three parts (I, II and III) is clear.	Likert	
1.c	The outline of each damage pattern in four subdivisions (A, B, C and D) is clear.	Likert	
3.a	The outline of the decision tree is clear.	Likert	
5.a	The hypotheses are arranged conveniently.	Likert	
6.a	The conditions are arranged conveniently.	Likert	
6.c	The relation between conditions and hypotheses is clear.	Likert	
Simplicity of putting instructions of use into practice			
3.d	With the decision tree, it is easy to determine which damage pattern is relevant to the damage case in my practice situation.	Likert	
3.e	At which damage pattern did you arrive after going through the decision tree?	Open	
4.a	Did you, after studying the characteristics of the damage pattern, decide to return to the decision tree to determine the damage pattern anew?	Yes / No	
4.b	In case you have answered the previous question with ‘Yes’: Could you indicate at which damage pattern you arrived before and after this check?	Open	
4.h	It is easy to check whether the damage pattern corresponds to the damage case in my practice situation.	Likert	
4.i	The characteristics of the damage pattern corresponded with the characteristics of the damage case in my practice situation.	Likert	
7.a	The method of working, in four steps, for using the tool is easy to put into practice.	Likert	*
Preference for digital or paper version of the tool			
7.g	I would prefer a digital version of this tool to a paper one.	Likert	
	Theme: Validity of content		
Clearness of provided information			
3.b	The statements in the decision tree are formulated in a clear way.	Likert	
3.c	The statements in the decision tree can be answered without ambiguity.	Likert	
4.c	The drawing of the damage pattern is clear.	Likert	
4.d	The characteristics of the damage pattern are formulated in a clear way.	Likert	
5.b	The hypotheses are formulated in a clear way.	Likert	
6.b	The conditions are formulated in a clear way.	Likert	
Relevance of provided information			
4.e	The examples shown belong to the damage pattern.	Likert	
4.f	The characteristics of the damage pattern are essential for determining this damage.	Likert	*
5.c	The hypotheses are relevant to the damage pattern.	Likert	*
5.e	In case ..., could you please indicate which hypothesis/es you think irrelevant?	Open	
6.d	The conditions are relevant to the corresponding hypotheses.	Likert	*
6.g	Do you agree with the hypothesis/es that the tool proposed for the damage case in your practice situation?	Yes / No	*
6.h	In case ..., could you please indicate which condition(s) you think irrelevant and to which hypothesis/es?	Open	
Completeness of provided information			
4.g	The characteristics of the damage pattern are sufficient for determining this damage.	Likert	*
5.d	The list of hypotheses is complete for the damage pattern.	Likert	*
5.f	In case ..., could you please indicate which hypothesis/es you miss?	Open	
6.e	The list of conditions is complete for the corresponding hypotheses.	Likert	*
6.i	In case ..., could you please indicate which condition(s) you miss and for which hypothesis/es? In other words: could you indicate additional conditions that would enable you to exclude a certain hypothesis?	Open	
	Theme: Helpfulness		
Support offered by the structure of the tool			
7.b	Using the tool structures my damage inspection.	Likert	⋇
Instructiveness of the tool			
7.c	Using the tool contributes to a better understanding of the symptoms of structural damage.	Likert	⋇
7.d	Using the tool contributes to a better understanding of the different causes of structural damage.	Likert	⋇
7.e	Using the tool contributes to a better understanding of the context conditions that influence the occurrence of structural damage.	Likert	⋇
Effectiveness of the tool			
6.f	Using the tool gave me a broader view of the possible causes of the damage case in my practice situation.	Likert	⋇
7.f	Using the tool gave me more confidence in my judgement on the cause of damage.	Likert	⋇
Participant's interest in using the tool further			
7.h	Would you like to use this tool in your practice?	Yes / No	
7.i	In case you have answered the previous question with ‘No’: Could you indicate why not?	Open	
	Theme: User's background		
8.a	What is your current position?	Open	⋇
8.b	How much work experience in the field of damage appraisal or inspection do you have?	Other options	
8.c	How often do you, on average, deal with damage to buildings, in your profession?	Other options	
8.d	Which type of damage do you see most often in your practice?	Open	
9.	Contact details	Open	⋇
	Theme: Test situation		
2.a	In which situation did you use the diagnostic tool?	Other options	
2.b	Did you already establish the diagnosis of this damage case, before you started using the diagnostic tool?	Yes / No	
2.c	Could you please provide a sketch of the damage case in the practice situation in which you used the tool?	Open	
	Suggestions		
10.	Suggestions	Open	⋇

⋇ = question included in preliminary version of inquiry form

To above persons (group B), a letter of invitation was mailed, which was accompanied by a leaflet amplifying the aims and outline of our user test. The letter announced a telephone call, in which we inquired after their readiness to cooperate in this test. These telephone calls were made in the three weeks following the mailing of the invitation letter, until we had received a reaction from all invitees. Interested parties were offered the possibility to order several copies of the tool, so that they could pass on our user test to colleagues or contacts (group C).

Partakers were subsequently sent the requested number of user test sets. Each set consisted of one copy of the diagnostic tool, a questionnaire and an envelope exempted from postage (reply paid). A short explanation of the user test was included at the top of the inquiry form, together with a reference that the instructions for using the tool could be found at the first pages of the tool itself. With this, the participants could start the actual test.

A few days after dispatching the user test sets, an email was sent to draw the participants' attention to this fact, and to inquire whether our tool had been received duly. Attached to this email was a Dutch-language excerpt of the tool, containing translations of the introduction (instructions of use), the decision tree and key terms used throughout the tool. This excerpt had been developed upon request of one of the participants. Since all but one of them were Dutch-speaking, it seemed beneficial to supply it to all testees.

Taking the summer holidays into consideration, a period of eight weeks had been reserved for performing the test. After these eight weeks, a reminder was emailed to all participants of whom no response had been received yet. For their convenience, a digital copy of the inquiry form was enclosed. Another six weeks later, a final reminder was sent to those still pending. Shortly after, the user test was closed.

9.2.3 Response

In total, 21 persons have been invited directly to participate in our user test. Of them, 19 accepted this invitation; 2 did not. As some invitees indicated that they would like to pass on our tool and questionnaire to colleagues or contacts, a total of 26 tools have been dispersed among these 19 people. Hence, a maximum of 26 responses was expected.

An overview of the number of people invited to, interested in, and responding to our user test is presented in Table 9.2. To allow us to analyse the response, they have been categorized in four groups (A-D), depending on the time at and the way in which they had been approached. At the closing of the user test, we had received 14 responses. This results in a total response rate of 53.8 %.

As becomes clear from Table 9.2, the response rate shows a high scatter between the four subsequent groups of invitees. From the first group of students (A) and the professionals with whom we had direct contact (B), we received significantly more reactions than from the other two categories.

The professionals in Group C (indirect contact) seemed not so interested: only one of them returned his questionnaire. Although we still think that it was a good opportunity to let our user test be dispersed among a wider group of people, the disadvantage of this part of the approach is clear: apart from the fact that we have not been able to inquire about their interest beforehand, we could also not actively reach these participants with further information or reminders.

Table 9.2 also provides information on the non-respondents. Besides the account that two participants had not been able to find time to perform the user test, one filled-out form was reported to be returned by the participant, but never reached us. Three other questionnaires were, apparently, filled out on behalf of two persons. Finally, for two students our tool turned to be unsuitable for their assignment, since, in the end, they did not really consider structural damage in masonry.

Finally, it is good to note that response rate in itself does not say anything about the statistical accuracy of a survey. To assess statistical confidence, the number of responses should not be compared to the number of invitees, but to the whole research population, i.e. in our case the number of potential users. This number is not known, but for the Netherlands, we would estimate it at about 1500 engineers and architects, assuming that a quarter of the total construction output is (residential) renovation, and that 30 % of the costs involved concern structures and façades. For the more specialist field of conservation of historical buildings, a minimum of 200 to 300 potential users is expected (30-40 Monument Watch inspectors, 70-100 engineering consultants, 50-75 students in conservation per year, 40-70 architecture agencies, and 10-15 researchers). This implies that our sample size and, thus, response is far too low to get statistically significant results. In the analysis of the results, this needs to be taken into account.

Table 9.2: Invitees, participants, respondents and non-respondents to the user test

	Group A	**Group B**	**Group C**	**Group D**	**Total**
Group characterization					
User type	- Students	- Professionals	- Professionals	- Students	
Contact type	- Direct	- Direct	- Not direct	- Not direct *	
User test version	- Preliminary	- Definitive	- Definitive	- Definitive	
Number of :					
Persons invited directly	3	13	0	5	21
Persons interested	3	11	?	5	19
Distributed user test sets	3	11	7	5	26
Received responses:	3	8	1	2	14
Response rate:	100.0%	72.7%	14.3%	40.0%	53.8%
Non-response:					
Form gone missing	0	1	0	0	1
Form filled out on behalf of two persons	0	0	2	1	3
Lack of time	0	2	0	0	2
Lack of suitable practice situation	0	0	0	2	2
No reason reported	0	0	4	0	4

* = all participants from group D have been invited directly; but only one of them could be contacted directly with reminders

9.3 Results of the user test

In the following subsections, the results of the user test will be reported. The responses are arranged according to the theme and subtheme to which they belong, as has been outlined earlier in Table 9.1 (Section 9.2.1). There, one can also find the full text of each question; in this section, these texts have been replaced with abbreviated descriptions.

Most questions used a five-point Likert scale, with as answer options: strongly disagree (- -), disagree (-), neither agree nor disagree (0), agree (+) and strongly agree (+ +). For each of these questions, the response is visualized with a stacked bar. The bar elements distinguish themselves by different shades of grey. Each colour represents an answer option, the lightest one denoting complete disagreement with the statement, and the darkest one pointing to complete agreement.

The length of each bar element and the figure reproduced within its area show the number of participants that have chosen the answer option in question. To be able to read off the general opinion at a glance, all stacked bars have been aligned to their zero point (i.e. the middle of the bar element representing the neutral (0) option). This makes it easy to see whether the response was predominantly negative or positive with regard to our tool: the further the bars extend to the right hand, the more participants were positive about our tool.

A few questions only allowed ‘yes’ or ‘no’ as an answer. These questions are presented in a similar way as the Likert-type ones. The answers have been interpreted as either positive or negative for our tool and have then been coded as agree (+) or disagree (-), respectively.

The themes concerning user background and test situation included closed questions with variant answer options. Since, for two pairs of questions, it is especially interesting to look at the correlation of characteristics, we have decided to show the answers to these related questions together. In Table 9.4, the average number of damage cases per year with which participants deal in their profession is compared to their work experience in damage appraisal. Table 9.6 characterizes the test situations in terms of location (on site or not) and of presence of a previously settled diagnosis.

Finally, for the open questions, the responses have been summarized. Since most of them refer to closed questions, they are presented in connection with the diagrams to which they belong. The same has been done with the suggestions that we obtained in response to question 10. Please note that it is just the essence of the arguments that is reproduced here; our findings regarding all results will be discussed in Section 9.4.

9.3.1 Test setting: user background and test situation

Table 9.3: Target group to which each participant belongs

Target group	Number of participants	Percentage
Engineering consultants	5	35.7%
Monument Watch inspectors	2	14.3%
Researchers	2	14.3%
Students	5	35.7%
Total	14	100.0%

Characterization based on responses to questions 8.a and 9.

Table 9.4: Participant's experience

Work experience in damage appraisal	Average number of damage cases < 1 per year		1 - 5 per year		5 - 10 per year		> 10 per year	
0 - 2 years	2	s	0		0		1	m
2 - 5 years	0		0		0		0	
5 - 10 years	0		0		0		0	
> 10 years	0		1	r	2	e	5	e, r, m

e = engineering consultant; m = monument watch inspector; r = researcher; s = student.
Data based on responses to questions 8.b and 8.c. Since these two questions were not contained in the preliminary version of the inquiry form, we do not have answers from the three early participants. However, one may expect that these three students have 0 - 2 years work experience, and have been involved in < 1 damage case per year.

Table 9.5: Type of damage each participant deals with most often

Our category	Our label	Their description	Target group
Damage type	Cracks	Cracks	e, m, s
		Wrongly diagnosed cracks	e
		Arching	e
		Decay of mortar	m
Cause type	Settlement	Problems with foundations	e
		Settlement, differential settlement	e, m
	Overloading	Ill-advised construction works	e
	Hindered dimensional changes	Problems related to building physics	e
		Problems related to temperature (lack of expansion joints)	e
		Ill-advised use of mortar for repair	m
		Erosion (frost and salt)	e
		Corrosion of iron elements	m
Context type	Walls	Façades	r
	Vaults	Vaults	r

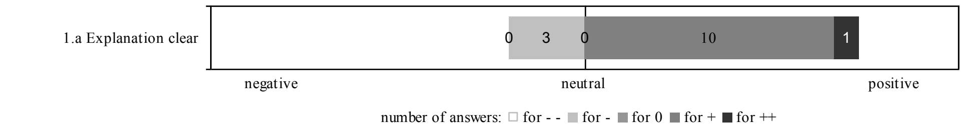
e = engineering consultant; m = monument watch inspector; r = researcher; s = student.
Data based on responses to question 8.d

Table 9.6: Test situation

Presence of diagnosis at start of using tool	User test situation: during on-site inspection	using photographs within 4 weeks after inspection	using photographs more than 4 weeks after inspection
Case not yet diagnosed	1	1	2
Case already diagnosed	0	2	5

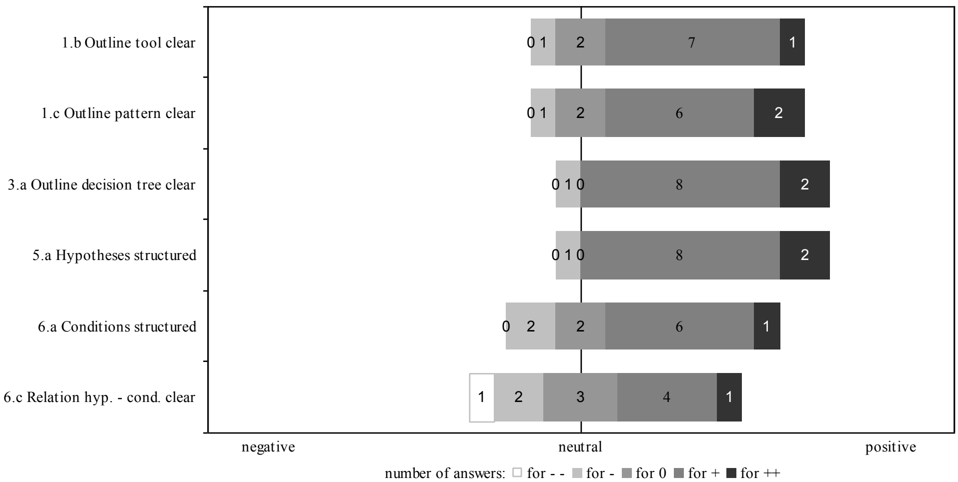
Data based on responses to questions 2.a and 2.b.
Since these two questions were not contained in the preliminary version of the inquiry form version of the inquiry form, we do not have answers from the three early participants. However, we expect that these three students used the tool on site, without having diagnosed the case yet.

9.3.2 Ease of use



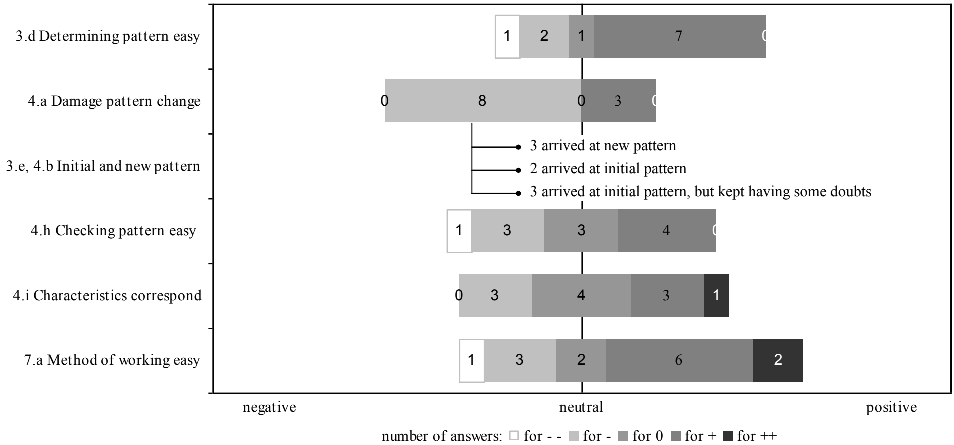
10. Comments and suggestions related to this theme:
- Provide Dutch-language version; improve Dutch inset
- Improve instructions of use (NB this suggestion has been implemented before distribution of definitive user test)

Figure 9.1: Ease of use – Clearness of explanation.



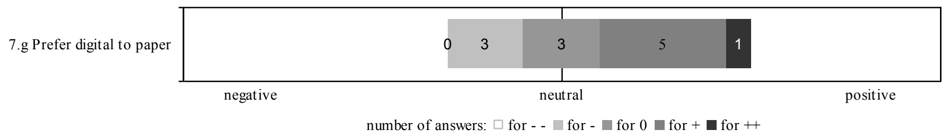
10. Comments and suggestions related to this theme:
- Outline of Part III Hypotheses for settlement is unclear
- Meaning of numbers in tables in Part III is unclear

Figure 9.2: Ease of use – Clearness of structure.



10. Comments and suggestions related to this theme:
- Simplify method of tool. Using the tool should take less time. Quick scan?
- Simplify Part I Decision tree

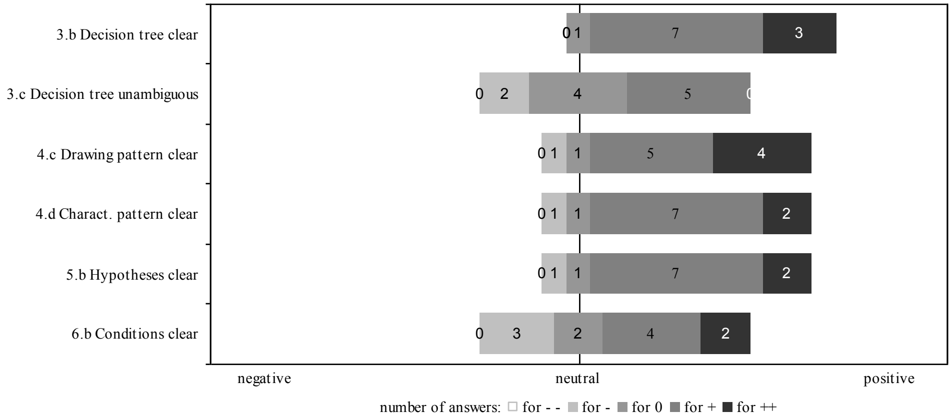
Figure 9.3: Ease of use – Simplicity of putting instructions of use into practice.



10. Comments and suggestions related to this theme:
- Provide both digital and paper version of the tool

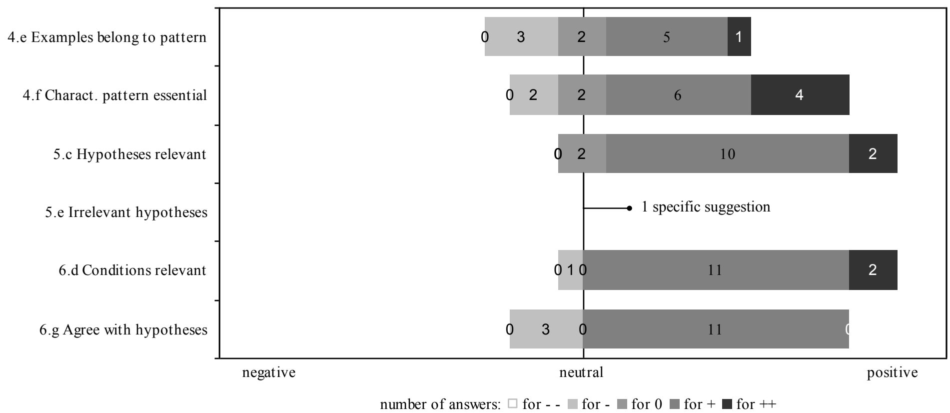
Figure 9.4: Ease of use – Preference for digital version to paper one.

9.3.3 Validity of content



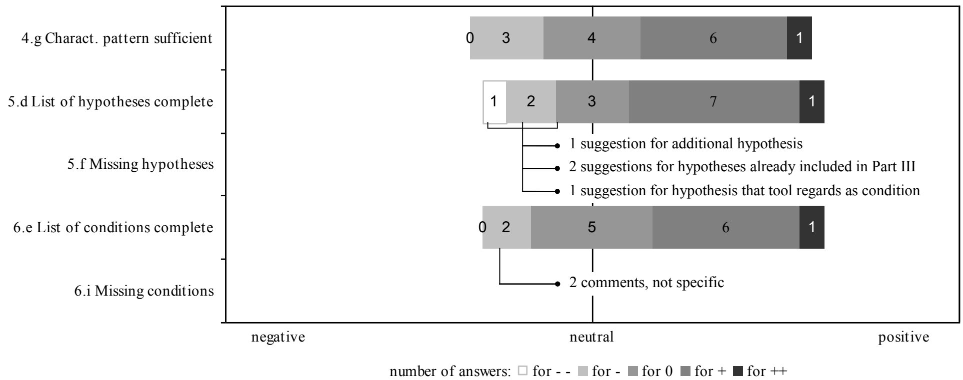
10. Comments and suggestions related to this theme:
- From answers to questions 5.f, 6.h and 6.i, it appears that our definition of and distinction between hypotheses and context conditions is not always clear to some of the participants. Information about this should be included in the tool, e.g. an explanation on the background and development
- Leafing through tool is used as an alternative to decision tree

Figure 9.5: Validity of content – Clearness of provided information.



10. Comments and suggestions related to this theme:
- Provide more photographs of examples from practice
- Examples from literature are sometimes ambiguous

Figure 9.6: Validity of content – Relevance of provided information.



10. Comments and suggestions related to this theme:
- Provide more information in Part III Hypotheses for settlement

Figure 9.7: Validity of content – Completeness of provided information.

9.3.4 Helpfulness

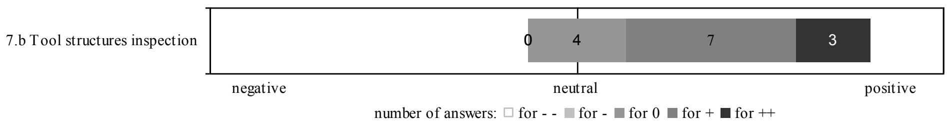
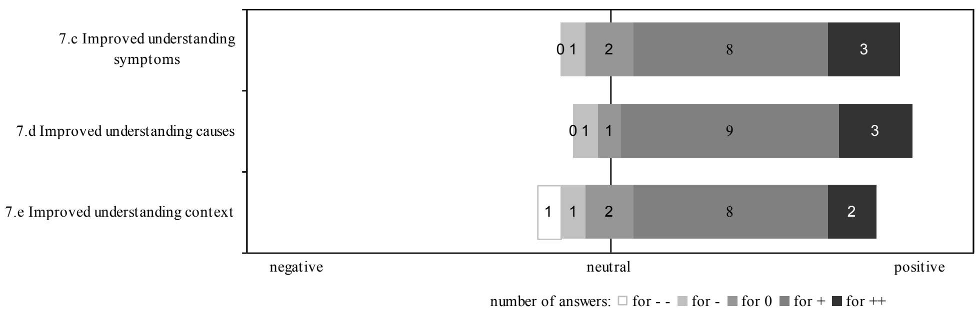
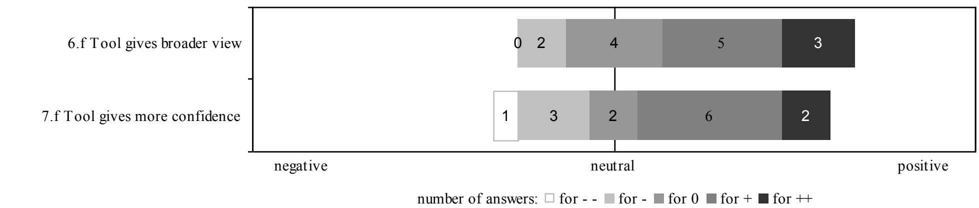


Figure 9.8: Helpfulness – Support offered by the structure of the tool.



10. Comments and suggestions related to this theme:
- Provide more information about how damage and context should be interpreted

Figure 9.9: Helpfulness – Instructiveness of the tool.



10. Comments and suggestions related to this theme:
- Provide more background information about the tool, including in which situations it can be used, and in which situations an expert should be consulted
- Point out that an open mind is essential when interpreting damage
- The tool is only helpful for inexperienced users
- The tool gives a sense of control and overview

Figure 9.10: Helpfulness – Effectiveness of the tool.

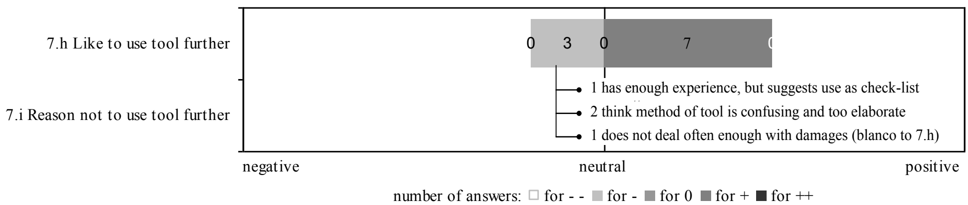


Figure 9.11: Helpfulness – Participant's interest in using the tool further.

9.3.5 Average scores per target group

Table 9.7: Average scores for themes and subthemes, per target group en in total

	Average score per target group on a scale from 1 to 5 (i.e. 3.00 is neutral)				Total average score on a scale from 1 to 5 (i.e. 3.00 is neutral)
	Engineers	**Monument Watch inspectors**	**Researchers**	**Students**	
Theme and subtheme	n = 5	n = 2	n = 2	n = 5	n = 14
Ease of use	3.73	2.96	3.54	3.23	3.44
Clearness of explanation	4.20	3.00	4.00	3.20	3.64
Clearness of structure	3.93	3.25	3.67	3.67	3.71
Simplicity of putting instructions of use into practice	3.20	2.60	3.00	3.06	3.05
Preference for digital or paper version of the tool	3.60	3.00	3.50	3.00	3.33
Validity of content	3.80	2.98	3.81	3.62	3.65
Clearness of provided information	4.00	3.42	4.00	3.50	3.80
Relevance of provided information	3.80	3.20	4.10	3.76	3.76
Completeness of provided information	3.60	2.33	3.33	3.60	3.38
Helpfulness	3.76	2.38	4.10	4.05	3.67
Support offered by the structure of the tool	4.00	3.00	4.50	4.00	3.93
Instructiveness of the tool	3.93	2.50	4.17	4.20	3.86
Effectiveness of the tool	3.50	2.00	3.75	4.00	3.50
Participant's interest in using the tool further	3.60	2.00	4.00	4.00	3.40

9.4 Discussion of results

In the previous section, the results of the user test questionnaire have been presented. In general, the responses look positive and consistent. The following subsections will discuss the results in detail, per theme.

9.4.1 Evaluation of the test setting

Target group

Before going more deeply into the participants' reactions to our tool, we will first evaluate the test settings in which the user test has been performed. Table 9.3 considers the target groups to which the respondents belong. As one can see, we have been able to reach a varied entry, originating from all four subpopulations. Moreover, the representation is proportional: the numbers of students and engineering consultants that participated are 2.5 times as high as those of the Monument Watch inspectors and researchers, which corresponds well to our estimate of the balance in the population of potential users in the field of conservation of historical buildings, see Section 9.2.3.

However, it is also clear that 14 responses are not sufficient to extrapolate the results and present them as being valid for the entire target group. 14 Responses are simply not enough to draw statistically significant conclusions on a population of about 250 people: one could only be approximately 95 % certain of a ± 20 % accuracy in the survey results. Nevertheless, what we do expect is that this user test will allow us to determine the main benefits and points for improvement of our tool.

Participant's experience

Table 9.4 shows the distribution in experience in dealing with damage of the participants. Two distinct groups can be distinguished. On one hand, there is a group of professionals (i.e. engineering consultants, Monument Watch inspectors, researchers) who have over 10 years of work experience in damage appraisal and who also deal with more than 10 damage cases on average per year. These are experts; we anticipate that, for this group, our tool could most of all function as a reminder, by bringing to mind alternative, less prevalent causes. At the same time, they are the right persons to assess the validity of the tool's content.

On the other side of the spectrum is a group with clearly less routine in the field: less than two years of work experience, and less than one damage case on average per year. Two participants indicated that they belong to this group, but we assume that three other persons, who did not answer this question because it was not included in the preliminary version of the inquiry form, can also be considered to be part of this group. All five are students. They are novices, and we anticipate that the tool can give them insight into how one should approach structural damage, what types of causes exist, and in what way these causes could be discerned. In addition, we think this second group may be most open to using the tool, exactly because they are not yet rooted in a settled method of working.

The remaining four participants, who make up the last one-third of the total entry, are between the above two extremes as regards experience. They are all professionals. Three of them have been working for a long time in the (historical) building sector. However, they are, at least at the moment, less involved in cases of damage. The fourth person, conversely, has relatively recently become active in the field, but frequently deals with damage cases. All things considered, we think the entry reflects the population well as regards experience.

Type of damage

Apart from their work experience, the participants were also asked to indicate the type of damage they see most in their practice. The answers to this question are reproduced in Table 9.5. What strikes one most are the different ways in which the respondents characterized the types of damage. In line with the handbooks we analysed in Section 2.1.2, their descriptions are based on appearance, on underlying cause, and on location (context type). We hope that regular use of our tool could help in 'synchronizing' these descriptions, so that a consistent terminology can make communication on building pathology easier.

When taking a closer look at Table 9.5, it shows that for the appearance of damage mainly cracks are mentioned. Apparently, deformations have a lower incidence, or they are less perceived as damage (either by the participant, or by his clients). All three types of causes we defined in Chapter 4 were mentioned, although overloading scored considerably lower than the other two categories. As for the context, façades and vaults were brought forward. Both are covered thoroughly in our tool.

Remarkable is also the mention of 'wrongly diagnosed cracks'. Apparently, one participant has often been called in for a second opinion, and has seen the consequences of incorrect or incomplete diagnosing. We hope our tool can improve this situation.

Test situation

Finally, we will also evaluate the test situation. Both the location where the test was performed and the presence of a diagnosis at the start of the test have been considered. Table 9.6 demonstrates that at least 4, and probably 7, out of the 14 participants used our tool on a case for which they had not settled a diagnosis yet. The remaining seven, however, did indicate that they already had established a diagnosis. We think this implies that the first group will have been quite open to the suggestions provided by the tool, without strong preference. The latter half of the respondents might have been more liable to confirmation bias, but, at the same time, they may have also paid closer attention to the lists of hypotheses, to verify whether the cause they had in mind was sufficiently covered by the tool. Therefore, we consider this distribution of test settings as suitable for our tool's review.

What is unfortunate, however, is that a large majority of the respondents (at least 10) did not test our tool during an on-site inspection, but applied it to photographs. We thought this would not be an ideal situation, as we have argued in Section 9.2.1: the point of view with which these photographs had been made may increase bias. Nevertheless, 3 out of the 10 cases in which photographs were used had not been diagnosed definitively yet. In that case, bias may be not so high.

From the above, we can draw another important conclusion: apparently, it is common practice to only settle a diagnosis definitively at the office, a good while after the on-site inspection. Hence, photographs may well play a more important role in the diagnostic process than we initially expected.

We suspect that, when users have to rely on photographs, the effectiveness of our tool may not manifest itself optimally. After all, using photographs makes it more difficult to verify the presence of symptoms or context conditions, especially when they have not been specifically checked during the inspection. Nevertheless, since this situation appears to represent an actual workflow, our tool could respond to this by enhancing its function as a check-list.

Summarizing, we can state that, although the number of participants is not sufficient to draw statistically significant conclusions, we have been able to reach a cross-section of the population we had in mind. We consider the backgrounds of the participants as representative. The test situation may have been less ideal for our tool, as we designed it primarily to be used on site. Nevertheless, we also deem this situation as representative.

9.4.2 Evaluation of ease of use

A diagnostic aid should, of course, be easy to use. To verify whether our tool meets this requirement, we have asked the participants for their opinions on statements on the subthemes clearness of explanation, clearness of structure, simplicity of putting instructions of use into practice, and preference for a digital version of the tool to a paper one. Their answers have been reproduced in Figures 9.1 to 9.4.

Clearness of explanation

From Figure 9.1, it is evident that the explanation of our tool is considered to be clear by the majority of the respondents. Of the three persons who did not agree with this view, two evaluated a preliminary version of the tool. In reaction to their comments, we improved the instructions of use and extended them with some illustrations to clarify procedure and structure of the tool. Of the 11 participants who were supplied with this improved version, only one person did consider the explanation insufficient.

The (English) language of the tool turned out to be a bigger obstacle than we had expected. Upon request, we provided a Dutch-language excerpt, with a translation of the introduction, the decision tree and all key terms. Albeit such an excerpt can be helpful, it does take extra time to use it in combination with the English tool. Judging by the suggestions put forward by the participants, a Dutch version of the complete tool would therefore be much appreciated.

Clearness of structure

The structure of the tool was considered to be clear, too, as Figure 9.2 shows. Most satisfied were the respondents with the outline of the decision tree and the structuring of the hypotheses. They were less content with the way in which the relations between conditions and hypotheses were presented. From their comments, it also appears that especially the role of Part III of the tool, in which hypotheses and conditions for settlement are presented separately from the damage patterns, was not always understood. Although the average opinion to question 6.c is still positive, it may be fruitful to improve the presentation of essential conditions throughout the tool.

Simplicity of putting instructions of use into practice

With regard to simplicity of putting the instructions of use into practice, the responses to the seven statements related to this subtheme are not as consistent as the answers to all other subthemes, see Figure 9.3. Moreover, this subtheme contains the only two questions of the questionnaire to which the overall reaction was negative. These questions, 4.a and 4.h, referred to the second step in using the tool. This step consists of checking whether the damage pattern determined via the decision tree indeed matches the damage one has under investigation.

From the response to question 4.h we can conclude that 4 out of 11 participants did not find it easy to perform this check in their practice situation. This seems consistent with the answers to questions 3.e, 4.a and 4.b: although the majority agreed that determining the damage pattern via the decision tree had been easy (question 3.d), eight respondents decided to return to the decision tree to determine the damage pattern anew. Five of them re-arrived at their initial pattern, but three of these five reported that they kept having some doubts.

Apparently, participants experienced difficulties trying to relate practice to pattern. This is confirmed by the responses to question 4.i, which indicate that 27.2 % of the respondents to this question did not agree with the statement that the characteristics of the damage pattern corresponded with the characteristics of the damage case in their practice. We can conclude from the above that the transition from practice to pattern may need further guidance. At the same time, our built-in, explicit check of the damage pattern seems to work: it made at least eight participants reconsider their choice.

Although the overall method of working was valued quite positively at the end of the user test (question 7.a), some respondents stated that using the tool was rather (or even too) time-consuming and laborious. Especially the group of Monument Watch inspectors was remarkably critical of the tool. Since diagnosing damage is everyday fare for this group, (time-) efficiency of the tool is even more important to them. Adjusting the tool to provide a better fit to their workflow seems an absolute necessity.

An option to remove this barrier would be to integrate a (digital) survey form within the tool. This would save the user time and, in addition, would facilitate an optimal information exchange: data needed to use the tool could then, at the same time, be stored and used for output such as inspection reports. Similarly, the inspection report could not just show the final diagnosis, but also which alternative hypotheses have been considered and on what grounds they have been rejected. In addition, providing a Dutch version of the tool instead of a Dutch-language excerpt would probably also improve the ease of use.

Preference for digital version to paper one

We believe that digitizing the tool could, in any case, save time. With a digital version, the provided information could be tailored even better to the user's input. In this way, the user would feel less overwhelmed by the wealth of information, while he also does not actively need to bother about the procedure of using the tool, because a digital tool can provide that guidance automatically, step-by-step. Since a majority of the participants already stated to welcome a digital version, as Figure 9.4 demonstrates, this will be one of our recommendations with regard to further developing this tool.

9.4.3 Evaluation of validity of content

The validity of content has been evaluated by asking the participants for their opinion on clearness, relevance and completeness of the provided information. For all three subthemes, the results were positive. They can be found in Figures 9.5 to 9.7.

Clearness of provided information

Regarding the clearness of the information, the respondents were particularly satisfied with the statements in the decision tree and with our drawings of the damage patterns. It is interesting to note that 10 out of 11 participants agreed that the statements in the decision tree are formulated in a clear way, but that, at the same time, only half of them considered these statements to be answerable without ambiguity (see Figure 9.5). Evidently, this implies that, although respondents may have had difficulties in answering the questions in the decision tree for their case, they did understand clearly to what these questions referred. This is in line with the remarks made in the previous subsection, where the response to question 4.i (in Figure 9.3) appeared to point out difficulties in translating practice to pattern.

To our tool, this can mean two things. Either the collection of damage patterns is still inexhaustive, or, on the contrary, the descriptions of these patterns are so specific that users find it hard to distinguish between them. In both cases, we think it would first of all help to provide the decision tree with a more direct visual link to the damage patterns. This would allow users to directly see the consequences of choosing one option over another. Especially in a digital version of the tool, this improvement could be implemented fairly easily.

Relevance of provided information

A similar conclusion regarding difficulties in translating practice to pattern emerges from Figure 9.6, where the relevance of the provided information has been assessed. There, statement 4.e gained little approval: 3 out of 11 respondents did not agree with the statement that the examples shown in the tool belong to the damage pattern they were reviewing. As was the case in the previous subsection, this may point to a need for further subdividing the damage patterns, but it can also be explained as a call for the opposite. Further inquiries would be needed to get a definitive answer to this question.

About the relevance of the hypotheses and conditions, however, the participants are very positive, with 12 and 13 agreeing reactions, respectively. The only comment concerned the relevance of the hypothesis of overloading due to vibrations resulting from machinery or traffic, for pattern 49. The extent to which heavy traffic or machinery may cause structural damage is, in fact, disputed by experts. Further research may be needed to find a conclusive answer on the relevance of this specific hypothesis for this damage pattern.

Completeness of provided information

The fact that 3 out of 11 respondents did not agree with the hypothesis/es that the tool proposed for the damage case in their practice situation (question 6.g in Figure 9.6) seems to indicate a sense of incompleteness, rather than irrelevance, of the lists of hypotheses. This is confirmed by the responses to question 5.d in Figure 9.7, where also three persons did not agree with the statement that the list of hypotheses is complete. The same can be said for the conditions: those presented were considered relevant (6.d in Figure 9.6), but, at the same time, other options were missed (6.i in Figure 9.7).

Nevertheless, when evaluating the suggestions for completing the lists of hypotheses and conditions, most suggestions turned out to be based on misinterpretation of, or unclearness about, the distinction our tool makes between causes and conditions. Especially the term ‘soil movement’ appeared to have led to misunderstanding, so that we decided to replace it with ‘settlement’ throughout both thesis and tool. Apart from that, it was suggested to include (lack of) expansion joints as a hypothesis. Another respondent interpreted geometrical conditions as causes. These two examples point out the need to explain the background of the tool and its outline (including the distinction we make between context conditions and causes) to future users. For this information, users of the tool should be referred to this thesis.

In the context of validity of content, the response of one participant deserves particular attention, because he applied our tool to a case resulting from one of the sources on which it has been based. Interestingly, this participant reports that the features of the damage pattern do not correspond with that of the practice situation (question 4.i in Figure 9.3); and that the list of hypotheses is not complete (question 5.d in Figure 9.7). On the basis of this reaction, we have re-evaluated input and output for this specific case. It turned out that we classed the damage to which this participant refers under a different damage pattern than the ones in which he thought to find it. Main difference in interpretation seems to lie in the presence or absence of tapering along the crack; a symptom that is difficult to determine from a photograph. Perhaps our categorization is incorrect here.

The second remark has already been discussed in a previous paragraph: a lack of expansion joints was brought forward as missing hypothesis. However, we consider this to be a context condition, not a cause. In our opinion, the cause would be a hindered dimensional change, a category which in both damage patterns (with and without tapering) is already sufficiently covered.

Above situation may raise questions whether the translation from sources to tool has been executed carefully enough or that (too much) essential information got lost. This question can only be truly answered after a more extensive evaluation of the content of the tool by a panel of experts in the field.

9.4.4 Evaluation of helpfulness

Support offered by the structure of the tool

The helpfulness of the tool was generally regarded positively. None of the respondents disagreed with statement 7.b that using the tool structured their damage inspection (see Figure 9.8). This is a good result, which may at least partly compensate for the apparent elaborateness of the procedure.

Instructiveness of the tool

The instructiveness of the tool was deemed to be good, too, as the consistent set of responses in Figure 9.9 demonstrates. An improved understanding of context conditions was accounted for least widely. More background information about these context conditions, as provided in this thesis, may be beneficial.

Effectiveness of the tool

As explained in Section 9.1.1, this user test does not allow us to measure effectiveness objectively. Instead, we have to rely on the participants' perceptions. Figure 9.10 shows that 8 out of 14 respondents (57.1 %) agreed or strongly agreed that the tool gave them a broader view of the possible causes for the damage case in their practice situation, while only 2 (14.3 %) did not agree.

Similarly, 57.1 % confirmed that the tool gave them more confidence in their judgement on the cause of damage, although 4 of 14 (28.6 %) disagreed. This slightly less positive reaction implies that a broader view does not necessarily result in more confidence on the diagnosis – a result that is, actually, quite beneficial, since it may demonstrate that experienced users of our tool are indeed reminded of alternative explanations they had not explicitly considered yet.

Participant's interest in using the tool further

Finally, Figure 9.11 presents the responses to the question whether the participant would like to use our tool in his practice. Seven of ten respondents are positive, three not. Those persons not interested in using our tool further indicate different reasons. One thinks the tool is not useful for himself, since he has ample experience, but suggests he could use it as a check-list. We agree with this suggestion. Two other deemed the procedure too elaborate. As explained in Section 9.4.2, we expect that this barrier could be removed with the development of a digital version of the tool. One person, who did not answer question 7.h, considered himself not as a potential user, because he does not deal often enough with damages.

From these answers, we can conclude that at least two of these four participants think the tool is not so much suitable for themselves; however, they may recommend it to others. For instance, it was suggested that using our tool would chiefly be beneficial for inexperienced users (see Figure 9.10). With hindsight, we should have included a question on this issue in the inquiry form.

9.4.5 Evaluation of average scores per target group

The previous subsections have discussed the overall opinion per theme and subtheme, as presented in Figures 9.1 to 9.11. In doing so, each response has been given even weight. Still, opinion may depend on the target group to which a participant belongs. Not only would it be interesting to know this relation, it is also important, since over twice as many engineers and students participated than researchers and Monument Watch inspectors (see Table 9.3). In this final subsection of Section 9.4, we want to evaluate to what extent the opinion of one group of potential users may differ from the overall opinion.

The easiest way to compare the response of one group with that of another group is by showing average scores. However, this is not as straightforward as it may seem. The responses we obtained using Likert-type questions are ordinal data, not interval. Ordinal data only imply a ranking. In other words, one cannot assume that the respondents perceived the difference between ‘agree’ and ‘strongly agree’ the same as that between ‘agree’ and ‘neither agree nor disagree’. This is the reason why we have first presented all results in bar charts, see Figures 9.1 to 9.11.

Although, for the above reason, it is statistically seen incorrect to calculate average values for ordinal data, this has become common practice. We, too, have reverted to this approach, for it offers the most structured way to set off the opinion of a certain target group against that of the entry as a whole. The average scores shown in Table 9.7 have been calculated by replacing the five text labels - - to + + by the numbers 1 to 5. This implies that a score of 3.00 corresponds with a neutral answer, while lower scores are negative and higher scores are positive for our tool. Table 9.7 shows the average opinion per target group, and the total average score. Please note that this total score is the mean value of all individual respondents, and not the average of the scores for the four target groups.

The most striking observation to emerge from Table 9.7 is the marked difference between the scores resulting from the group of Monument Watch inspectors and the other three groups. Every single subtheme was valued less by the Monument Watch inspectors; all three main themes received a negative average score. Especially the effectiveness of the tool seems not to have been convincing enough for them. In line with this, they are not so much interested in using our tool in their practice.

For the other three target groups of engineers, researchers and students, the scores are much more positive; in fact, there is not a single score that drops below the neutral value of 3.00. Respondents belonging to these three groups appear to have been least satisfied about the ease of use. In particular, they did not so much agree with the statement that it was easy to put the instructions of use into practice. Simplifying the procedure could further increase their appreciation.

Interesting to note is also that both researchers and students appear highly content about the helpfulness of our tool. Their average scores for this theme are 4.10 and 4.05, respectively, which contrast sharply with the mean opinion of 2.38 that the Monument Watch inspectors gave. Since the group of engineering consultants is also fairly positive about the tool's helpfulness, we think we can rule out the participant's work experience as factor that may explain the difference between Monument Watch inspectors and the rest (see Table 9.4).

As has been signalized in Section 9.4.2, it was especially the group of Monument Watch inspectors that considered the tool to be laborious. We suspect that this is the main reason for their negative attitude: for them, the advantages of using our tool do not seem to outweigh the drawback of it being time-consuming.

Another reason may be that the Monument Watch inspectors feel that they are too experienced to benefit from our tool. As mentioned before, diagnosing during visual inspections lies at the heart of their work. The interpretation of damages is their personal decision, and they may not value the support of a tool in this process. However, as we have seen in Chapter 2, it is exactly their experience that can lead to bias. Our tool intends to by-pass this negative side-effect of experience, but the inspectors that participated in the user test have probably not been aware of this.

With this, we may well have pointed out the most important handicap that our tool suffers from: the paradoxical situation that surveyors who are unaware of the bias that is inherent to being an expert in the current method of diagnosing, are also unlikely to recognize the benefits using this tool can have. As one of the respondents puts it: "the tool … suffers from the problem that the people who might use it do not really need it, and those who need it have no idea of their inability."

From these results, it is clear that actions need to be taken if one does want to reach the specific target group of Monument Watch inspectors with our tool. We think it would, first of all, be necessary to prove that using our tool can lead to better results in diagnosing. In addition, we would recommend enlisting the help of members of this group in developing a version of the tool that is better tailored to their workflow.

9.5 Conclusions

In this chapter, we have put the product of this research project to test. A number of potential users was asked to use and evaluate our diagnostic decision support tool in a real-life setting. With their opinion, we wanted to find out whether our tool can indeed facilitate the formulation and ranking of hypotheses and, thus, support, simplify and improve the diagnosis of structural damage in masonry. Three themes have been evaluated in this user test: ease of use, validity of content, and helpfulness. The overall outcome was positive.

Four different target groups have participated in the user test. Interestingly, the group of Monument Watch inspectors was remarkably more sceptical about our tool in general, and about its effectiveness in particular, than the engineering consultants, researchers and students. This may partly be attributed to their feeling that the tool in its current set-up is too time-consuming. Moreover, we fear that the most important handicap our tool may suffer from is that surveyors are not all aware of the extent of the problem that our tool wants to tackle: that their experience makes them biased.

Based on the responses to our user test questionnaire, two important improvements have already been implemented in the edition of the tool that is supplied with this thesis. Firstly, the instructions of use have been extended. Secondly, the term 'soil movement' has been replaced with 'settlement' throughout thesis and tool.

From the responses, we can conclude that efforts to further improve our tool should follow two parallel paths. On one hand, simplifying the procedure of using the tool would be much appreciated. Work in this direction should particularly focus on:

- Developing a Dutch-language version;
- Providing further guidance on the transition from practice situation to damage pattern;
- Improving the presentation of essential conditions, especially for settlement; and
- Providing access from the tool to background information, as is currently contained in this thesis.

We expect that developing a digital version of our tool (which can be used parallel to a paper edition) could substantially improve the ease of use, as it would allow for further tailoring of the provided information to the user's input. In addition, it would be possible to integrate a survey form, so that using the tool could reduce administrative work. Nevertheless, one should take care that the user remains in charge, and can keep the overview: the tool should remain a support system, not a diagnostic 'black box' solution. Ideally, representatives from the target groups should be involved in such developments.

On the other hand, we would recommend having the tool's effectiveness determined in a more objective way. In Section 9.2.3, it has already been stated that the relatively small number of participants does not allow drawing statistically significant conclusions representative for the whole target population. This user test should, therefore, rather be seen as a pilot test. After implementing above suggestions for improvement, our tool should be tested further.

We would recommend to not just carry out this user test at a larger scale, but also to ask a panel of experts to evaluate and approve the tool's content in detail. With the help of these experts, it may even be possible to include directions for further investigations (if necessary with using more sophisticated equipment) that can help distinguishing between the likely hypotheses for a pattern and reach a final diagnosis. The panel could also suggest a set of damage cases, with diagnosis. By having both a test and a control group surveying these predetermined cases, as explained in Section 9.1.1, it will be possible to objectively determine the tool's effectiveness.

Chapter 10

Conclusions and recommendations

In the previous chapter, our diagnostic tool for structural damage in masonry has been tested and evaluated. With that, we have come to the end of this PhD research project. To conclude, this chapter will evaluate the scientific and societal relevance of this project.

The outline of Chapter 10 is as follows. In the first section, we will summarize the main scientific findings of the study. Section 10.2 will discuss its practical implications. Subsequently, in Section 10.3, recommendations will be provided for further research in the field of building pathology, after which we will conclude this thesis with some final remarks.

10.1 Scientific findings

A sound diagnosis is indispensable for a proper assessment and treatment of damage. Especially with regard to structural damage, correctly establishing the underlying cause can be difficult. This research project has been aimed to improve and facilitate the process of diagnosing structural damage in traditional (loadbearing, solid, unreinforced) masonry. While the main focus has been on the Netherlands, and specific attention has been paid to historical buildings, the results are expected to allow use in a broader context.

An analysis of current diagnostic approaches and recent attempts for improvement made us focus on the initial phase of the diagnostic process, in which hypotheses are formulated and ranked. It appeared that the interpretation of damage tends to rely heavily on personal experience, and that this entails a risk of bias. To try and overcome this bias in interpreting structural damage, we have concentrated on two questions: Which symptoms and context conditions are essential for establishing a correct diagnosis? And what clues do they actually provide?

Departing from the idea that the symptoms and context of a damage should be sufficient to deduce its cause, we have developed a diagnostic decision support tool that should help users in correctly interpreting structural damage. The tool is based on the collective experience of many experts, which has been deduced from publications. All information derived from literature has been restructured and its value for diagnosing has been examined. Potential users have tested our tool in a real-life setting, evaluated its merits and suggested points for improvement.

The consecutive steps completed in this research project have led us to a number of findings. In the following subsections, these will be summarized and commented on. First, we will recapitulate our answers to the research questions that were formulated in Chapter 1. Then, our other conclusions will be discussed.

10.1.1 Research questions revisited

In Section 1.2, the objectives of this research project have been outlined. The main research question set out to address here was to what extent structural damage in masonry in the Netherlands can be diagnosed from its symptoms and context. This main question was divided into six subquestions. Below, we will first answer these subquestions, and then the main question.

What causes lead to structural damage in masonry in the Netherlands?

With a study of literature and, in particular, a review of more than 500 diagnosed cases included in this literature, we have collected typical causes of structural damage in masonry. To create a clear and useful overview, these causes needed to be grouped in a logical way. As no standard, unambiguous classification was available yet, we have proposed a new, systematic approach to describing causes of structural damage. In this approach, all structural damages are seen as the result of a change in force equilibrium. Consequently, the cause of the damage is a change, either in time or in place, that unbalances the equilibrium. This basic principle allows for a consistent description of causes of structural damage in masonry.

To further structure the causes, we have introduced a classification based on scale level. Three main categories have been discerned: settlement, which concerns the interaction between building and soil; overloading, which occurs at the level of the building; and hindered dimensional changes, which refer to changes between individual building parts. For each of these categories, we have described the course of the damage process, and the variants in which they occur. These subdivisions have been confined to a level of detail that is helpful in the initial phase of diagnosing.

What are the symptoms of structural damage in masonry in the Netherlands?

Using the same literature and cases, we have created an overview of important symptoms of structural damage in masonry. As for the causes, also for the symptoms a consistent classification was lacking. Here, too, we have developed a categorization that is suitable for visual inspection.

We think the best way to approach damage is by decomposing it into separate symptoms. We have defined a set of clear, consistent and recognizable basic symptoms that allow one to specify structural damage. Besides the main types of failure (crack, deformation or tilt), important damage characteristics are direction of displacement, variations in displacement and symmetry.

What context conditions influence the occurrence and the development of structural damage in masonry in the Netherlands?

From the same set of diagnosed cases, we have collected context conditions. Context conditions are factors that influence structural damage processes: they affect the course of such a process, or the extent of its effects. In other words, their presence or absence can determine if and how structural damage develops.

We have organized these context conditions into four categories. Three are based on scale level: material, geometrical and environmental conditions. The fourth group of factors is related to time. With an eye to applicability during visual inspections, only conditions that are both easy to assess and informative have been selected.

In what way can the above-defined symptoms be used to diagnose structural damage in masonry?

Using principles of applied mechanics, we have analyzed what symptoms of structural damage may tell us about their origin. Starting point for this evaluation has been that all structural damage is, in fact, a deviation in shape caused by loading. Hence, to interpret damage in relation to its cause, one needs to trace back the load, or, to be more precise, stress state, from this deviation. In doing so, one may need to make assumptions on the original shape, which we have explicated, too.

From our analysis, it has become clear that many of the symptoms that are frequently used in nowadays publications are indeed easy to identify visually and, as such, very suitable to describe damage; however, that these symptoms are not very explanatory about the underlying cause. The direction of a crack, for instance, says little about its origin.

The main information one can obtain from interpreting symptoms of structural damage is the direction of (relative) movement that a building part has undergone. For deformations and tilts, this interpretation is rather straightforward. For cracks, numerical and small-scale physical tests have demonstrated that the tapering offers the best starting point to establish the relative movements that have occurred over a crack.

In what way can the above-defined context conditions be used to diagnose structural damage in masonry?

The analysis of damage cases has shown that there are two ways in which context conditions can be used profitably in the diagnostic process: either they can be applied to specify a certain damage; or they can be utilized to trace back its cause. In the latter case, it is usually the absence of a condition that helps to refute a hypothesis.

Unfortunately, context conditions can also directly influence the appearance of a damage. Especially in settlement processes, this direct influence can be quite substantial, as numerical and small-scale physical tests have shown. For example, it has been demonstrated that material properties can have a considerable effect on the appearance of damage, since these properties make the difference between deformations and cracks. This implies that the occurrence of a crack instead of a deformation does, in itself, give no clue about the cause of damage. For diagnosing, this is an unfavourable situation, since symptoms and context will provide fewer indications of the cause of damage.

To what extent can insight into the relations between symptoms, contexts and causes of structural damage in masonry improve its diagnosis?

Sound diagnostic decisions are based on insight into the relations between causes, effects and circumstances. After studying causes, symptoms and context conditions separately, we have examined how they relate. Most relations have been determined using literature and principles of applied mechanics. Some have been investigated further using numerical and small-scale physical tests.

We have laid down the relations between symptoms and context conditions in 60 characteristic damage patterns: typical presentations of structural damage in masonry, composed of the most recognizable and informative symptoms and context conditions. For each pattern, the causes possibly underlying it have been indicated. Subsequently, distinguishing conditions that allow one to discriminate between different causes for one pattern have been added.

Above relations between symptoms, contexts and causes of structural damage in masonry constitute the core of the diagnostic tool we have created. Although the effectiveness of this tool could not be determined objectively yet, we did ask participants of a user test for their opinion. The results are promising: a majority of the testees was positive about the helpfulness of the tool. This consolidates our research hypothesis that increased insight into the relations between causes, symptoms and context conditions can indeed improve the diagnosis of structural damage in masonry.

Main research question: the extent to which structural damage in masonry can be diagnosed from its symptoms and context

This research project aimed to determine those symptoms and context conditions that are essential and sufficient for diagnosing structural damage in masonry. By combining these symptoms and context conditions in characteristic damage patterns, and by linking them to causes, we have created a diagnostic tool. In theory, this tool could allow one to reach a sound hypothesis during an initial visual inspection.

Whether this theory can stand up in practice, has been assessed in a user test. In this test, potential users have applied our tool to a damage case from their practice, and evaluated the tool on ease of use, validity of content and helpfulness. The overall outcome of this user test was positive, and the general approach on which the tool has been based was not questioned. From this, we may conclude that the participants agree with our approach in which a visual inspection of symptoms and material, geometrical, environmental and time-related context conditions is given a prominent role in diagnosing.

Evaluating the research project in its entirety, we can conclude that our research hypothesis has proved to be true to an important extent. Symptoms and context conditions are indeed often sufficient to deduce the cause of damage. Whether this is the case for a specific damage depends, however, on the extent to which the appearance of this damage is determined by its cause, or by its context.

The stronger a damage pattern has been influenced by its cause, the easier it generally is to read this cause from the damage. If, however, context conditions have played a more influential role, the appearance of damage may tell more about the context than about its cause. Diagnosing just on the basis of symptoms will then be more difficult. Nevertheless, the context may in those cases still be used to assess the probability of certain damage processes to have occurred.

Summarizing, a visual inspection of symptoms and context conditions is not always sufficient to establish a sound diagnosis; however, if interpreted correctly, symptoms and context can help narrow down the hypotheses substantially. Although additional investigations may still be needed to reach a final diagnosis, our tool can be a great support in the diagnostic process.

10.1.2 Other findings

Beside answers to the research questions, this PhD project has also resulted in additional findings. These findings can be clustered around three themes: knowledge exchange, the need for a consistent terminology, and the dangers of bias. These themes will be discussed here successively.

Knowledge exchange

Although this study has aimed at deepening the knowledge available in the field of building pathology, we have focused on the existing information concerning structural damage in masonry. We found this information to be highly fragmented and often seemingly contradictory. Our principal mission has been to combine and structure this information, so that it can be transferred and its merits for diagnosing assessed objectively.

Current knowledge in the field of building pathology has, for the greater part, directly been derived from practice situations. As a result, it is highly personal. With our expert questionnaire, we have demonstrated that each expert uses his own version of this knowledge, which is based on the practical and theoretical experiences of this person alone.

In this study, we have sought to translate a selection of these implicit, personal experiences into explicit knowledge. By combining all information and establishing it in an unambiguous way, we wanted to make it transferable. Moreover, we hope that this will open the knowledge to verification and improvement, and will invite to deliberations and debate.

Our set of damage patterns, for example, combines the experience of many (recognized) experts in the field of building pathology, using only those cases that these experts were sure enough about to publish. In this way, our patterns should suffer less from the drawbacks that are inherent to the implicit damage patterns used in traditional pattern recognition. As criticized in Chapter 2, these implicit patterns are mostly unverified and unverifiable, since they only exist in the mind of the surveyor in question. Our explicit damage patterns are meant to replace and complete the personal ones.

One final remark should be made in this context. During this study, it has struck us that problems in building industry are rarely reported by those in charge. Only very few experts have had the courage to not only elaborate upon their successes, but to also contemplate on failures. Still, exactly these failures or near misses can be very instructive. In our opinion, exchange of this kind of experiences should be stimulated.

The importance of this issue has been emphasized in a recent paper of Bussell and Jones [2010]. In this paper, the consequences of the partial collapse of the Ronan Point block of flats in 1968 have been examined – not only for the building in question and its inhabitants, but also for construction industry and building regulations. Bussell and Jones remark:

"There is a concern that the construction industry's memory is too short. Although we learn from experience gained while active in the industry, passing this experience on is more difficult. It is therefore essential that those with experience gained from the investigation of key failures within the industry are encouraged to relay this to the next generation, albeit in the context of modern construction practice."

In the United Kingdom, the Standing Committee on Structural Safety (SCOSS) has gathered information from general sources on structural failures and incidents since 1976. More recently, in 2005, the programme Confidential Reporting on Structural Safety (CROSS) was launched, following the US Aviation Safety Reporting System (ASRS) developed by NASA. CROSS is supplementary to SCOSS. It functions in a more direct way, as a platform for sharing information on failures and potential failures, with the purpose to learn from the experiences of others [Soane 2008]. Dutch construction industry has started a similar initiative, the *Platform Constructieve Veiligheid* (Platform Structural Safety), at the end of 2009. Hopefully, this leads to better exchange of information on structural damage.

Summarizing, building industry tends to solve problems at an ad hoc basis. But its people can do better than that. Sharing information would be an important step forward towards defining a system of best practices.

Consistent terminology

To allow for knowledge exchange, one important condition should be fulfilled: people must use the same vocabulary to be able to communicate unambiguously. In this study, it has been shown that such a consistent terminology is lacking in the field of building pathology. For describing damages as well as causes, various approaches are followed. The illustrated glossary on stone deterioration patterns as published by ICOMOS-ISCS [2008] gives an overview of the divergent, overlapping and sometimes confusing terms that are currently used in practice.

We have tried to overcome this obstacle in knowledge exchange by describing damages and their occurrence in a new way. Our method differs from existing approaches in two respects. First of all, we have made a clear and consistent distinction between causes, symptoms and context conditions. Secondly, we have structured the individual components on scale level. These are the basic assumptions for the damage mechanism concept, which we have developed and used throughout this project to structure the research data as well as our thoughts. In creating the diagnostic tool, this concept has proved to be practicable.

In addition to this, we have uniformized the definitions of causes, symptoms and context conditions by analysing them from a mechanics point of view. Symptoms of structural damage have first been related to types of loading, before linking them to specific, concrete causes. In this way, we hope to have reduced the adverse effects of bias.

A consistent terminology will not solve all basic problems in knowledge exchange. It is, for example, still hard to make an unambiguous overview of causes of structural damage. There will always be room for discussion, if only because damages can be considered either as a shortcoming of a building, or as the result of an unforeseen incident.

Nevertheless, we are convinced that the terminology proposed in this thesis, and the approach on which it has been based, form a solid starting point for further developments. The tool has already proved to be a helping hand in communication between parties: in a vivid discussion between the author and one of the participants of the user test, our tool functioned as a reference for both damage patterns and their interpretation. In a similar way, the tool could support a clear communication in discussions between specialists and surveyors.

Dangers of bias

A third important theme within this research project is bias. It has been shown that the current diagnostic process depends for a large part on pattern recognition. The more experienced a person is, the easier pattern recognition may seem to go – but this experience also entails a risk: bias. This study has aimed to help reduce bias in the diagnosis of structural damage by making the process of pattern recognition more explicit: using our tool should reduce scatter and increase objectivity in diagnosing.

The products of this study, a thesis and a tool, differ from handbooks on diagnosing damage as available so far. Most of those handbooks have been written by authors who look back at a long working life and a large experience in assessing structural defects which this PhD candidate has not yet gained. We think this seemingly lack of experience has allowed us to follow a relatively uninhibited approach towards describing, systematizing and interpreting structural damage in masonry.

Bias is inherent to how humans function and, as such, it is not confined to the field of building pathology. Three studies in different domains, published in the course of this PhD project, are particularly interesting to mention here. They may put the basic assumptions of this project in a different light and, by doing so, also our interpretation of our results.

The first study, written by Derksen [2010], concerns the legal field, and deals with common shortcomings in the process of establishing the truth in criminal law. Both the mechanisms that underlie these shortcomings, such as tunnel vision, and the dangers it may involve are discussed. Derksen wrote the book in reaction to a miscarriage of justice that received much attention in the Netherlands between 2001 and 2010. In the case in question, conviction of the suspect had been based on an incorrect interpretation of probability and coincidence statistics. While the initial trial assumed that several murders had been committed, at the ultimate verdict of the court of justice it turned out that in these alleged murder cases there was no prove of any criminal offence at all: the supposed victims had probably died a natural death.

For our research, this case and the publication of Derksen are of interest, because they demonstrate that the different types of bias we came across in the expert questionnaire do not stand alone. A series of innate cognitive deficits is discussed in Derksen's book: the tendency of people to see causal links, the impulse to interpret other people's behaviour as continuously intentional, and the 'deafness' to series of coincidences. These are all typically human instincts, which are extremely useful from an evolutionary point of view. However, one should note that they can have serious consequences when adopted outside daily routines, for example in court.

Derksen argues that the process of establishing the truth is always linked to a theory and, therefore, bias is an inevitable part of this process. The only way to overcome this bias is by consciously introducing an alternative theory in opposition to the first one. In building pathology, this has been recognized by Cook and Hinks [1992], who state that: "It is important not to allow the suggestion of a possible defect to dictate the objective analysis of all symptoms." Our tool tries to realize this goal by enumerating, for each damage pattern, all alternative hypotheses.

The second study originates from the medical discipline, and it regards the prevention of unnecessary mistakes in routine actions. Building on international researches, the Academic Medical Centre of the University of Amsterdam has designed a comprehensive, multidisciplinary check-list that follows the surgical pathway from admission to discharge of a patient. This Surgical Patient Safety System (SURPASS) covers all checks that should be done before, during and after operating upon a patient.

Implementation of this check-list in six hospitals with high standards of care led to a decrease in complications from 27.3 % to 16.7 %, and a decrease of in-hospital mortality from 1.5 % to 0.8 % [de Vries et al. 2010]. These results show that consciously focusing on what one is doing can indeed prevent errors creeping into routine acts, and that this prevention of small mistakes can have a substantial impact, especially when human lives are involved. By providing a blueprint of the ideal situation, SURPASS is thought to reveal safety risks and to trigger improvements in all stages of the surgical pathway. Our diagnostic tool should be able to function in a similar way.

Despite the foregoing, one should not forget that the instincts out of which bias can arise usually work to a person's advantage. The third study, from Stolper et al. [2009], does also concern the medical field. With a qualitative research including four focus group discussions, it has assessed the diagnostic role of gut feelings in general practice in the Netherlands. From this study, it appears that general practitioners use these gut feelings, being either a sense of alarm or a sense of reassurance, as a kind of compass in uncertain and difficult situations.

Stolper et al. attribute the source of these gut feelings to pattern recognition. They point out that the method of working of Dutch general practitioners is essential for developing (helpful) gut feelings. In the Netherlands, general practitioners usually follow their patients over many years. As a result, they tend to know a lot about their history and background.

Noticeable is the conclusion of Stolper et al. that pattern recognition is not so much used for establishing a diagnosis, but rather for coming to a prognosis or intervention. They state: "Pattern recognition seems an important mechanism to explain the gut feelings that arise. (…) In contrast to what is claimed in literature on diagnostic reasoning, the pattern of signs and symptoms does not always fit in and does not give rise to a diagnosis, but to a prognosis and/or intervention. The prognosis is then not a specific prediction of the course of a disease but rather a general feeling that action is required."

Above remark seems to imply that a diagnosis is not always indispensable for selecting a treatment. In the medical field, this may indeed partly be the case. For many of the most frequent complaints (headache, stomachache) diagnoses tend to be a description of the symptom instead of a description of the cause, simply because the cause is not known. In that case, treatment is also focussed on alleviating the symptoms, rather than on removing the cause. This procedure may also work for certain structural causes – especially when the situation has stabilized and damage does not increase.

Apart from that, it is also interesting to mention that both Stolper et al. and the members of their focus groups are very positive about using their gut feelings. Would the positive effects counterbalance the negative effects of bias? In our opinion, this asks for further research.

10.2 Practical implications

Apart from the scientific findings, this research project has also resulted in a practical outcome: an operational diagnostic decision support tool. From this practical point of view, the thesis can be seen as supplementary: it provides background information on the topics considered in the tool.

We expect that using our tool will lead to a more efficient and effective diagnostic process for assessing structural damage in existing masonry buildings. Three particular effects have been aimed at:

- Reducing bias and subjectivity;
- Facilitating communication on structural damage; and
- Improving the exchange of knowledge on building pathology.

With that, the societal relevance we had in mind should be achieved.

In Section 3.1, we listed the criteria that our diagnostic tool should address. These criteria concerned both the content of the tool and the access to this content. We will now evaluate to what extent these conditions have been fulfilled.

With regard to the content, we started from the idea that our tool should include information on three sets of components: the symptoms, context conditions and possible causes of structural damage in masonry. Furthermore, it needed to specify the relations between each of these components. Additional criteria concerned the inclusion of both common and less common causes of damage, and the incorporation of feedback on tests for distinguishing between alternative hypotheses. Finally, it was argued that the descriptions of symptoms should not preclude assumptions on the cause of damage, since this may arouse or reinforce bias and prevent surveyors from noticing alternative explanations. All these aspects have been secured in Chapters 4 to 8 of this thesis.

Recapitulating the criteria related to the access to this content, our diagnostic tool was intended to provide a broad overview of structural damage and its causes in a general picture; to enable insight into structural damage and its causes in detailed descriptions; to be practical and easy to use; and to keep the user in charge. To pave the way for successful implementation, it was added that the tool should be comprehensive, verifiable and supportive. These items have been evaluated, partly directly, partly indirectly, in the user test. The positive outcome of this test demonstrates that our tool adequately satisfies these criteria. Further improvements to the tool have been suggested in Section 9.5.

As regards comprehensiveness, we want to make an additional remark. This thesis has already shown that knowledge in the field of building pathology is not static: it is in ongoing development. As a result, to keep a diagnostic system up-to-date, it should be flexible enough to allow for adjustments and extensions.

To facilitate open discussions and jointly accomplished improvements, we have decided to license both this thesis and our diagnostic tool under the Creative Commons Attribution-Noncommercial-Share Alike 3.0 Netherlands License. This licence allows people to copy, distribute and transmit the work, and to adapt the work, as long as they attribute the work correctly, they do no use it for commercial purposes, and they distribute the resulting work under the same or a similar licence to this one. More information can be found on the webpage about this licence [Creative Commons 2010]. Please note that the pictures we have reproduced from other publications remain protected according to the 'normal' copyrights, the conditions of which can be found in the respective books.

We anticipate that, after carrying through the recommendations brought forward in Section 9.5, our diagnostic tool will be ready for introduction in practice. The target groups we have in mind are broad. The tool can function as a guideline for novices in the field of building pathology, to structure their approach to damage. For experts, it could serve more as a check-list, reducing bias and keeping them aware of alternative explanations. Moreover, the tool can be helpful as a reference for all parties involved in the maintenance of (historical) masonry buildings, by equipping them with a clear, unambiguous terminology regarding structural damage in masonry. We are convinced that using our tool will stimulate surveyors to approach damage with an open mind, explicitly and systematically checking facts.

10.3 Recommendations

This research project has answered a number of questions; however, it also raises new ones. Based on the present work, we can make some recommendations on the directions in which development would be welcomed from a scientific or societal point of view. We distinguish three main themes.

First of all, we would suggest undertaking further studies on damage mechanisms. As indicated in Section 1.3, some aspects of the structural behaviour of masonry are not so well understood yet (e.g. creep). Moreover, the influence that specific causes and particular context conditions have on the appearance of structural damage asks for more study. In our project, this type of study has been performed using numerical and small-scale physical tests. As these parameter studies are time-consuming, we had to limit ourselves to settlement processes. However, the results have been extremely useful for developing the diagnostic tool. We expect that further work in this direction can augment insight into the occurrence of structural damage.

Secondly, we think that widening the scope of this research would be fruitful. Especially integrating the structural behaviour of other building materials in the tool should be considered. Not only would this fit in better with the practice of surveyors, it would also do more justice to the phenomenon that different building materials, when combined, can induce structural damage processes.

Our tool has been developed with a view to the Dutch situation. Nevertheless, the literature we used originated from a much wider area. Since especially sources from north-western Europe (United Kingdom, Germany) were well represented, we anticipate that our tool could be applied profitably in these neighbouring countries, as well. Still, to avoid issues, it would be good to have the tool evaluated by local experts first. In addition, it may be good to include a multilingual lexicon for the key terms, so that a consistent terminology can ease communication and knowledge exchange.

Our third recommendation concerns the digitization of our tool. We expect that a digital version would be easier to use, while at the same time more background information could be provided to users. Implementation of our work in MDDS would be a logical next step, since their contents would complement each other well.

If work in this direction is undertaken, which we would applaud, we would advocate investigating the possibility of including probabilistic data on the incidence of damages. In our diagnostic tool, inferring has currently been based on logical chaining of if-then rules. This implies that certainty in the relationships among observations and causes is assumed. However, in complex real-life systems, this assumption of determinism between observation and causes is typically invalid [Plantamura et al. 1994]. There are several ways to deal with uncertainty, such as inexact reasoning, the Bayesian approach, or fuzzy logic. Further research should be done to examine whether such approaches could be beneficial for a diagnostic decision support system for buildings. If so, it will also be necessary to collect more statistical information from damage assessments, for example on the prevalence of certain causes. This type of information, which has shown its value in the medical field, is not commonly available in the field of building pathology yet.

Finally, we want to state that it is our express intention that the information contained in our tool will be further assessed, corrected and completed by professionals working in the field of building pathology. In this way, we hope this research project can serve as a starting point for further improvements in the diagnosis of structural damage in masonry.

10.4 Final conclusions

This PhD research project has resulted in a diagnostic decision support tool for structural damage in masonry. As a tool, it is not infallible, or even indisputable. Engineering judgement is always needed when using this type of aid. Moreover, as many experts in the field of building pathology have argued before, the two most important pieces of equipment a surveyor should bring to a visual inspection are “a pair of open eyes and an open mind” [Beckmann and Bowles 2004].

Our tool is a proposal, bringing together practical knowledge and scientific findings. In fact, part of the originality of this study lies in its multidisciplinarity, combining knowledge from the field of mechanics with that of the field of restoration. In the mean time, it has also crossed borders with the field of diagnostics in medicine, which is ahead of the building diagnostics discipline.

The main aim of our tool is to raise a discussion among people involved in the maintenance of buildings. By gaining more explicit knowledge, building pathology can keep up with current developments in health care, where emphasis more and more shifts from experience-based towards evidence-based practice. Reaching a consensus on the diagnosis of specific damages will open the way to mitigation of these damages and to improvements in interventions.

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Definitions of key terms

Cause	That which produces an effect; that which gives rise to any action, phenomenon or condition. Definition derived from the Oxford English Dictionary [OED Online 2010a].
Context condition	Each of the concurring (material, geometrical, environmental or time-related) circumstances in which a damage appears (adopted from OED Online [2010b]. Context conditions may influence the occurrence of damage in a prerequisite or contributory way. If a condition is prerequisite, the damage process will not take place without its presence. If a condition is only contributory, its presence affects the rate at which the damage process occurs or the extent of damage to which the process leads.
Crack pattern	A characteristic combination of cracks with different crack directions.
Damage	Physical injury to a thing, such as impairs its value or usefulness (adopted from OED Online [2010c]). Damage is the perceptible manifestation of a defect.
Damage mechanism	The combination of a damage process and the context conditions influencing this process.
Damage pattern	A characteristic damage presentation, composed of a typical combination of symptoms and context conditions.
Damage process	A sequence of steps or events, starting from the cause and leading to damage.
Defect	A shortcoming or failing; a fault, blemish, flaw, imperfection [OED Online 2010d]. A building has a defect when it can not, or no longer, meet the demands it should implicitly or explicitly satisfy. This defect is shown as damage.
Diagnosis	Identification of a disease or damage by careful investigation of its symptoms and history; also, the opinion (formally stated) resulting

	from such investigation (adopted from OED Online [2010e]). A diagnosis can give insight into how a damage has occurred, how severe the present situation is and what is to be expected in the future.
Extrados	The upper or exterior curve of an arch [OED Online 2010f].
Hypothesis	A provisional supposition, for example on the cause of damage, put forth to account for known facts, which serves as a starting-point for further investigation by which it may be proved or disproved (adopted from OED Online [2010g]).
Intrados	The lower or interior curve of an arch [OED Online 2010h].
Structural damage	In this thesis: all damage that appears to manifest a lack of strength, stiffness or stability, by showing crack development, deformation or tilt. It differs from other kinds of damage because it may not only affect aesthetic or functional demands, but may also endanger the physical safety of people.
Symptom	A characteristic sign (phenomenon, circumstance, change of condition) of some particular disease or defect, accompanying this disease or defect and constituting an indication or evidence of it (adopted from OED Online [2010i]). A symptom is an individual characteristic of the damage itself. The three main symptoms of structural damage are crack development, deformation and tilt.

Notation

Symbol	Designation	Unit
E	Young's modulus, modulus of elasticity in tension and compression	N/m^2
f_c	compressive strength	N/m^2
f_t	tensile strength	N/m^2
G^I_f	mode-I tensile fracture energy	$N.m/m^2$
g	gravitational acceleration	m/s^2
h	crack band width of an element in DIANA	m
H	relative height of wall (i.e. uninterrupted by openings)	m
I_z	moment of inertia of a cross-section, with respect to the z-axis	m^4
k_n	normal interface stiffness	N/m^3
k_t	tangential interface stiffness	N/m^3
ℓ	length	m
L	length of settlement trough below building	m
M_L	magnitude of an earthquake on the Richter scale	-
$\vec{s}$	crack size	m
$u_{y;n}$	vertical displacement at node *n*	m
x_n	horizontal distance of node *n* to the left end of the model	m
w	crack width	m
α	thermal expansion coefficient	$°C^{-1}$
Δu_n	change in displacement in normal direction	m
Δu_t	change in displacement in tangential direction	m
ε	strain	-
ε_{ft}	strain of an element at tensile strength	-
ε_u	ultimate strain	-
ν	Poisson's ratio	-
ρ	density	kg/m^3
σ	normal stress	N/m^2
σ_1	maximum principal stress	N/m^2
σ_2	minimum principal stress	N/m^2
τ	shear stress	N/m^2

Appendix A

Table A: Standard investigation tools for on-site inspections, categorized by their application

Instrument, tool, or aid	**Recording data**	**Visual inspection**	**Measuring dimensions**	**Measuring conditions**	**Monitoring**	**Opening up a construction**	**Taking samples**	**Additional and safety aids**	**Consulted sources**
Photo camera, with flashlight, wide angle lens, telephoto lens	■	·	·	·	·	·	·	·	a, b, c, d, e, g, h, j, k, l, n
Notebook	■	·	·	·	·	·	·	·	a, b, d, e, h, k, l, n
Clipboard, with clear plastic flip-sheet	■	·	·	·	·	·	·	·	a, b, c, e, g, l, n
Coloured pens or pencils, eraser, sharpener, spare leads	■	·	·	·	·	·	·	·	a, b, c, e, k, l, n
Dictaphone	■	·	·	·	·	·	·	·	a, b, c, d, g, n
Video camera	■	·	·	·	·	·	·	·	a, b
Ruler	■	·	·	·	·	·	·	·	a, l
Colour reference card	■	·	·	·	·	·	·	·	g
Laptop computer	■	·	·	·	·	·	·	·	n
Prints of drawings or photo-mosaics	■	·	·	·	·	·	·	·	n
Magnifying glass	-	■	·	·	·	·	·	·	a, b, c, d, e, g, i, j, n
Torch	-	■	·	·	·	·	·	·	a, b, c, e, g, j, k, l, m
Ladder	-	■	·	·	·	·	·	·	b, c, e, g, h, k, l, n
Binoculars, f.e. 7 x 40, 7 x 50	-	■	·	·	·	·	·	·	a, b, c, d, e, j, n
Borescope	-	■	·	·	·	·	·	·	a, b, c, g, j, k, n
Mirror, with telescopic handle	-	■	·	·	·	·	·	·	a, b, c, e, k
Mobile access tower	-	■	·	·	·	·	·	·	b, h, n
Scaffolding	-	■	·	·	·	·	·	·	j, n
Plumb line, theodolite, with eyepiece prism	-	·	■	·	·	·	·	·	a, b, c, e, g, h, j, l
Tape measure, digital laser distancemeter	-	·	■	·	·	·	·	·	b, c, e, g, h, l, n
Crack width gauge	-	·	■	·	·	·	·	·	a, b, g, h, i
Calliper gauge	-	·	■	·	·	·	·	·	a, c, h, n
Cover meter	-	·	■	·	·	·	·	·	a, c, d
Right angle prism	-	·	■	·	·	·	·	·	j
Level, self levelling rotating level laser	-	·	■	■	·	·	·	·	a, b, c, e, g, h, j, l
Moisture meter	-	·	·	■	·	·	·	·	a, c, d, e, k
Compass	-	·	·	■	·	·	·	·	a, c, g, l
Thermometer	-	·	·	■	·	·	·	·	a, c, g, k
Hygrometer	-	·	·	■	·	·	·	·	a, c, g
Metal detector	-	·	·	■	·	·	·	·	c, d
Infrared thermography camera	-	·	·	■	·	·	·	·	g
Infrared thermometer	-	·	·	■	·	·	·	·	a
Leak finder	-	·	·	■	·	·	·	·	c
pH test strips, with distilled water	-	·	·	■	·	·	·	·	n
Salt detector	-	·	·	■	·	·	·	·	a
Temperature and relative humidity recorder	-	·	·	■	■	·	·	·	a, b, f, g, h
Tell tale	-	·	·	·	■	·	·	·	b, c, d, e, f, g, h, i, j, n
Extensometer	-	·	·	·	■	·	·	·	b, e, f, g, h, i, n
Datum points, for repeated measurements	-	·	·	·	■	·	·	·	b, d, j
Vibration transducer	-	·	·	·	■	·	·	·	j
Hammer, with cold chisel	-	·	·	·	·	■	·	·	a, c, e, g, j, k, l, n
Screwdriver, with impact-resistant handle	-	·	·	·	·	■	·	·	a, b, c, e, k, l, n

Table A (continued)

Instrument, tool, or aid	**Recording data**	**Visual inspection**	**Measuring dimensions**	**Measuring conditions**	**Monitoring**	**Opening up a construction**	**Taking samples**	**Additional and safety aids**	**Consulted sources**
Crowbar	-	·	·	·	·	■	·	·	c, e, k, n
Pliers, with cutters	-	·	·	·	·	■	·	·	a, n
Bolster	-	·	·	·	·	■	·	·	k
Chisel	-	·	·	·	·	■	·	·	k
Dustpan and brush	-	·	·	·	·	■	·	·	g
Saw	-	·	·	·	·	■	·	·	k
Sheet metal shear	-	·	·	·	·	■	·	·	n
Pocketknife	-	·	·	·	·	■	■	·	a, b, c, e, k, n
Power drill	-	·	·	·	·	■	■	·	a, c, k
Diamond or carborundum sawing and drilling	-	·	·	·	·	■	■	·	a
Air-tight, sealable sample bags	-	·	·	·	·	·	■	·	c, d, e, k, n
Labels to mark photographed objects and samples	-	·	·	·	·	·	·	■	a, b, c, n
Overall	-	·	·	·	·	·	·	■	b, c, e, k
Safety boots	-	·	·	·	·	·	·	■	b, c, m
Safety glasses	-	·	·	·	·	·	·	■	c, l, m
Safety helmet	-	·	·	·	·	·	·	■	b, c, m
Spare light bulbs, for torch, borescope, flash	-	·	·	·	·	·	·	■	b, c, k
Tripod, with cable release	-	·	·	·	·	·	·	■	b, g, l
Adhesive material for temporary fixing	-	·	·	·	·	·	·	■	a, l
Companion surveyor, assistant	-	·	·	·	·	·	·	■	b, e
Ear muffs	-	·	·	·	·	·	·	■	c, m
Face mask	-	·	·	·	·	·	·	■	c, m
Mobile phone	-	·	·	·	·	·	·	■	b, m
Spare batteries	-	·	·	·	·	·	·	■	b, k
Tissues, towel and soap	-	·	·	·	·	·	·	■	b, e
Work gloves	-	·	·	·	·	·	·	■	l, m
Bag	-	·	·	·	·	·	·	■	n
Cable reel	-	·	·	·	·	·	·	■	l
First aid kit	-	·	·	·	·	·	·	■	k
Gum boots, waders	-	·	·	·	·	·	·	■	e
High-visibility over-jacket vest	-	·	·	·	·	·	·	■	c
Safety belt, safety harness, with lanyard, catches	-	·	·	·	·	·	·	■	n
Spare films for camera	-	·	·	·	·	·	·	■	n
Umbrella	-	·	·	·	·	·	·	■	k

a: Addleson [1989]; b: Beckmann and Bowles [2004]; c: Douglas and Ransom [2007]; d: Eldridge [1976]; e: Feilden [2003]; f: Hinks and Cook [1997]; g: Maier [2002]; h: Marshall et al. [2009]; i: Meichsner and Rohr-Suchalla [2008]; j: Pieper [1983]; k: Richardson [2001]; l: Stenvert and Van Tussenbroek [2007]; m: Watt [2007]; n: Weaver and Matero [1997]

Appendix B

Table B: Dimensions of 81 Dutch church buildings showing signs of structural damage: crack development and/or deformations

Reference number	Number of naves	Span of the nave [m]	Span of the aisle [m]	Number of bays	Length of bay [m]	Length of bay at crossing [m]	Height of sidewall [m]	Internal height of aisle [m]	Internal height of nave [m]	Height of roof [m]	Length of window [m]	Height of window [m]	Height of wall below window [m]	Thickness of wall [m]	Thickness of buttress [m]	Consulted sources
1	3	14.0	6.5	5	6.5	14.0	11.0	8.5	18.0	22.7	3.0	3.6	3.6	1.2	-	a, g
2	3	7.5	5.0	6	5.0	7.5	7.0	7.7	12.6	14.2	0.9	2.3	3.5	0.3	0.4	a, o, q
3	1	12.0	-	6	5.2	-	3.3	-	12.0	12.7					-	a, l, p, q
4	3	9.0	3.4	9	4.5	7.0	8.6	10.1	13.2	15.6	2.5	4.6	3.1	0.9	1.7	a, l, p
5	1	11.0	2.6	3	2.6	11.0	6.0	6.0	16.0	16.0	0.3	1.2	4.8	0.3	-	a, l, p
6	3	6.7	3.2	8	3.6	10.4	5.5	6.6	8.2	9.9	1.5	3.3	1.7	0.5	1.3	k, l, p, q
7	1	10.0	-	4	5.0	5.0	10.0	-	16.3	18.0	1.7	5.5	4.0	0.6	1.3	a, l, p
8	1	9.6	-	3	3.2	9.6										a, l, q
9	5	11.5	7.5	11	6.0	12.0	13.7	13.0	29.4	33.5	3.0	8.5	4.3	1.0	2.5	a, b, l
10	3	11.0	5.5	10	5.5	11.0	12.8	14.7	22.0	25.7	1.7	1.8	5.5			a, l, q, r
11	3	9.0	4.5	9	4.5	9.0	9.0	10.8	15.8	18.0	1.9	3.6	3.6			a, m, q
12	3	7.5	4.0	10	4.0	7.5	8.0	10.0	14.0	16.0	1.5	3.5	1.5	1.0	1.8	a, l, m, n, o, p, q, s
13	3	10.0	6.0	6	6.0	6.0	12.0	7.5	15.0	18.0	3.0	6.0	4.5	0.8	1.5	a, m, o
14	3	22.0	4.2	8	4.8	4.8	7.1			19.2	2.2	3.2	1.9			a, k, l, n
15	3	12.5	12.5	13	5.0	12.5	11.1	15.6	26.7	30.0	3.0	6.7	3.9	1.0	2.0	a
16	3	11.3	8.7	16	5.0	11.0	10.0	12.5	15.0	30.0	3.0	5.8	3.3	1.0	1.5	a, l, n, r
17	3	15.9	9.0	13	6.9	12.1	16.1	19.5	37.9	42.5	2.8	9.2	2.9	1.0	2.4	a, c
18	1	8.8	-	5	4.1	-	5.5	-	8.3	11.0	1.4	2.8	1.8		-	a, p, r
19	5	13.9	9.2	10	6.9	13.3	13.0	13.1	29.1	35.6	4.2	9.2	3.4	1.1	1.7	a, c, r
20	1	10.3	-	7	4.4	6.3	8.8	-	13.1	17.5	1.6	3.3	5.5	0.6	1.3	a, p, s
21	3	10.2	4.8	7	4.9	-	8.5	-	18.0	20.5	2.3	4.1	3.9			a, l, p, r, s
22	3	8.6	3.5			7.5			15.0	20.3						a, p, s
23	3	10.3	10.3	12	6.3	-	11.0	17.0	17.0	20.0	3.3	8.0	2.6	0.8	1.9	a, l, p
24	3	16.3	4.3	11	3.4	6.9					2.2			0.6	1.6	a, l, s
25	3	11.0	10.0	7	8.1	8.9	13.0	16.0	18.0	20.0	3.6	7.4	3.8			a, l, m, p
26	1	12.0	-	8	6.4	10.2										a, l, r
27	3	7.8	3.9	8	3.8	-	7.7	10.6	18.2	20.2	1.7	3.8	2.9	0.6	1.4	a, l, p, s
28	2	9.6	-	10	4.3	-	8.8	-	12.0	15.0	2.2	6.2	1.6	0.7	1.7	a, l, q, r, s
29	1	10.5	-	6	5.0	-	12.5	-	13.0	14.0	2.2	4.4	5.6		-	a, l, p
30	3	11.4	7.5	10	5.7	11.4	13.2	14.5	27.0	35.0	3.2	8.1	4.2	0.9	3.0	a, l, m
31	3	11.0	5.4	7	5.4	11.0	14.0	14.0	19.0	22.0	2.0	5.9	4.9	0.5	-	a, h
32	3	10.8	10.8	12	5.8	10.8	24.2	17.0	22.0	24.5	3.1	14.8	4.6	0.8	3.1	a, c, l, p
33	1	10.0	-	8	4.8	9.7	7.6	-	11.0	13.0	2.2	4.2	2.8			l
34	3	10.6	9.2	12	5.3	-	22.0				2.2	13.2	7.3	0.7	2.5	a, c
35	2														-	a, l, p
36	3	12.5	3.9	9	5.3	7.6	9.5	11.5	14.5	16.5	2.5	5.4	3.8	0.9	2.3	l, n, p, q
37	3	8.4	7.9	5	5.0	-	7.8	10.2	10.2	12.5	1.7	4.9	2.1			a, l, p, r, s
38	3	8.9	2.3	5	4.6	7.6	4.4	4.8	9.5	12.6						a, l, p, s
39	3	5.9	2.8	5	4.7	-	7.1	9.6	12.3	13.8	2.1	3.1	3.3			a, k, l, p
40	3	9.6	4.8	8	5.4	9.2										a, m, p, r
41	5	8.6	6.4	11	6.4	8.6	11.6	13.2	21.2	25.0	3.0	8.0	2.4	0.9	2.7	a, c, l, p
42	3	10.5	5.6	7	5.7	9.8	8.0	10.0	15.0	20.0	2.0	4.4	2.8			a, l, m, p, q, r
43	3	11.2	8.8	9	6.5	9.7	16.0	17.0	19.0	23.0	3.5	11.0	4.4	1.0	2.4	a, j, k, l
44	3	10.9	6.8	11	5.6	-	9.8	13.1	21.4	23.6	2.3	6.3	2.4	1.1	1.8	a
45	3	9.4	5.0	12	4.5	9.6	9.8	10.0			2.2	6.5	3.2			a, l, n, p

Table B (continued)

Reference number	Number of naves	Span of the nave [m]	Span of the aisle [m]	Number of bays	Length of bay [m]	Length of bay at crossing [m]	Height of sidewall [m]	Internal height of aisle [m]	Internal height of nave [m]	Height of roof [m]	Length of window [m]	Height of window [m]	Height of wall below window [m]	Thickness of wall [m]	Thickness of buttress [m]	Consulted sources
46	3	10.9	10.9	10	5.4	-	11.7	17.0	17.0	20.0	3.0	8.1	2.7	0.7	2.2	a, l, s
47	3	5.8	1.9	5	3.5	8.2	8.3	8.5	10.5	14.3	1.4	3.7	1.4		-	a, r, s
48	3	6.1	3.6	5	5.8	-	9.6	9.0	9.0	17.2	1.8	5.5	3.6	0.7	1.5	a, k
49	1	8.1	-	6	4.2	6.2	11.0	-	12.4	13.2	1.6	5.7	4.4			a, l, r
50	3	8.8	3.3	6	4.9	-	12.9	15.1	18.4	20.0	2.4	7.6	3.7			a, k, l
51	2	10.0	3.3	8	4.4	10.2	14.6	14.3	15.6		2.0	6.9	5.6			a, l, p, r, s
52	1	11.1	-	6	4.2	8.9	9.4	-	14.0	17.5	2.0	5.2	2.6		-	a, l, m, q, r, s
53	3	9.6	4.0	8	4.5	8.5	6.1	7.4	13.0	15.0	1.5	1.8	3.6			a, k, l, m
54	1	4.2	-	4	2.5	-	9.4	-	12.4	14.4	0.9	2.5	6.2		-	a, l, p, r, s
55	3	9.3	4.7	9	4.2	-	10.1	16.0	18.0		1.8	4.2	10.8			a, l, p, r
56	3	9.3	4.7	7	4.0	-	5.8	7.4	11.1	12.7	2.1	3.6	1.9			a, k, l, p, r
57	1	10.0	-	7	3.1	-	8.0	-	10.0	12.0	1.9	4.2	2.7			a, k, l, r
58	4	8.2	5.6	6	5.9	-	8.6	10.0	17.0	20.0	2.0	5.2	3.0	0.7	1.4	a, k, l, n, r
59	2	11.4	6.1	9	6.3	-	17.3	18.0	20.0	24.0	3.3	9.9	5.6	0.5		a, k, l, m, p, s
60	1	9.1	-	5	6.3	-	7.8	-	9.7	13.4	1.3	4.9	2.0	1.1	2.2	d, e, l, m, s
61	3	10.0	7.2	10	5.1	10.6	15.0	18.0	20.0	22.0	2.0	10.7	2.9			a, b, f, i, k, l, p, r
62	3	15.0		6	8.0	-	15.0	18.0	28.0	32.0	3.7					a, l, m, n, p, r
63	3	10.5	10.2	6	6.9	4.8	11.8	14.0	16.6	22.0	2.0	3.6	6.4		-	a, m, n, s
64	1	12.5	-	8	4.1	-	10.5	-	12.7	15.0	1.9	4.7	4.6			a, l, r, s
65	3	9.4	5.0	11	5.2	10.0	7.5	9.0	15.0	20.8	1.5	3.7	3.2	0.7	1.9	a, l, m, p, r
66	1	8.8	-	8	3.8	8.9	11.2	-	15.8	19.0	1.9	6.7	3.7	0.8	1.5	a, l, p, s
67	5	11.2	5.7	12	5.4	11.2	9.5	12.0	20.0	27.7	3.1	4.0	4.7			a, l, n, p, s
68	1	13.6	-	4	3.9	13.0		-	13.0	19.3						a, l, p, q, s
69	1		-	6	5.0	-	7.6	-	11.8	14.0	1.5	3.5	2.8		-	a, l, p, r, s
70	1	6.3	-	8	2.9	8.6	4.7	-	6.8	9.0	1.1	2.5	1.1			a, r, s
71	1	15.2	-	5	4.2	8.2	10.0	-	13.1	20.1	2.2	3.5	2.2			a, l, r, s
72	3	11.0	5.5	6	5.5	7.5	9.3	11.0	15.0	26.0	1.5	5.3	3.5	0.8	2.3	a, l, p, s
73	1	10.1	-	8	3.1	5.4	5.6	-	9.3	11.3	1.2	2.8	2.3	0.5	-	a, l, p, r, s
74	1	10.2	-	7	3.5	6.1	6.2	-	7.3	11.5	1.6	4.4	1.0		-	a, l, r, s
75	3	10.0	6.4	6	7.0	-	8.5	8.5	14.7	17.0	1.8	6.1	0.4			a, l, s
76	1	8.3	-	5	4.6	-	19.0	-	21.0	23.0	2.0	5.3	8.8		-	a, k, l, p, q, r
77	1	7.7	-	5	2.9	-	4.8	-	6.8	8.2	1.1	2.6	1.6			a, l, m, r
78	3	13.9	3.6	8	4.4	13.1	9.0	10.6	16.0	20.6	2.9	2.6	3.9			a, l, p, r
79	1	13.0	-	6	5.2	12.0	10.2	-	13.0	17.0						l, p, r, s
80	2	8.8	6.7	6	3.7	-	7.3	9.5	9.5	11.4	1.8	4.1	2.7			a, k, l, p, r
81	3	10.0	4.4	12	4.0	9.8	7.4	15.0	18.0	23.0	1.7	4.3	3.0	0.9	2.1	a, b, f, i, k, l
Average value	2	10.3	5.9	8	4.9	9.2	10.1	12.1	15.7	19.2	2.1	5.3	3.6	0.8	1.9	
Standard deviation	1	2.6	2.5	3	1.2	2.3	3.8	3.7	5.8	6.7	0.7	2.6	1.7	0.2	0.6	
Minimum value	1	4.2	1.9	3	2.5	4.8	3.3	4.8	6.8	8.2	0.3	1.2	0.4	0.3	0.4	
5% Lower limit	0	5.2	1.0	3	2.6	4.7	2.5	4.8	4.4	6.0	0.7	0.2	0.2	0.3	0.8	
95% Upper limit	5	15.5	10.8	13	7.3	13.8	17.6	19.3	27.0	32.3	3.6	10.5	7.0	1.2	3.0	
Maximum value	5	22.0	12.5	16	8.1	14.0	24.2	19.5	37.9	42.5	4.2	14.8	10.8	1.2	3.1	

a: series "Monumenten in Nederland" [1996-2006]; b: Ter Kuile [1944]; c: Fockema Andreae et al. [1948]; d: Steensma et al. [2002]; e: Kars [2007]; f: Rijksdienst voor de Monumentenzorg [1977]; g: De Vent [2005]; h: Van der Plas [2006]; i: Monumentenwacht Zuid-Holland; j: presentation Constructiebureau De Prouw B.V.; k: photographs made by the author; l: www.reliwiki.nl; m: nl.wikipedia.org/wiki; n: www.archimon.nl; o: www.kerkgebouwen-in-limburg.nl; p: website on church or church community; q: maps.google.nl; r: maps.live.com; s: other websites. All websites have been accessed between November 2008 and February 2009.

Summary

This thesis deals with the diagnosis of structural damage in masonry. Structural damage is characterized here as damage that appears to manifest a lack of strength, stiffness or stability, by showing crack development, deformation or tilt. It differs from other kinds of damage because it does not only affect aesthetic or functional demands, but can also endanger the physical safety of people.

To be able to effectively treat damage, one needs to have insight in the process that caused it: one needs a diagnosis. With this research project, we have aimed to improve and facilitate the diagnosis of structural damage in masonry by offering support in the initial phase of the diagnostic process: the phase in which hypotheses are generated.

Hypothesis generation is an essential step in diagnosing, and one that can have a large influence on process and outcome, too. After all, the more precise hypotheses are formulated, and the more accurate they are classified, the more effective the further process of verification will be and the greater the probability that the final diagnosis is correct. Surprisingly enough, improvement of this phase of the process has hardly been given any attention so far in building pathology. A pity, but also an opportunity we liked to seize.

We have started this study with the assumption that symptoms of a damage and its context (in terms of material, geometry, environment and time) give sufficient clues to be able to deduce its cause. We have specifically focused on characteristics that can be assessed in a first survey, either visually or with the help of some simple tools or archive material. This with the aim to enhance the results produced in initial visual inspections carried out with limited time and means.

In Part I of this thesis, we have used a questionnaire to investigate how experts reach a hypothesis. Pattern recognition has proved to play a major role in this. Although it can be an efficient technique, pattern recognition has some limitations. Most importantly, it can make surveyors unaware of implicit assumptions they make during a diagnostic process, and of alternative explanations that are possible, too.

To improve this situation, we have developed a diagnostic decision support tool that should help surveyors to distinguish between causes by offering support in interpreting the symptoms of a damage within their context. The information contained in the tool has been based upon a literature review. This was done because we assume that the cases of damage selected for publication are the ones that the authors consider important and representative.

From our literature sample, we have collected over 500 examples of structural damage in traditional (loadbearing, solid, unreinforced) masonry for which both a clear

photograph or drawing and a statement on the cause of damage was provided. Each of these cases has been dissected into separate components: symptoms, causes and context conditions. These components have been described in Part II of this thesis. There, an unambiguous terminology has been proposed, encompassing those characteristics that are important during a visual inspection of structural damage in masonry.

Subsequently, in Part III of this thesis, relations between individual components have been established. First, we have examined to what extent four factors (trough length, trough position, presence of openings and masonry properties) can influence settlement processes. Both numerical finite element and small-scale physical simulations have been used. It was shown that tapering of a crack says more about its cause than its direction does. However, for settlement, the symptoms of damage may depend more on the context than on the underlying cause of damage. The presence of window openings, for example, can substantially alter the appearance of damage. Surveyors should be aware of this.

The relations between all other components have been deduced from literature. Symptoms and (descriptive) context conditions have been combined to 60 characteristic damage patterns. For each of these damage patterns, possible causes have been listed. The added essential (explanatory) context conditions should allow one to discriminate between these hypotheses.

To come to an operational tool, these data have been opened up through a decision tree. The decision tree helps users determine which of the 60 damage patterns most closely matches the damage they are investigating. All further information on hypotheses and conditions is provided tailored to the selected pattern. For settlement-related damage processes, a separate part gives more details on underlying causes and essential conditions.

As final step in this research project, our tool has been submitted to a panel of potential users: Monument Watch inspectors, engineering consultants, researchers and architecture students, all involved in the structural appraisal of masonry buildings. They have applied our tool to a damage case from their practice. With a questionnaire, they were asked to give their opinion on ease of use, validity of content and helpfulness of the tool.

The overall outcome of this user test is positive. The tool has generally been considered as instructive, the information provided as clear and relevant, and the structure as clear, too. Seven out of eleven participants indicated that they would like to use our tool in their practice. Main point of criticism was the procedure, which some participants considered too time-consuming. We think this problem could be overcome by developing a digital version of our tool, in which the provided information could be tailored even better to the user's input. A majority of the participants already stated to welcome this option.

Evaluating the research project in its entirety, we can state that our research hypothesis has proved to be true to an important extent. A visual inspection of symptoms and context conditions is not always sufficient to establish a sound diagnosis; however, if interpreted

correctly, they can help narrow down the list of hypotheses substantially. Although additional investigations may still be needed to reach a final diagnosis, our tool can be a great support in the diagnostic process.

The main contribution of this study lies in improving knowledge exchange. The existing, but highly fragmented and often seemingly contradictory information has been combined, structured and assessed on its value for diagnosing structural damage in masonry. With this thesis and the accompanying tool, expert knowledge is now made accessible to a wider group of people.

Samenvatting

Deze dissertatie, waarvan de titel in het Nederlands '*Constructieve schade in metselwerk: het ontwikkelen van een diagnostisch beslissingsondersteunend systeem*' luidt, gaat over de diagnose van constructieve schade in metselwerk. Constructieve schade is daarbij gedefinieerd als schade die, in de vorm van scheurvorming, vervormingen of scheefstand, lijkt te wijzen op een gebrek aan sterkte, stijfheid of stabiliteit. Het verschil met andere soorten schade is dat constructieve schade niet alleen esthetische of functionele gevolgen kan hebben, maar ook de fysieke veiligheid van mensen in gevaar kan brengen.

Om schade effectief aan te kunnen pakken, is inzicht nodig in het proces waardoor deze veroorzaakt is: er moet een diagnose gesteld worden. Dit onderzoek had tot doel de diagnose van constructieve schade in metselwerk te verbeteren en vereenvoudigen. We wilden dit bereiken door ondersteuning te bieden in de eerste fase van het diagnoseproces: de fase waarin hypotheses worden gegenereerd.

Het genereren van hypotheses is een essentiële stap binnen het diagnosticeren, die grote invloed kan hebben op het verdere diagnoseproces en de uitkomst daarvan. Immers, hoe preciezer hypotheses worden geformuleerd, en hoe nauwkeuriger ze worden gerangschikt, des te effectiever zal de verificatie verlopen, en des te groter zal de kans zijn dat de uiteindelijke diagnose correct is. Verrassend genoeg is, binnen de bouwpathologie, tot nu toe weinig aandacht besteed aan verbeteringen van deze fase van het proces. Ten onrechte, zo vonden wij. Maar tegelijk een kans die wij graag wilden aangrijpen.

We zijn deze studie begonnen vanuit de aanname dat de symptomen van een schade en zijn context (in de zin van materiaal, geometrie, omgeving en tijd) voldoende aanwijzingen bieden om de oorzaak van deze schade te kunnen afleiden. We hebben ons specifiek gericht op kenmerken die tijdens een eerste inspectie beoordeeld kunnen worden, ofwel visueel, ofwel met eenvoudige hulpmiddelen of archiefmateriaal. Dit met het doel om de resultaten te verbeteren die in een eerste visuele inspectie, met beperkte tijd en middelen, te behalen zijn.

In Deel I van deze dissertatie is middels een enquête onderzocht hoe experts tot een hypothese komen. Patroonherkenning bleek daarbij een zeer grote rol te spelen. Hoewel het een efficiënte techniek kan zijn, heeft patroonherkenning wel zijn beperkingen. De belangrijkste is dat het inspecteurs onbewust kan maken voor de impliciete aannames die zij tijdens het diagnoseproces doen, en ook voor alternatieve verklaringen die mogelijk zijn.

Om deze situatie te verbeteren, hebben wij een beslissingsondersteunend diagnosehulpmiddel ontwikkeld. Dit hulpmiddel moet inspecteurs helpen bij het maken van onderscheid tussen oorzaken, door hen ondersteuning te bieden bij het interpreteren

van de symptomen van een schade binnen hun context. De informatie die dit hulpmiddel bevat is gebaseerd op een literatuuronderzoek. We zijn er daarbij vanuit gegaan dat de voorbeelden van schade die deze auteurs voor publicatie hebben geselecteerd door hen als belangrijk en representatief worden gezien.

Uit onze literatuurselectie hebben we 500 gevallen verzameld van constructieve schade in traditioneel (dragend, massief, ongewapend) metselwerk waarvan een duidelijke foto of tekening was opgenomen, en tegelijk een omschrijving van de oorzaak. Elk van deze gevallen is ontleed in losse onderdelen: symptomen, oorzaken en context condities. Deze componenten zijn beschreven in Deel II van deze dissertatie. Daar hebben we een eenduidige terminologie voorgesteld, waarin die kenmerken zijn opgenomen die van belang zijn tijdens een visuele inspectie van constructieve schade in metselwerk.

In Deel III zijn vervolgens de relaties tussen de individuele componenten gelegd. Eerst hebben we onderzocht in hoeverre vier factoren (troglengte, trogpositie, aanwezigheid van gevelopeningen en materiaaleigenschappen van het metselwerk) zettingprocessen kunnen beïnvloeden. Hiervoor is zowel gebruik gemaakt van numerieke eindige elementen simulaties als van fysieke testen op kleine schaal. Hieruit bleek dat het al dan niet taps toelopen van een scheur meer zegt over zijn oorzaak dan zijn richting doet. Niettemin worden voor zettingen de symptomen van schade soms sterker beïnvloed door de context dan door de onderliggende schadeoorzaak. De aanwezigheid van raamopeningen kan, bijvoorbeeld, een schadebeeld aanzienlijk veranderen. Inspecteurs zullen zich hiervan bewust moeten zijn.

De relaties tussen alle andere componenten zijn uit de literatuur afgeleid. Symptomen en (beschrijvende) context condities zijn gecombineerd tot 60 karakteristieke schadepatronen. Voor elk van deze patronen is een lijst opgesteld van mogelijke oorzaken. Met behulp van de daaraan toegevoegde essentiële (verklarende) context condities zou men deze moeten kunnen onderscheiden.

Om tot een bruikbaar hulpmiddel te komen, hebben we deze gegevens door middel van een beslisboom ontsloten. De beslisboom helpt gebruikers vast te stellen welke van de 60 schadepatronen het best past bij de schade die zij onderzoeken. Alle verdere informatie over hypotheses en condities wordt afgestemd op het geselecteerde patroon. Voor schade door zettingen is een apart deel aan het hulpmiddel toegevoegd, waarin meer details worden gegeven over de onderliggende processen en de daaraan verbonden essentiële condities.

Als laatste stap in dit onderzoek is het door ons ontwikkelde hulpmiddel voorgelegd aan een panel van potentiële gebruikers: Monumentenwachters, constructeurs, onderzoekers en architectuurstudenten, allemaal betrokken bij constructieve beoordeling van metselwerk gebouwen. Zij hebben ons hulpmiddel toegepast op een schadegeval uit hun dagelijkse praktijk. Met een enquête werd hen gevraagd aan de hand van stellingen hun mening te geven over de gebruiksvriendelijkheid, de inhoudelijke juistheid en de geboden ondersteuning van ons hulpmiddel.

De uitslag van deze gebruikerstest is positief te noemen. Ons hulpmiddel werd over het algemeen gezien als informatief, de geboden informatie als helder en relevant, en ook de opzet werd positief ervaren. Zeven van elf deelnemers gaven aan het hulpmiddel verder te willen gebruiken in hun praktijk. Het belangrijkste punt van kritiek betrof de werkwijze, die sommige deelnemers als te tijdrovend ervoeren. Wij denken dit probleem te kunnen ondervangen door een digitale versie van het hulpmiddel te ontwikkelen, waarin de aangeboden informatie nog beter afgestemd kan worden op de input van de gebruiker. Een meerderheid van de deelnemers heeft al aangegeven deze optie te verwelkomen.

Wanneer we dit onderzoeksproject in zijn geheel beschouwen, dan kunnen we stellen dat onze onderzoekshypothese voor een belangrijk deel is bevestigd. Een visuele inspectie van de symptomen en context condities is niet altijd voldoende om een juiste diagnose te kunnen stellen; maar wanneer deze correct worden geïnterpreteerd, kunnen ze wel helpen om de lijst van mogelijke hypotheses sterk terug te brengen. Hoewel aanvullend onderzoek nodig zal blijven om tot een diagnose te komen, kan ons hulpmiddel een waardevolle ondersteuning zijn binnen het diagnoseproces.

De belangrijkste bijdrage van dit onderzoek ligt in de verbetering van kennisuitwisseling. Reeds bestaande, maar sterk gefragmenteerde en vaak ogenschijnlijk tegenstrijdige informatie is gecombineerd, geordend en beoordeeld op zijn waarde voor de diagnose van constructieve schade in metselwerk. Met deze dissertatie en het bijgevoegde hulpmiddel is expertkennis toegankelijk gemaakt voor een bredere groep mensen.

Curriculum vitae

Ilse de Vent was born on September 3, 1980 in Geleen. After completing gymnasium (grammar school) cum laude at Scholengemeenschap St. Michiel in 1998, she went to Delft University of Technology to study at the Faculty of Architecture. In 2005, she graduated with honourable mention on a structural assessment and redesign of the church of Sint Lambertus in Maastricht, in a combined master track of architecture and building technology.

During her education, Ilse had part-time jobs at Edah Janssen supermarket (1997-2000) and at Inter IKEA Systems B.V. (2000-2004), where the customer-oriented aspects of the jobs gave much satisfaction. Subsequently, from 2003 to 2006, she worked as an architect at Vis Restauratie Architecten in The Hague.

Although she enjoyed seeing drawings come to life in building projects, Ilse felt there was more still to be learned regarding the technical aspects of building maintenance and conservation. Hence, after receiving her master's degree in 2005, she became attached to the chair of Mechanics in Buildings, Faculty of Architecture, Delft University of Technology. She first worked as a research fellow, effecting non-linear finite element calculations in support of a PhD research concerning building response on soil deformations induced by underground excavation works. In 2006, she started her own PhD research on diagnosing structural damage in masonry, of which this thesis and the accompanying diagnostic tool are the end results.

Since June 2010, Ilse has been employed by Staatstoezicht op de Mijnen (Dutch State Supervision of Mines). As senior inspector geo-engineering, she has been entrusted with the aftercare for the former coal mining in southern Limburg. Here, she can put the knowledge she acquired during this PhD research into practice, and dedicate it to the public interest.

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In the course of this research project, three questionnaire surveys have been conducted. I would like to seize this opportunity to express my gratitude towards all people who participated in one – or more – of these inquiries. Their feedback has been invaluable, and I appreciate that they were willing to provide information about the damages they encountered, to study our test cases, to try out our tool, and to fill out the forms. Without their participation, this research could never have become so practice-oriented.

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During the last year at TU Delft, I have found a challenging new position at *Staatstoezicht op de Mijnen* (Dutch State Supervision of Mines (SodM)). I am most grateful that SodM granted me the opportunity to start on a part-time basis, allowing me to slowly grow into the matter of mining while finishing writing this thesis. This combination certainly worked out for me. But most of all, the support and interest of all my SodM-colleagues (including the people from EL&I and from the Tcbb) has been heartwarming and kept me going in this past year. Again, I praise myself lucky to have found such a nice group of people to work with.

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The final sentences are, of course, reserved for Harmen, who has supported me with endless love and encouragement. You have kept the social and household plates spinning while I buried myself in my job. I have tested your patience, but I promise it is now time to enjoy life outside work again.

Ilse de Vent

This thesis deals with the diagnosis of structural damage in traditional masonry: cracks, deformations and tilts. Establishing the cause of this type of damage can be difficult. This research project has aimed to improve and facilitate the diagnostic process by offering support in the initial phase in which hypotheses are generated. The more precise hypotheses are formulated, and the more accurate they are classified, the more effective the further process of verification will be and the greater the probability that the final diagnosis is correct.

This study has specifically focused on characteristics that can be assessed in a first survey, either visually or with the help of some simple tools or archive material. With questionnaires, a literature review of over 500 cases of damage and numerical and small-scale physical tests, the relations between symptoms of damage, their causes and their contexts (in terms of material, geometry, environment and time) have been investigated. This has resulted in a diagnostic decision support tool that helps surveyors to distinguish between causes by offering support in interpreting structural damage in masonry. The results of a user test, in which potential users applied our tool to damage cases from their practice, are positive: our tool was generally considered to be very instructive.

The main contribution of this study lies in improving knowledge exchange. The existing, but highly fragmented and often seemingly contradictory information has been combined, structured and assessed on its value for diagnosing structural damage in masonry. With this thesis and the accompanying tool (ISBN 978-90-8570-760-8), expert knowledge is now made accessible to a wider group of people.

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