STRUCTURAL SAFETY

Study into critical factors in the design and construction process

Proefschrift

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Samenvatting

Constructieve veiligheid: studie naar kritieke factoren in het ontwerp- en uitvoeringsproces

24 april 2003: vijf balkons van het appartementengebouw Patio Sevilla in Maastricht stortten in, waarbij twee mensen omkwamen. Inwoners waren geschokt bij het idee dat hun woning onveilig kon zijn. Na deze ramp werden diverse initiatieven gestart om constructieve veiligheid te verbeteren.
Constructieve veiligheid is de afwezigheid van onacceptabel risico door constructief falen. Risico is een functie van de kans op een bedreigende gebeurtenis en de bijbehorende gevolgen. Binnen regelgeving zijn limieten voor acceptabele risico's vastgesteld.

De Eurocode beoogt constructieve veiligheid op twee manieren te borgen. In de eerste plaats met een berekeningsmethode waarmee betrouwbare en robuuste bouwwerken worden ontworpen. Hierbij wordt gebruik gemaakt van geaccepteerde faalkansen voor constructieonderdelen. De tweede manier is het voorschrijven van kwaliteitsmanagement voor het bouwproces. De maatregelen zijn echter weinig concreet gedefinieerd en organisatorische factoren krijgen vrijwel geen aandacht.

Uitgebreide studie naar constructieve schadegevallen in Nederland laat zien dat het huidige aantal overleden burgers tijdens verblijf in hun woning door constructief falen binnen acceptabele grenzen blijft, al zijn deze grenzen arbitrair. Er dient wel te worden vermeld dat een zeldzame ramp met veel slachtoffers in de bestudeerde periode niet is voorgekomen. Deze studie toont ook dat ongeveer 90% van de schadegevallen wordt veroorzaakt door menselijke fouten in ontwerp, uitvoering en gebruik. Menselijk gedrag is echter niet opgenomen in de probabilistische berekeningsmethode van de Eurocode. Het lijkt een paradox dat individuele risico's binnen de acceptabele limieten blijven, maar dat de belangrijkste beïnvloedende factor, de menselijke fout, niet is opgenomen in de berekeningsmethodiek. Dit kan worden verklaard door het feit dat de werkelijke sterkte van constructies vaak groter is dan de berekende sterkte door redundantie en doordat waarschuwend gedrag van constructies de omvang en aard van gevolgen beperkt.

Al blijft het aantal dodelijke slachtoffers binnen de arbitraire grenzen, het blijft noodzakelijk om te werken aan verbetering van constructieve veiligheid. Het aantal slachtoffers en gewonden zou volgens het ALARP principe zo laag als redelijkerwijs mogelijk moeten zijn. Daarnaast zijn gevolgen niet beperkt tot het aantal doden of gewonden. Faalkosten van meer dan 10% van de jaarlijkse omzet in de bouw vinden velen terecht onacceptabel.

Daarom is het doel van deze studie om dié factoren in het ontwerp- en uitvoeringsproces te bepalen die verbetering behoeven met betrekking tot constructieve veiligheid in de huidige Nederlandse bouw. De huidige bouw is complex door een groot aantal actoren, zoals opdrachtgevers, adviseurs, aannemers, onderaannemers en toeleveranciers, die in

verschillende samenwerkingsvormen werken. Daarnaast worden projecten vaak steeds complexer door wensen van opdrachtgevers en de mogelijkheden van geavanceerd computerondersteund ontwerpen.

Studie van management- en veiligheidskundige literatuur heeft een lijst met mogelijke invloedsfactoren opgeleverd op macro (sector/land), meso (bedrijf/project) en micro (individueel) niveau. Deze factoren zijn gecombineerd in een theoretisch raamwerk. Studie van schadegevallen en een literatuurstudie van Nederlandse literatuur over constructieve veiligheid illustreren op welke manier de gevonden factoren van invloed kunnen zijn op constructieve veiligheid in de Nederlandse bouw.

Op landelijk niveau zijn een aantal factoren geobserveerd die constructieve veiligheid negatief beïnvloeden. Dat zijn met name: de focus op laagste prijs en krappe tijdsplanning, fragmentatie van de bouw, een reactieve cultuur, anti-autoritair gedrag, twijfelachtig niveau van hoger technisch onderwijs, beperkt gebruik van aanwezige kennis en een laag niveau van aansprakelijkheid van adviseurs.

Kritieke factoren voor constructieve veiligheid zijn de factoren in het bouwproces waarvoor het essentieel is om aandacht aan te besteden in de huidige bouwprojecten. Om deze te bepalen is een nationaal enquête-onderzoek uitgevoerd. In deze enquête werd respondenten gevraagd om de aanwezigheid van factoren op meso en micro niveau voor een succesvol en minder succesvol project (betreffend constructieve veiligheid) te bepalen. Daarnaast werd hun gevraagd om direct de meest relevante factoren voor het borgen van constructieve veiligheid op meso niveau in een lijst aan te geven. In het enquête-onderzoek zijn kritieke factoren voor constructieve veiligheid die factoren, die het grootste verschil in aanwezigheid vertoonden bij succesvolle en minder succesvolle projecten, en die door de respondenten als de meest belangrijke werden gezien om veiligheid te borgen. Kritieke factoren werden allemaal op projectniveau gevonden, te weten:

- communicatie en samenwerking
- risico management
- controle
- allocatie van verantwoordelijkheden
- veiligheidscultuur
- kennis infrastructuur

Er wordt van uitgegaan dat projectkarakteristieken, zoals de complexiteit van een ontwerp of een bouwproces, het relatieve belang van onderliggende factoren kan beïnvloeden. Voor een eenvoudig project, met slechts één betrokken partij die het bouwwerk ontwerpt en bouwt, zullen de factoren op project niveau en de relaties tussen de verschillende partijen in het geheel niet van invloed zijn.

Tenslotte zijn er maatregelen benoemd, die kunnen leiden tot verbetering van de genoemde kritieke factoren. Er werd geconcludeerd dat veel van deze maatregelen reeds eerder zijn genoemd in Nederlandse publicaties, zonder dat deze breed werden opgevolgd.

Voor met name constructief risicomanagement van product en proces dienen duidelijker richtlijnen in de huidige bouw beschikbaar te komen. Voor allocatie van verantwoordelijkheden en controlemechanismes behoeft de implementatie van eerder voorgestelde maatregelen aandacht. Daarnaast zal een verhoging van de aansprakelijkheid van adviseurs mogelijk leiden tot verbeteringen in de manier waarop taken daadwerkelijk worden uitgevoerd.
De veiligheidscultuur in de procesindustrie en luchtvaart zijn voorbeelden van een ontwikkelde veiligheidscultuur, met verplichte melding van faalgevallen en een hoog niveau van veiligheidsbewustzijn. De bouw kan hiervan leren. Communicatie en samenwerking kunnen worden verbeterd door adequate toepassing van BIM, meer toepassing van ketenintegratie en geïntegreerde contracten. Best practices van kennismanagement moeten worden gedeeld om de kennisinfrastructuur binnen projecten te verbeteren.

Het is te verwachten dat extra aandacht voor de kritieke factoren en gebruikelijke aandacht voor de andere beïnvloedende factoren zullen leiden tot verbetering van constructieve veiligheid van projecten binnen de Nederlandse bouwsector.

Summary

Structural safety: study into critical factors in the design and construction process

April 24, 2003: five balconies of the apartment building Patio Sevilla in Maastricht collapsed, resulting in two fatalities. Citizens were shocked by the idea their dwellings might be unsafe. After this disaster, several major initiatives have been started to improve structural safety.
Structural safety is the absence of unacceptable risk associated with structural failure. Risk is a function of the likelihood of a hazard and the consequences. Within regulations acceptability limits are set.

Eurocode provides a framework to assure structural safety in two ways. The first way is a calculation method in which reliable and robust structures can be designed. Eurocode uses acceptability limits for the probability of failure of single elements. The second way of assuring structural safety is a prescription of quality management that should be applied in the building process. In this approach measures are sometimes ill defined and organizational factors largely neglected.

An extensive study of structural failures in The Netherlands has shown that the current number of fatalities among residents due to structural failures remains within assumed acceptable limits, although a high impact - low probability disaster did not occur in the observed time interval. This study showed also that about 90% of the failures are caused by human errors, although human behaviour is not included in the probabilistic calculation approach of the Eurocode. It seems a paradox that the individual risk remains within acceptable limits, although the main influencing factor, human error, is not included in the calculation approach. This can be explained because the actual strength of structures is often higher than the calculated strength due to redundancy. In addition, warning behaviour of structures can limit consequences.

Although the number of fatalities meets the questionable requirements, it still remains indispensable to work on improvement of structural safety. The number of fatalities and injuries should be as low as reasonably practicable (ALARP). Furthermore, consequences are not limited to fatalities or injuries. Failure costs of more than 10% of the annual turnover are unacceptable.

The main aim of this study is therefore to determine factors in the design and construction processes within current Dutch building industry that need improvement with respect to structural safety. The current Dutch building industry is complex with a variety of actors, like clients, advisors, contractors, subcontractors and suppliers, who work on projects in various forms of collaboration. In addition, the projects tend to become increasingly complex, due to wishes of clients and opportunities of computational design.

A literature survey on management theory and safety science has resulted in possible factors on macro (sector/country), meso (company or project) and micro (individual) level. These factors were combined in a theoretical framework. Failure case studies and Dutch literature on structural safety have demonstrated in what way the derived factors can influence structural safety in the Dutch building industry.

Some threats within Dutch building industry were observed, which are assumed to negatively influence structural safety. The main observed threats are a focus on lowest price and short design and construction time, fragmentation in the building sector, reactive culture, anti-authoritative behaviour, questionable level of technical higher education, limited use of available knowledge and low level of liability for advisors.

To derive the critical factors for structural safety, those factors in the building process that are essential to pay extra attention to in current building projects, a national survey was performed. In this survey respondents were asked to rate the presence of factors on meso and micro level for a successful and less successful project regarding structural safety. In addition, they were asked to directly assess the most relevant factors to assure structural safety on meso level. Critical factors for structural safety were expected to be those factors which showed the largest difference in presence in successful and less successful projects. In addition, these factors were regarded by respondents as most important to assure structural safety. Critical factors are all related to project level. The following factors appeared to be critical:

- communication and collaboration
- risk management
- control
- allocation of responsibilities
- safety culture
- knowledge infrastructure

It was recognized that the project characteristics like complexity of the project or complexity of the process might influence the relative importance of influencing factors. For a simple project, with only one actor who designs and builds the structure, the factors on project level and interrelationships between various parties will not be of influence at all.

Finally, measures are suggested that can lead to improvement of the six critical factors. It was concluded that for many of these factors measures have been suggested before in Dutch publications, without proper implementation.

It appeared that especially for structural *risk management* of product and process in current building practice more guidance is needed. For *allocation of responsibilities* and *control mechanisms*, the implementation of already suggested measures needs attention.

Furthermore, an increase of the liability of advisors might lead to improvements in the way tasks are performed and covered.

For *safety culture* it is believed that process industry and aviation provide useful examples of a developed safety culture, with mandatory failure reporting and a high level of safety awareness. Adequate application of BIM, and increase of chain integration and integrated contracts can improve *communication and collaboration* in the current building industry. Best practices of knowledge management need to be shared and implemented to improve *knowledge infrastructure*.

It is expected that extra attention to the critical factors and usual attention to the other influencing factors will lead to an improvement of structural safety in projects and in the Dutch building sector.

Table of contents

PART II: CRITICAL FACTORS FOR STRUCTURAL SAFETY

PART III: EXPLORING IMPROVEMENTS

1

Introduction

1.1 Motivation

1.1.1 Ticking time bomb

In 1997 Vambersky and Sagel published a series of three papers with the title: 'The ticking time bomb under the building industry' (Vambersky and Sagel 1997). In these publications the authors argued that the building failures at that time were no incidents, but results of deficiencies in the Dutch building industry. They observed a lack of professionalism at clients, a focus on lowest price and a lack of coordination. They highlighted the role of changes in the building plan, the relevance of adequate detailing and the importance of control and coordination.
However, their warning: "Waiting until the first disasters will happen, before adequate measures will be taken, might not be wise" proved to be idle, when in April 2003 some balconies collapsed in Maastricht, resulting in two fatalities. Citizens were shocked by the idea that it was possible that their houses might not be safe to live in. After this disaster, several major investigations were started. Finally, the engineer of record was convicted with a fine of € 22 500, by a criminal court. This case of the collapse of balconies in Maastricht has been a wakeup call for Dutch government and building industry (Terwel, Boot et al. 2014).

1.1.2 Response from government and building industry

Government and building industry responded with a number of initiatives to improve structural safety. Figure 1.1 gives an overview of major failures and accompanying public reports from government and building industry, starting from 2001. From this figure it can be concluded that many national reports, focusing on single accidents or on comparison of failures with similar causes, were released after major failures.

The Inspectorate of the Ministry of Housing, Spatial Planning and the Environment (in Dutch: 'VROM-inspectie' or 'Inspectie Leefomgeving en Transport') was one of the first organizations that performed an integral problem analysis of Dutch building industry (Inspectorate of Housing 2007; VROM-inspectie 2007b). As a follow up to this analysis, building industry responded with an abundance of possible solutions to improve structural safety, ranging from broad to very detailed measures. An important idea was the mandatory institution of an engineer of record, who would connect all the fragmented information within a building project (VROM-inspectie et al. 2006). In addition, the building industry and government promoted a clear allocation of responsibilities in the publication: Compendium Structural Safety (Spekkink 2011). Furthermore, a start was made with the certification of structural engineers. Finally, many detailed suggestions towards improvement were issued, like the advice for employees of local building control to join a spaghetti-bridge contest to improve structural skills (VROM-inspectie 2008, p. 37).

The Platform Structural Safety, which was established in 2008, elaborated on the work of VROM-inspectie. The Platform's aim is to make the attention for and the assuring of structural safety in the Dutch building industry common practice. It investigates structural failures, as well as successful projects, and manages a confidential reporting system of structural incidents (CUR Bouw & Infra 2011). These studies reveal that structural failures are predominantly caused in the design and construction process and not during use. The Platform uses a broad approach towards structural safety, by presenting a general framework with causes of failures on macro level (sector), meso level (organization) and micro level (individual) (CUR Bouw & Infra 2010a). The framework is based on the work by Van Duin (Van Duin 1992), who emphasized that failures can be studied on these three levels. By using this multiple level approach, the platform avoids a single, narrow focus on human errors.

Although these suggestions and initiatives undoubtedly have achieved some success, like an increased awareness of structural safety within the building industry and the setup of a certification system for structural engineers, the problem of structural safety has not been solved yet. The engineer of record was not established, the Compendium did not achieve a formal status and many of the measures were too detailed or poorly motivated.
And moreover, large structural accidents still have occurred, after the first initiatives for improvement had been started. In 2010 the temporary struts of a floor of the B-tower in Rotterdam collapsed during the casting of concrete (Onderzoeksraad voor Veiligheid 2012b), injuring 5 craftsmen. In 2011 the roof of a stadium of FC Twente collapsed during erection, causing 2 fatalities and 16 injuries (Onderzoeksraad voor Veiligheid 2012a).

These two accidents resulted in some extensive reports of the Dutch Safety Board (Dutch: Onderzoeksraad voor Veiligheid). In the B-Tower report the board acknowledges that the sector has started various initiatives towards improvement, to solve the problems regarding structural safety. On the other hand, the board is concerned that the acquired knowledge is not used on execution level and they wonder if the case of the B-tower and the poor learning ability is symptomatic for the Dutch building industry (Onderzoeksraad voor Veiligheid 2012b, p. 6). By citing the Dutch Minister Spies, the board gives insight into the scientific gap within the field of structural safety: " …a clear picture of the cause of structural failures has appeared: fragmentation, lack of coordination and insufficient responsible behaviour ***seem*** to be the most important causes…"(Spies 2012)-*highlighting by the author*.

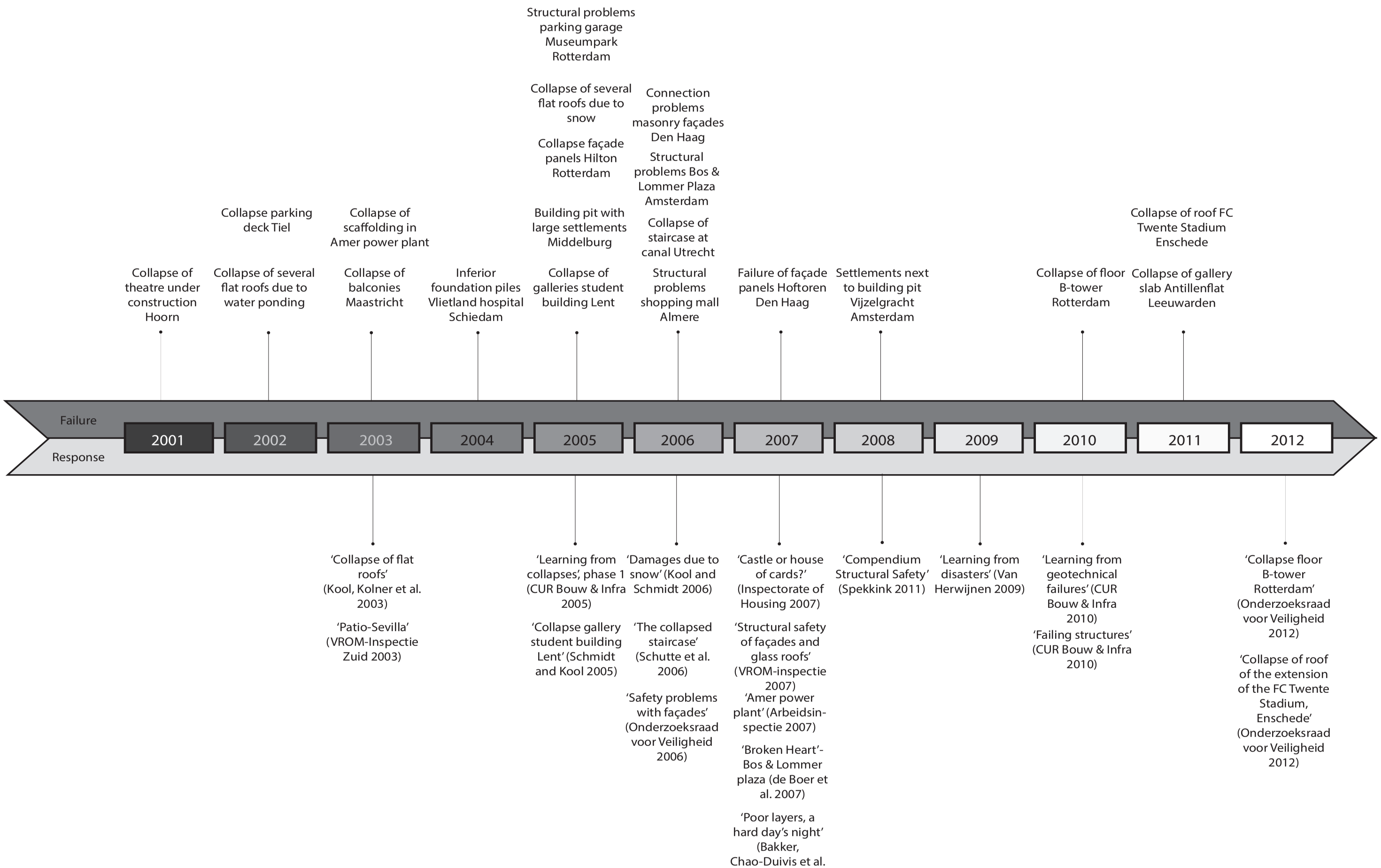


Figure 1.1 *Major failures and responses (Dutch report and book titles translated in English)*

1.1.3 Scientific gap

Although there ***seems*** to be some notion of the causes, it is questionable if Spies' list of causes is complete. When listing the main problems, Spies reasonably used the problem analysis of VROM-inspectie from 2007. However, this analysis knows some drawbacks.

The first drawback is, that it is not well structured. Although the distinction of micro, meso and macro levels provides some structure, the nearly infinite number of possible factors within these levels are not structured or categorized. The large number of possible factors results in an abundance of suggested measures. It might not be easy for building industry to select the relevant measures from this large list.
In this study this drawback will be avoided by developing a structured theoretical framework, based on an international literature study, that will be customized for the Dutch building industry (see 1.3).

Second, the problem analysis did not serve a scientific aim and, thus, the scientific soundness is questionable. It is predominantly based on particular opinions of a limited number of persons in expert meetings and anecdotic evidence of a small number of failure cases. This study, however, will make use of a theoretical framework based on a multidisciplinary literature study (chapter 5), will be based on a larger number of publications regarding structural safety in the Netherlands (chapters 6 and 7), will use more evidence from failure cases by including more recent studies (chapters 4 and 7), and will make use of over 200 experts from building industry in an evaluation of their projects (chapter 8). Another general scientific weakness in the majority of current initiatives, like ABC registration, is that the assumed presence of process factors in failure cases is no real evidence that these factors actually contributed to the failure; these factors might also be present in 'successful' projects.
This study will avoid this pitfall by making a comparison between successful and less successful projects in chapter 8.

Third, the current problem analysis has a narrow focus on the situation in the Dutch building industry. There is hardly any comparison with other safety related industries, like health industry or (chemical) process industry. Furthermore, comparisons with other countries' building industries are usually lacking.
Within this study the outcomes of a comparison from building industry with aviation and process industry (Terwel and Zwaard 2012) and the outcomes of an initial survey of forensic practices within various countries (Terwel et al. 2012) will be included (chapter 6).

Finally, the results of the problem analysis of 2007 might be outdated.
This study will include relevant studies until 2012 regarding structural safety.

It can be concluded that a thorough, recent problem analysis regarding structural safety of the Dutch building industry, which avoids a single focus on failure cases and makes use of insights from other safety related industries, is lacking. This problem analysis is necessary to be able to propose adequate measures to improve structural safety.

1.2 Aim of this research

Society and building industry would like to know in what way structural safety can be assured, even in a complicated and changing building industry. The building industry can be regarded as complicated with the large number of actors involved and the increasing complexity of design. It is also changing, with new wishes from clients and new opportunities in new forms of collaboration, alternative forms of building control, new computer applications and new building materials.
Science might provide knowledge to help answering the question from society.

1.2.1 Aim and main research question

The aim of this PhD study is to determine factors in the design and construction process that are expected to be critical with respect to structural safety in the Netherlands. Critical factors with respect to structural safety are those few key areas, in which favourable results are absolutely necessary to assure structural safety (after Rockart (1982), see 5.2.2).

The accompanying main research question of this thesis will be:

What factors in the design and construction process within current Dutch building industry need improvement with respect to structural safety?

The various aspects of this main question and the scope of this research will be explained in the following subsection.

1.2.2 Scope of the research

This study will be focused on factors within the *design and construction process* of structures. Factors within the use phase (like amount of inspection and maintenance) are generally beyond the scope of this thesis, because these factors are different in nature. It is expected that the majority of structural problems stems from the design and construction phase, although this assumption will be checked in chapter 4.

Various parties within the building process that are responsible for the assurance of structural safety will be regarded in this study. The focus will not be on possible forms of collaboration or types of contracts, but on underlying issues, like coordination and allocation of responsibilities which are part of every type of contract (see subsection 3.2.2). Furthermore, local building control will not be subject of this study. It is believed that the building industry itself is responsible for structural safety and that building control just has to check if the building industry has taken this responsibility. The role of building control is changing. Other studies have focused on alternative forms of building control (Van der Heijden 2009; Helsloot and Schmidt 2012).

In addition, the focus will be on *Dutch building industry*, because this situation is perceived as problematic (Inspectorate of Housing 2007) and for this situation information is easiest accessible for the author. The results might be used for other countries, although intervening cultural factors may play a role.

Moreover, this study primarily focuses on *the current building industry* (around 2010), with brief attention to recent history and possible trends. Failure cases from 1990 up to 2011 will be included, because 1990 was a starting point for digital availability of various sources of failure cases (see chapter 4).

Furthermore, in this thesis *structural safety* is studied. Structural safety is tightly related to reliability and quality, but can be distinguished from these (see chapter 2). Structural unsafety is often associated with structural failure and accompanying failure costs.

Finally, the focus will not be limited to certain *types of structures*. Building Decree 2012 makes a distinction in buildings and 'other structures than buildings' (Building Decree 2012, art. 1.2). Buildings can have various functions, like residential, health care, industrial, office, sports or leisure. The Building Decree does not specify 'other structures than buildings'. However, it is possible for this category to make a distinction in civil structures and other structures. Civil structures are structures, such as bridges, tunnels, barriers, roads, dams and dikes. Other structures can be temporary structures, like scaffoldings, or other structures that cannot be classified as buildings of civil structures, like pipes and masts. This classification will be used in chapter 4.
In addition, various materials, like steel, concrete and timber, will be included. It might be possible that the type of structure or material influences the factors that are relevant for structural safety.

1.2.3 Key questions

To answer the main research question, the following key questions have been developed:

1. What is structural safety?
2. What is the current way to assure structural safety according to regulations?
3. What is the relationship between human errors and structural failure?
4. What is the current state of structural safety in the Netherlands?
5. What factors influencing safety or quality are suggested by literature?
6. In what way can these factors be grouped and presented in a consistent framework of possible factors influencing structural safety?
7. In what way are factors on macro/meso/micro level expected to influence structural safety?
8. What factors in the design and construction process are critical for the assurance of structural safety in the Dutch building industry?
9. What measures in the building process are expected to lead to improvements?
10. In what way can the current Eurocode approach be improved based on the outcomes of this study?

Every chapter will cover one or two key questions (see figure 1.3).
The thesis will be divided in three parts. Part I will give a description of structural safety within the Dutch building industry (chapter 2-4). Part II will derive the critical factors for the assurance of structural safety based on a theoretical framework (chapter 5-8). Part III will suggest measures that are expected to lead to improvement (chapter 9 and 10). The three parts will be preceded by this introduction and will be accomplished by a final chapter with conclusions and recommendations.

1.3 Methodology

For this study a mixed method (Creswell 2009) will be used, consisting of a combination of qualitative and quantitative methods (failure data and expert opinions) to answer the key questions and, ultimately, the main research question.

Part I: Structural safety in the Dutch building industry
For part I, insight in the current way of assuring structural safety according to Eurocode will be provided by a literature study on definitions and regulations. The current state of structural safety will be clarified by a broad quantitative analysis and comparison of available failure data from four different sources. It will be investigated if the current risks related to structural failure are within risk acceptance criteria.

Part II: Critical factors for structural safety
Part II is the core of this thesis. First, an initial theoretical framework with factors possibly influencing safety or quality is set up, which is based on literature from project management and safety science. This literature is not necessarily focusing on the building industry. A first check on suitability for the building sector is provided by discussing the framework with experts from Dutch building industry.

To understand how macro level can influence structural safety, observations of macro level factors that might threaten structural safety in the Netherlands will be made, that are based on a literature study of key Dutch publications.

To understand how meso and micro levels can influence structural safety a cross case analysis (Yin 2009) is performed. Three major failure cases are selected that were investigated by independent boards. These cases are analyzed with a focus on the factors from the theoretical framework, to illustrate how these factors can influence structural safety.

To derive critical factors on meso and micro levels an approach called: 'the Wheel of science' (see fig. 1.2) will be used, which is based on the work of Wallace (1971).

The principle of the 'Wheel of science' is that, based on an initial theory, hypotheses are developed to test this theory. The hypotheses are tested with observations to prove them true or false. The number of observations is usually limited. When it is reasonable to assume that observations are representative for a larger population, empirical generalizations can be considered. This might lead to new theory or adjustments of the initial theory. The process of hypothesis testing is called deduction, which is a process of reasoning, starting from theory or general statements. The process from observations to theory can be called induction, a process that aims for broader generalizations based on particular observations.

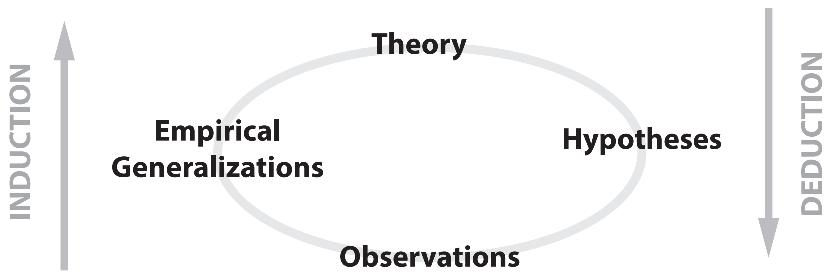


Fig. 1.2 *'Wheel of science', based on Wallace (1971)*

The 'Wheel of science' will start with the theoretical framework with possible influencing factors and uses the idea from the theory of Critical Success Factors that critical factors can be derived. For every factor from the framework the hypothesis will be that the factor is critical for structural safety. These hypotheses will be tested with a national survey. The definition of criticality of factors has to be operationalized for this survey. Critical factors are expected to be those factors that show the largest difference in presence in successful and less successful projects regarding structural safety. Because a statistical relationship is not equivalent to a causal relationship, the derived critical factors will be compared with the list of factors that are directly judged by respondents to be of largest influence for assurance of structural safety.

The outcomes of the survey will be discussed with experts from building industry, to discover if these are actually the factors that need improvement.
Empirical generalization will be made by considering if the critical factors from this survey can be used for general applicability within Dutch and other building industries.

Part III: Exploring improvements
Measures for improvement of structural safety within the Dutch building sector will be suggested in part III. These measures will be based on literature study, interviews, and personal opinion of the author. Furthermore, the possibility of including human and organizational factors to a larger extent within the current Eurocode will be discussed. The mixed methods that are used to answer the key questions are presented in figure 1.3.

1.4 Outline

For every part the contents of each chapter will be explained.

Part I: Structural safety in the Dutch building industry

Chapter 2 discusses the concept of structural safety and the relationship with risk, reliability and quality and will evaluate the current Eurocode approaches to assure structural safety. A description of the Dutch building process and the relationship between human errors and structural failures are presented in chapter 3. Subsequently, structural incidents in the Netherlands are analysed in chapter 4, by presenting Dutch failure statistics based on newspaper publications, a confidential reporting system and Dutch arbitration awards, with a focus on causes and consequences. The figures on fatalities will be compared with figures from Dutch Labour Inspectorate to determine whether current individual risks within building industry meet the requirements.

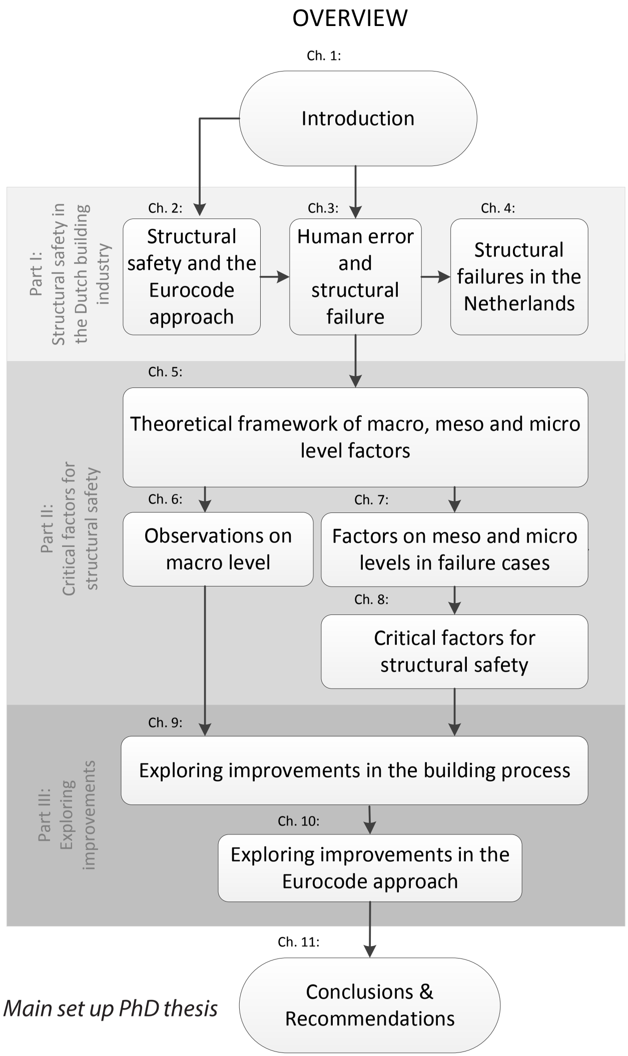
Part II: Critical factors for structural safety

Chapter 5 presents a theoretical framework of possible influencing factors. The factors are derived from management theory and safety science. A categorization for various levels of factors will be proposed. To understand how the macro level factors can influence structural safety, in chapter 6 observations of the external factors (macro level) are listed for the Dutch situation, which might negatively influence structural safety. Chapter 7 continues with an illustration of how meso and micro level factors can influence structural safety, by providing a cross case analysis of three failure cases in the Netherlands, using the theoretical framework. In chapter 8 critical factors for structural safety will be derived on meso and micro levels by analysing the results from a survey within the Dutch building industry.

Part III: Exploring improvements

Chapter 9 explores improvements in the current building practice and chapter 10 modeling opportunities to reinforce the current Eurocode approach to deal with human errors. In chapter 11 the main research question will be answered, followed by recommendations for government, building industry and future research.

Figure 1.3 presents an overview of the chapters of this thesis, together with the key research questions and the methods used.

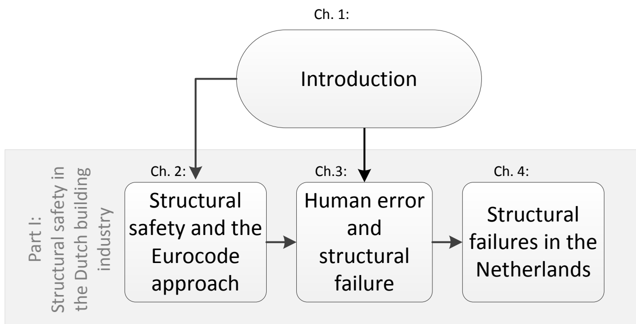


KEY QUESTIONS	CONTENT	METHOD/ SOURCES
• What is the problem?	-scope -aim -methodology -outline	-literature study problems structural safety in Dutch building industry
• What is structural safety? • What is the current way to assure structural safety according to regulations? • What is the relationship between human errors and structural failure? • What is the current state of structural safety within the Dutch Building industry?	-definition structural safety -Eurocode approach -relationship human error and structural failure -presentation failure data	-literature study structural safety, Eurocode, quality management, human error -failure analysis Cobouw, Arbitration, ABC registration and Storybuilder
• What factors influencing quality or safety are suggested by literature? • In what way can these factors be grouped and presented in a consistent framework of possible factors influencing structural safety?	-presentation of distinction in macro/ meso/ micro levels -explanation of possible influencing factors on each level	-literature study management theory (CSF) and safety science -discussion with experts
• In what way are factors on macro/meso/micro levels expected to influence structural safety?	-review of Dutch literature on factors influencing structural safety on macro level -Investigation of Dutch failure cases on factors influencing structural safety on micro level and meso levels	-literature study relevant Dutch publications -Cross case analysis for meso and micro factors
• What factors on micro/meso levels are critical factors for the assurance of structural safety in the Dutch building industry?	-explanation method and results national survey	-questionnaire -statistical analysis results questionnaire -interviews
• What measures in the building process are expected to lead to improvements?	-suggestions for improvement	-qualitative analysis
• In what way can the current Eurocode approach be improved based on the outcomes of this study?	-review of Eurocode with outcomes of this study -options modeling human error and structural reliability	-qualitative analysis -quantitative exploration of models

MAIN RESEARCH QUESTION:
What factors in the design and construction process within current Dutch building industry need improvement with regard to structural safety?

Figure 1.3 *Main set up PhD thesis*

PART I:



STRUCTURAL SAFETY IN THE DUTCH BUILDING INDUSTRY

"Understanding failure is the foundation of engineering success."
C. Georgopoulos

2

Structural safety and the Eurocode approach

2.1 Introduction

Safety is a broad concept. It is possible to distinguish at least 100 types of safety (Zwaard 2007). This thesis will focus on structural safety in the Netherlands. As a starting point, this chapter will provide a definition of structural safety and will explain the current formal way to assure structural safety, according to the Eurocode.

Dutch building structures have to meet the requirements of the Building Decree (in Dutch: 'Bouwbesluit'), regarding safety, health, usability, energy efficiency and environment. This Decree designates parts of the Eurocode for structural design. This chapter will focus on the Eurocodes, because these are the current regulations and will be the regulations for the near future. Therefore, it will not describe the Dutch TGB-codes which were applicable until 2012.

In this chapter, first, hazard, risk and structural safety will be defined, based on the definitions as used in the Eurocode. In addition, the two-fold way Eurocode prescribes to assure structural safety is presented. The first way is a calculation method in which reliable and robust structures can be designed. The second way is a prescription of quality management that should be used during the building process. For both ways some relevant aspects are listed.

2.2 Hazard, risk and structural safety

Safety is a multifaceted concept, which is often looked at in terms of threats to life or in terms of the economic costs of failure (Elms 2004). Safety cannot be quantified directly, as is pointed out by several authors (Schneider 1997; Elms 1999; Suddle 2004). Safety is a state and it cannot be measured and presented directly, with the currently available units. To objectify the assessment of safety, it can be operationalized by the concept of risk (CUR 1997).

The following subsections will explain the concepts of hazard, risk and structural safety. In addition, an introduction will be given on the level of acceptable risk as is agreed upon in the Netherlands.

2.2.1 Hazard and risk

Risk is associated with the likelihood that a hazard will be realized and the consequence should it do so (Cormie 2013, p. iv). Hazard is defined in Eurocode as "an unusual and severe event, e.g. an abnormal action or environmental influence, insufficient strength or resistance, or excessive deviation from intended dimensions" (art. 1.5.2.9, NEN-EN 1990:2002). A hazard is often associated with something which has the potential to cause harm (Cormie 2013, p. iv). Hazards can be foreseeable or unforeseeable. With regard to structures a distinction can be made in natural hazards (wind, earthquake, floods) and man-made hazards (terrorism, human errors). Vrouwenvelder (2014) provides a more extensive overview of foreseeable hazards (actions) relevant for structural engineering, as depicted in table 2.1.

Table 2.1 *Overview of foreseeable hazards (derived from Vrouwenvelder (2014))*

Normal loads (including tail values)	Accidental/natural	Accidental/manmade	Human influences	Human errors
Self-weight	Earth-quake	Internal explosion	Vandalism	Design error
Imposed loads	Land slide	External explosion	Demonstrations	Material error
Car park loads	Hurricane	Internal fire	Terrorist attack	Construction error
Traffic	Tornado	External fire		Misuse
Snow	Avalanche	Impact by verhicle etc.		Lack of maintenance
Wind	Rock fall	Mining subsidence		Miscommunication
Hydraulic	High groundwater	Environmental attack		
	Flood			
	Volcano eruption			

Schneider (1997) points out that it is important to use hazard scenarios, because combinations of hazards might occur.

Risk can be defined as the function of the probability and the consequences (CUR 1997). Kaplan and Garrick (1981) emphasize, similar to Schneider, that it is important to have a scenario, a plausible story, of how a consequence could actually present itself to set the probability to a non-zero number. When various failure scenarios are taken into account, this results in the function:

$$R = \sum_{i=1}^{n} P_{f;i} \cdot C_{f;i}$$

Hence, the total risk of failure is the sum of the product of the probabilities of failure ('P_f') and the consequences ('C_f') of 'n' scenarios ('i').

Risk is usually quantifiable, as probabilities as well as consequences can often be quantified. Consequences can be quantified as, for instance, a number of fatalities, injuries or amount of failure costs among others (Janssens, O' Dwyer et al. 2012).

2.2.2 Acceptability of risks

People in general are willing to accept a certain amount of risk, although the acceptability depends on many factors: extent and probability of damage, catastrophic potential, involuntariness, lack of equity, uncontrollability, lack of confidence, new technology, non-clarity about advantages, familiarity with the victims and harmful intent (Ale 2009). People, therefore, will vary in the way they perceive and accept risks. Some people are thrill seekers and voluntarily expose themselves to the high risks of mountaineering and deep sea diving. Many others are more risk averse.

One of the most severe risks is the likelihood of fatalities. Usually, people do not like the concept of acceptable fatalities. After a disaster, in press people often argue that "this should not happen in a developed country like the Netherlands", indicating a probability of failure of zero. Although this is not realistic, public opinion tends to be more deterministic than probabilistic; to many people safety seems to be the absolute freedom from harm.

Although risk acceptance criteria are confronted with ambiguity, for rational decision making and structural calculations in accordance with a probabilistic approach, it is necessary to agree upon acceptability limits.

Ale (2009) explains the difference between individual risk and group risk. Individual risk is the probability that a person will come to a particular harm. For various individual risks different limits are suggested. In the Netherlands, as a starting point it is assumed that "the risk from a hazardous activity to a member of the public should not be significant to the risk in every day life" (Ale 1991). The risk in every day life is taken as 10^{-4} (probability of death for an individual person per year). For new hazardous installations (related to external safety) the maximum acceptable level for individual risk was set to 10^{-6} which implicates an increase of the risk in every day life of 1% (Ale 1991).

After flooding of part of the Netherlands in 1953, the Technical Advisory Committee for Water Retaining Structures (TAW) proposed a model for deriving safety standards(Vrijling et al. 1995; CUR 1997, p. 4-19). In this model the voluntariness of activities was included with a policy factor. For the risk of flooding, generally an individual risk limit between 10^{-5} and 10^{-6} was used. However, in 2013 the Ministry of Infrastructure and the Environment proposed to use an individual risk of 10^{-5} (Schultz van Haegen 2013). The Ministry explained that this choice was made because this risk is caused by nature, which is harder to influence than a manmade hazard. In addition, it was explained that a level of 10^{-6} for the entire area of the Netherlands would not be cost effective.

For existing structures, Vrouwenvelder and Scholten (2008) suggest an acceptable individual risk of 10^{-5} for death of an individual person due to failure of a structural element. Although there is currently no general agreement regarding the individual risk of dying due to structural failures, for this thesis this value of 10^{-5} will be used.

Group risk, or societal risk, is the probability or frequency that a group of a certain size will be harmed simultaneously by the same event or accident (Ale 2009). It is usually presented in the form of an FN curve, where each point on the line represents the probability that the extent of the consequence is equal to or larger than the point of value. Based on individual risk limits, societal risk limits have been set in the 'Premises for Risk Management' (Ale 1991). Within structural engineering of buildings the notion of group risks is usually neglected.

In addition to fixed acceptability probabilities, several approaches to reduce risk have been suggested, especially for application in the UK (Cormie 2013). An example is the ALARP principle which states that all risks have to be reduced to a level As Low As Reasonably Practicable. In this approach the definition of 'reasonable' is disputable (Ale 2009).

As stated before, limits for the acceptability of the risk of fatalities are confronted with ambiguity. Eurocode circumnavigates this by only setting acceptability limits for the probability of failure of single elements, without an explicit relationship with the probability of death. This study will assume, as a starting point for the acceptability of risks, that the level of structural safety is adequate when the requirements for existing structures are met. In chapter 4 it will be checked if this assumption is reasonable.
Furthermore, this section did not focus on the acceptability of risk of failure costs. In some situations, where failure of a structure can result in a considerable amount of failure costs, this criterion might result in stricter requirements than the limits related to the risk of fatalities.

2.2.3 Structural safety defined

Eurocode uses the concept of risk, by defining safety as "a state in which the risk of harm (to persons) or damage is limited to an acceptable level" (ISO 8402, art. 2.8). At this point, Eurocode makes a distinction in safety of people (related to the risk of harm to individual persons) and safety of the structure (related to the risk of damage and accompanying costs). However, in general safety is associated with the freedom from personal harm (see (Elms 2004)).

This study focuses on structural safety. In Eurocode structural safety is defined as the "capacity of a structure to resist all action(s), as well as specified accidental phenomena, it will have to withstand during construction work and anticipated use" (NEN-ISO 6707-1: 2004 art. 9.3.82). This straightforward technical definition is closely related to reliability of structures, which is defined as "the ability of a structure or a structural member to fulfil the specified requirements, including the design working life, for which it has been designed" (EN 1990: 2002, see also section 2.3).

For this study the concepts of safety and structural safety as defined within Eurocode are combined, resulting in an adapted definition:

Structural safety can be defined as the absence of unacceptable risk associated with failure of (part of) a structure.

The primary focus of this study will be on the absence of unacceptable individual risk, although the relevance of the risk of failure costs will be acknowledged.

In section 2.3 and 2.4 Eurocode's two-way approach to assure structural safety will be clarified. Structural failure will be defined in section 2.3.

2.3 Structural calculation in conformity with Eurocode

Within Eurocode reliability and robustness of structures are the central concepts, which will be explained in the following subsections.

2.3.1 Reliability

Reliability is defined in EN 1990:2002 as:

"the ability of a structure or a structural member to fulfil the specified requirements, including the design working life, for which it has been designed. Reliability is usually expressed in probabilistic terms".

In addition, EN 1990:2002 states: "Reliability covers safety, serviceability and durability of a structure". In the vision of Eurocode safety is just one aspect of reliability.
The central idea within Eurocode is that the resistance of a structure (R) with sufficient reliability should be larger than the effects of the loads (E). The resistance of an element will depend on the amount of applied material, the material characteristics and the boundary conditions of the system (for instance length and type of support). The failure probability P_f can be calculated as:

$$P_f = P(g \leq 0)$$

Where: g = R - E.

Reliability (P_s) is directly related to the failure probability:

$$P_s = 1 - P_f$$

It is common to express the failure probability (P_f) as a reliability index (β):

$$P_f = \Phi(-\beta)$$

Where: Φ is the cumulative distribution function of the standardized Normal distribution (EN 1990:2002, C5).

Although Eurocode provides the option for a probabilistic approach (which is called a level II or III method), structural engineers generally use partial factor design (which is called level I method). Level I calculations are based on the assumption that an element is sufficiently reliable if a certain margin is present between the representative values of the resistance and the loads. The use of partial factors in the design ensures this margin (CUR 1997). With these factors stochastic variability is covered, which is related to uncertainties in materials, geometry, calculation models and loads. Stochastic variability does not include gross human errors (see also section 3.6).
The partial factors might be different for individual countries, because a country can prescribe its own factors in national annexes. For the Netherlands the factors are based on factors in previous national codes, although a probabilistic approach was used to check the validity of existing factors.

Partial factors for loads are dependent on the reliability class (RC) and the limit state. The reliability class takes the necessary level of reliability into account, which is dependent on the severity of possible consequences regarding loss of life and economic, social or environmental consequences.
Each reliability class has another reliability index β; for structures with an expected higher loss (high consequence class) a lower probability of failure is accepted (higher β factor). This usually corresponds with a failure probability of 10^{-4} for structural elements (corresponding to a β value of 3.8 for a 50 year reference period and RC2, according to B3.2 of EN 1990:2002. Higher or lower values in RC3 and RC1 can be reached by adding a factor K_{fi} on the loads.). For RC1 the lowest level of reliability is required, because of the limited consequences in the case of a failure, RC2 and RC3 correspond with higher consequence classes.

Thus, the reliability approach is usually based on an accepted failure probability of 10^{-4} for single structural elements. However, if an element fails just in some cases persons will get harmed. Therefore, the probability of death will be lower than 10^{-4}. Eurocode does not give a quantitative acceptable limit for the accompanying probability of death (individual risk). However, Vrouwenvelder and Scholten (2008) assume this to be 10^{-5} per year for existing buildings, as explained in 2.2.

Eurocode covers various limit states. Ultimate Limit States (ULS) are associated with collapse or similar structural failures (EN1990:2002, 1.5.2.13). Examples are loss of equilibrium, attainment of maximum (or ultimate) capacity, transformation into a mechanism and instability are covered.
In the Serviceability Limit State (SLS), situations like local damage, unacceptable deformations and excessive vibrations are covered (Chryssanthopoulos and Frangopol 2005).

For this study a definition of structural failure is used, which is closely related to Eurocode's definition of reliability. Structural failure is defined as the inability of a structure or a structural member to fulfil the specified requirements. Structural failure is associated with exceedance of the resistance of (part of) a structure by the effect of the loads. Structural failures can manifest themselves in various forms (see section 3.4). This study will have a primary focus on structural failures associated with exceedance of the ULS, because these situations usually result in a higher level of risk for persons and structures.

Figure 2.1 presents the relationship between structural failure, reliability and structural safety in an event tree as used in this thesis.

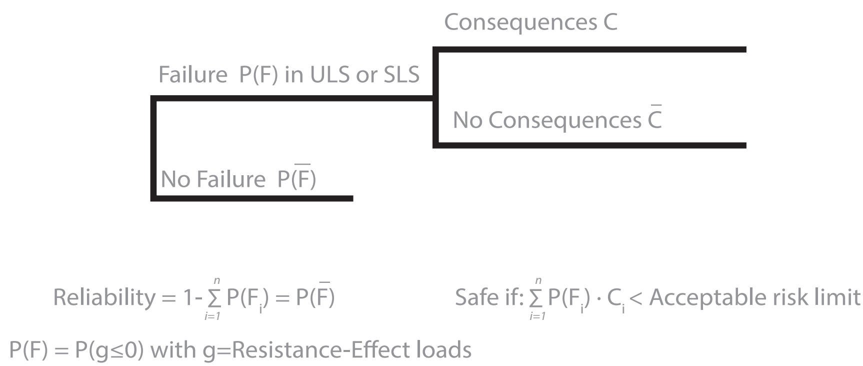


Figure 2.1 *Relationship structural failure, reliability and structural safety*

A structure can fail (with probability P(F)) in various limit states or cannot fail. It was explained that reliability can be expressed as: $P_s = 1 - P_f$. When various scenarios of failure are possible and it is assumed that the events are exclusive, this can be expressed as:

$$P_s = 1 - \sum_{i=1}^{n} P(F_i)$$

When a structure fails, this might lead to consequences of a specified type but not necessarily. Subsection 2.2.1 explained that a state of structural safety meets the acceptability limits for risks of damage or personal harm.

This state can be expressed as:

$$\sum_{i=1}^{n} P(F_i) \cdot C_i < R_{acceptable}$$

With:
$P(F_i)$ = probability of failure of a structure given a scenario i
C_i = magnitude of the consequences given a scenario i
$R_{acceptable}$ = acceptability limit of the total risk.

Structural safety is generally related to reliability, because an increased probability of failure will usually lead to an increased probability of consequences (like damage or personal harm) and, thus, in an increased risk. However, it will be hard to determine the total risk, because various kinds of risk might have different entities.

Furthermore, determining if a structure is acceptably safe is not possible by examining safety of a single element of that structure. Safety should be regarded as 'an emergent property of systems that arises from the interaction of system components' (Leveson 2004, p. 11). The single element should be regarded in the context of the whole. Therefore, it will be hard to determine the total risk, because the likelihood of a consequence might not be directly related to P(F) of a single element.

Eurocode includes this notion with the concept of robustness.

2.3.2 Robustness

Although Eurocode primarily focuses on the reliability of single elements, the coherence of the individual elements as part of an integral structure is ensured by stating:

"A structure shall be designed and executed in such a way that it will not be damaged by events such as: explosion, impact, and the consequences of human errors, to an extent disproportionate to the original cause." (EN 1990:2002, 2.1.4).

This can be achieved by designing robust structures. Robustness is defined as (EN 1991-1-7:2006) "the ability of a structure to withstand events like fire, explosions, impact or the consequences of human error, without being damaged to an extent disproportionate to the original cause" or, in fewer words: "the ability of a structure to survive after some initial damage" (Vrouwenvelder 2011).

Robustness deals with accidental situations like explosions, fires and human errors. Eurocode distinguishes two types of strategies to cope with such situations, depending on whether they are the result of an identified accidental action (like explosions and impact) or an unidentified accidental action (limitation of the extent of localized failure). Unidentified actions can be design errors, execution errors, material defects, terrorist attacks or abuse by users (Terwel, Wijte et al. 2011). For these latter actions structural measures are proposed, like enhanced redundancy, key element approach and prescriptive rules, as well as non-structural measures (Terwel, Wijte et al. 2011).

Section 2.5 will focus on the quality management method Eurocode suggests to deal with human errors and it will elaborate on non-structural measures.

2.3.3 Problematic aspects of the calculation method

Although Eurocode provides a clear framework and it is widely believed that the quality of the codes is on a high level (VROM-inspectie 2007, p. 19), some remarks on the Eurocodes can be made.

First of all, an increasing complexity of building codes can be observed. For example, in Dutch codes of 1972, only 10 pages were spent on wind loads, while in current Eurocode EN 1991-1-4 this issue involves 163 pages (Van Herwijnen 2009). In addition, the level II and III calculations, which are an option in Eurocode EN 1990, are rarely used by building engineers, because they prefer the easier level I calculations, which are similar to the usual deterministic approach.
The complexity of the codes can be a source of human error in itself when engineers do not understand the various aspects of complicated calculations, although it should be noted that including advanced knowledge within codes is expected to lead to models that better reflect reality.

In addition, some authors argue that failure can occur in complex structures due to unexpected interference between reliable elements (Perrow 1999; Hollnagel, Wood et al. 2006). However, this phenomenon is not often reported for buildings and civil structures. Probably just a small number of structures can be regarded as complex, which is a necessary prerequisite for this unexpected interference. In chapter 8 it will be checked if complex structures are more prone to errors than usual structures.

Finally, Eurocode provides target reliability indices (β), which are not firmly based on failure data, but are merely a political decision. It is not known if the actual failure probabilities are really acceptable. Eurocode primarily focuses on the probability of structural failures and not on the probability of fatalities or injuries. At the moment, the accepted failure probability of single elements in Eurocode (10^{-4}) is not related to the accepted individual risk due to external threats of industry (10^{-6}, see subsection 2.2.3), although an acceptable individual risk of 10^{-5} in the case of structural failures is assumed (see subsection 2.2.3). However, Madsen et al. (2006) counter-attack this critic by stating that it is not the aim of a technical model to portray reality, but to substitute reality and a technical model should be an aid to decision making.
In chapter 4 it will be investigated if safety of Dutch structures stays within acceptability limits.

2.4 Quality Management

The second way of Eurocode to ensure structural safety is quality management. Quality management in conformity with Eurocode aims to eliminating gross human errors, to meet the assumptions of the structural calculations. The following subsections will explain the way Eurocode intends to assure quality. In addition, the way quality is supposed to be assured in accordance with the widely accepted quality system ISO 9001 will be described. But first the difference between safety and quality and the difference between quality management, quality assurance and quality control will be explained.

2.4.1 Definitions quality management

Quality is regarded as the degree to which a set of inherent characteristics fulfils requirements (NEN ISO 9000: art. 3.1.1). Bea (1994) assumes that serviceability, safety, durability and compatibility are all aspects of quality. Thus, safety is strongly related to quality as Booth (2005) states: "Safety is only one of a number of aspects of 'quality' though it is clearly a very important one". Hence, quality is a broader concept than safety.

NEN ISO 9000 provides definitions for quality related issues that can be used for interpretation of the Eurocode.
Quality management is defined as "the coordinated activities to direct and control an organization with regard to quality" (NEN ISO 9000: art. 3.2.8). Generally, this includes the establishment of the quality policy, quality objectives, quality planning, quality control, quality assurance and quality improvement.
Quality assurance is the "part of quality management that is focused on providing confidence that quality requirements will be fulfilled" (NEN ISO 9000: art. 3.2.11)
Quality control can be defined as "the operational techniques and activities that are used to fulfil requirements for quality" (ISO 8402 was the precursor of NEN ISO 9000, as cited in (Booth 2005)).

From these definitions the difference between quality assurance and quality control is not completely clear. A practical distinction is that quality assurance aims to prevent defects and quality control aims to detect and correct defects (Bea 1994, p. 12). Although some authors point out that quality control is part of quality assurance, for this study Bea's distinction will be used, with for quality assurance the proactive, preventive approach to determine measures and for quality control a reactive approach of checking the products.

2.4.2 Quality management in conformity with Eurocode

Eurocode provides some guidance in relevant issues of quality assurance.
EN 1990:2002 assumes minimum requirements on the skills and experience of personnel (EN 1990:2002 art. 1.3). Personnel should be acquainted with the knowledge and good practice that is generally available at the time the design of the structure is carried out (art. 2.1.7). In addition, it assumes the use of suitable materials and the existence of control and inspections (art. 1.3). Furthermore it gives some unspecified suggestions, like application of measures related to quality management (art. 2.2.5c and 2.5), "measures aimed to reduce errors in design and execution of the structure, and gross human errors" (art. 2.2.5d), implementation of safety barriers (art. 2.2.5a) and application of organizational measures (art. 2.5). Finally, it states that "the measures to prevent potential causes of failure and/or reduce their consequences may, in appropriate circumstances, be interchanged to a limited extent provided that the required reliability levels are maintained" (art. 2.2.6). This statement is not further clarified.

Eurocode provides little guidance on structural risk analysis in the informative Annex B of EN 1991-1-7: 2006. A general approach for qualitative or quantitative risk analysis is suggested, although information on specific application for structures is primarily limited to an enumeration of accidental loads (art. B 4.1) and quantification of risks (art. B 9.2). However, guidance on risk analysis of potential threats within the building process is generally lacking.

Eurocode provides more specific guidance for quality control. First, it explicitly states that appropriate quality management measures should be in place, such as controls at the stages of design, execution, use and maintenance (art. 2.5.1).
Furthermore, it explains that "quality management and control measures in design, detailing and execution which are given in B4 and B5 aim to eliminate failures due to gross errors, and ensure the resistances assumed in the design" (note in appendix B1b). Moreover, several types of supervision in the design phase are related to the reliability classes (appendix B4 of EN 1990:2002, see table 2.2), although this appendix is only informative and not prescriptive. In appendix B5 of EN 1990:2002 a similar categorization has been made for inspection during construction.

Table 2.2 *Levels of supervision design phase (appendix B4 of EN 1990:2002)*

Design supervision levels	Characteristics	Minimum recommended requirements for checking of calculations, drawings and specifications
DSL3 relating to RC3	Extended supervision	Third party checking: checking performed by an organization different from that which has prepared the design
DSL2 relating to RC2	Normal supervision	Checking by different persons than those originally responsible and in accordance with the procedure of the organization
DSL1 relating to RC1	Normal supervision	Self checking: checking performed by the person who has prepared the design

Finally, Eurocode suggests that "design supervision differentiation may include a classification of designers and/or design inspectors (checkers, controlling authorities, etc.), depending on their competence and experience, their internal organization, for the relevant type of construction works being designed".

It can be concluded that Eurocode gives very little guidance on quality assurance with a primary focus on appropriate skills and gives some guidance on quality control with various types of supervison. Hence, it is to be expected that the factors (appropriate skills and adequate supervision) do not cover all procedural issues influencing the structural safety of projects. In addition, some suggested procedural measures are ill-defined, like "the application of safety barriers".

In a note of Eurocode EN 1990:2002 art. 2.5.1 it is stated that "EN ISO 9001:2000 is an acceptable basis for quality management measures, where relevant". The folowing sub-section will explain this standard.

2.4.3 Quality management in conformity with ISO 9000 and ISO 9001

An internationally accepted standard for quality management is ISO 9001:2008. It does not establish requirements for products, but specifies requirements for a quality management system. Many Dutch building companies are working in accordance with these requirements.

ISO 9000:2005 provides the fundamentals and vocabulary for the quality management approach of ISO 9001:2008. This broad approach is based on eight principles (ISO 9000:2005, art. 0.2)

1. Customer focus
2. Leadership
3. Involvement of people
4. Process approach
5. System approach to management
6. Continual improvement
7. Factual approach to decision making
8. Mutually beneficial supplier relationships.

Within this approach the role of top management is very important (art. 2.6), and the relevance of appropriate documentation is underlined (art. 2.7).

The general requirements of ISO 9001:2008 are that an organization determines its processes needed for the quality management system, determines the sequence and interaction of these processes, determines criteria and methods needed to ensure that both operation and control of these processes are effective, ensures the availability of resources and information (human resources, infrastructure, working environment), monitors and analyses these processes and implements actions for improvement (ISO 9001:2008, art. 4.1).

Internal and external audits are performed to check if a company is still working according to its formal procedures. This procedure is based on the Deming circle: Plan the activities, Do the activities, Study (or check) how you did the activities and Act if there are deviations from the planned procedure that might result in a change of methods (ISO 9001:2008: figure 1).

The basic philosophy of ISO 9001:2008 is that a structured and controlled process will lead to a good product. Favie (2010) finds a 95% agreement among 50 experts for this basic assumption that a good process will lead to a good product. However, care should be taken with this assumption, because, as Elms (2001) states ,"a good quality assurance scheme is essential to safety; but while necessary, it is not sufficient". In other words, a good process will not always result in a good product. The next subsection will deal with some other problematic aspects of quality management.

2.4.4 Problematic aspects of quality management

First, some general critics regarding quality management will be listed and in addition the ambiguous way Eurocode deals with human errors will be discussed.

A general critic on quality management is that it generates an abundance of paperwork, and it might give a false sense of security (Booth 2005, p. 150). Furthermore, the ISO standards use terms and languages that are rather inaccessible for structural engineers and not in the least for persons on the building site, who will not be familiar with legal phrases. Within Eurocode the use of definitions of quality management, quality assurance and quality control is sometimes unclear or inconsistent.
These aspects might have contributed to a skeptical attitude towards quality management within building engineering. When several building participants were asked for the effectiveness of several measures to improve structural safety, stricter regulation and certification were at the lower end (CUR Bouw & Infra 2011, p. 88).

Dijkstra (2006, p. 201) adds to this criticism:

"Quality management focuses on compliance with procedures, rules and regulations of people and organisations in their activities. The approach that quality guarantees safety builds on a world view that compliance is always possible, that all procedures are perfect, that no failures outside the design occur, that all performance is constant, and that no constraints exist which limit the ability of people to have full knowledge certainty and time to do their work. This view explains that accidents are caused by deviations from the approved procedures, rules and regulations, thus quality and safety have a complete overlap.
A more realistic view is that the complexity and dynamics of our world are not so predictable that all rules, regulations and procedures are always valid and perfect…Quality as a pro-active approach to safety is a limited (approach-KT) but research and science has not yet delivered practical alternatives."

In addition to general critics on quality management, the way Eurocode deals with human errors may be criticized.

First, several types of human errors are distinguished in literature, like errors of concept (stupidity, ignorance), errors of execution (carelessness, forgetfulness, negligence) and errors of intent (venality, irresponsibility) (see subsection 3.3.2). It is not made clear in Eurocode how to deal with these different type of errors.

Related to this issue, the effectiveness of self checking to correct human errors (table 2.2, RC1) is questionable and with third party checking it is hard to ensure that various parties are really independent. In addition, providing differences in the level of checking are not reflected by additional (reduction) factors in the partial factor approach, similar to K_{fi}.

Furthermore, the organizational factors influencing human errors are largely neglected. However, factors like communication, coordination and collaboration are expected to be of importance for the assurance of structural safety.

Moreover, the Eurocode provides a two-way approach, where each way is not developed to the same extent. The one way is a (detailed) calculation with partial load factors, based on a probabilistic philosophy. The other way is a general, often ill-defined quality management approach. It might be useful to bring these two ways on the same comparable level, for instance, by combining them in an integrated, probabilistic approach. Chapter 3 will highlight the relationship of human performance and structural performance and section 10.3 will elaborate on an integrated approach to combine both.

A final remark on the Eurocode approach is that the prescribed risk analysis for consequence class 3 structures is insufficiently clarified within Eurocode. Other sources with a focus on implementation of risk management are available (Adviesbureau ir. J. Hageman B.V. 2007; Faber et al. 2008; Cormie 2013). However, if no further guidance on a risk analysis of the structure as well as the building process is prescribed within Eurocode, every building participant can make his own interpretation of the content of a risk analysis.

It can be concluded that an elegant incorporation of human errors in Eurocode and ways of dealing with it are still lacking or immature.

2.5 Conclusion

The main focus of this chapter was to define structural safety and to explain in what way the Eurocode intends to assure structural safety.

Structural safety has been defined in this chapter as the absence of unacceptable risk associated with failure of (part of) a structure. To assure a state of safety, it is desirable to set acceptability limits of risk, which are available for various types of risks in the Netherlands. In chapter 4 it is checked if the current situation regarding structural safety meets the requirements for acceptability of individual risk, as presented in this chapter.

One should be aware that public often regards safety in deterministic terms as the absolute absence of harm. However, this assumption cannot be regarded to be reasonable.

The current Eurocode philosophy to assure safety is a combination of two approaches. First, calculations have to be made in which the resistance of a structure should be larger than the effect of the loads, to meet the acceptable failure limits. By including the concept of robustness, it is recognized that a focus on single elements is a limited one. Second, quality management is suggested to provide reliable design and construction processes.

The latter approach is still under development within Eurocode; measures are sometimes ill-defined and organizational factors are largely neglected.

Therefore, a study of process factors, related to quality management, will be the primary focus of this thesis, in order to suggest measures for improvement of current weaknesses in the quality management approach of Eurocode (chapter 10).

Human error and structural reliability are separate concepts within the two-way Eurocode approach. Chapter 3 will elaborate on these concepts and will explore if they can be related to each other and combined in an integrated approach.

3

Human error and structural failure

3.1 Introduction

In chapter 2 the Eurocode approach to assure structural safety was explained. Structural safety is in this study regarded as a state within limits of acceptable risk. The risk is associated with structural failure. When investigating structural failures, as for instance in chapter 4, it is important to know the physical behaviour of the structure when the failure occurred. But to learn from failures, it is as least as important to understand the role of human performance and its influence on the structural failure.
Therefore, a classification is needed of various types of structural failure and human error, and the relationship between human error and structural failure should be clarified.

In this chapter, first, attention will be paid to the building process, the various tasks that have to be performed to realize a structure and the possibilities of human error during this process. Second, various types of structural failure will be explained. Finally, the contribution of human error to structural failure will be clarified.

3.2 Building process

A process can be defined as "any activity, or sets of activities, that uses resources to transform inputs to outputs" (ISO 9000:2005, art. 2.4). A structure is usually developed in the form of a building project. Within a project various phases are distinguished, in which tasks have to be carried out by various actors. The following subsections cover various parts of the building process, starting with the characteristics of a project.

3.2.1 Project

A project is a "unique process, consisting of a set of coordinated and controlled activities with start and finish dates, undertaken to achieve an objective conforming to specific requirements, including the constraints of time, cost and resources" (ISO 9000:2005, art. 3.4.3). This type of organization of work is distinct from improvised work or routine work.

According to Wijnen et al. (1996, p. 17) working in a project is useful when:

- The expected results are not completely new, although there are some new elements or aspects
- People from various disciplines should accomplish the goals together

- A one-off maximum performance should be accomplished
- Resources are limited

Within current building practice the design and construction of structures is usually regarded as a project because they often have a one of a kind design, which should be made with various unique project partners from various disciplines, within limited budget and time. This situation with unique projects distinguishes the building industry from other industries, like the manufacturing of airplanes and process industry. The low amount of repetition impedes learning, because every project can be regarded as a prototype (Terwel and Zwaard 2012). A way to change this system with unique projects will be suggested in section 9.9. This study, however, will use the current system as a starting point.

3.2.2 Actors

Within building projects various actors are relevant. First, the client, who will occupy and/or use the structure. A distinction can be made between experienced and inexperienced clients. The first group will execute various building projects, and will usually be professional clients, such as social housing organizations, municipalities, provinces, Directorate General for Public works and water management (in Dutch: Rijkswaterstaat), corporate housing divisions, investors, and project developers. The second group consists of incidental clients who are inexperienced in building projects. They can be private or professional clients.

The financier of the project might be the same as the client, but sometimes external financiers are present. Often a client hires a project developer who coordinates all activities by the design and the construction team.

The design team of larger projects usually consists of an architect, structural engineer, MEP consultant (Mechanical, Electrical, Plumbing) and cost advisor, although the nature of a project might demand extra advisors. The construction team usually consists of a main contractor, who hires subcontractors for various elements. In addition, he buys building products directly from suppliers.

Municipality currently plays a role within the process in building control, although it is expected that this role will be reduced (Helsloot and Schmidt 2012). In this study the basic assumption is that the private parties (client, advisors and contractor) are responsible for the quality of the structure, and the role of municipality will just be regarded as an additional way of (system) control (see subsection 1.2.2). This assumption is chosen, because it meets the current philosophy of Dutch government.
These are the main actors directly involved in the projects, although others actors, like action groups, users etc. might play a role in the building process.

Various participants have to collaborate within a building project. In the traditional approach a client hires various advisors for the design and a main contractor for the execution (fig. 3.1). Some authors relate the main problems for structural safety to the interaction between various building parties (see chapter 6-8).

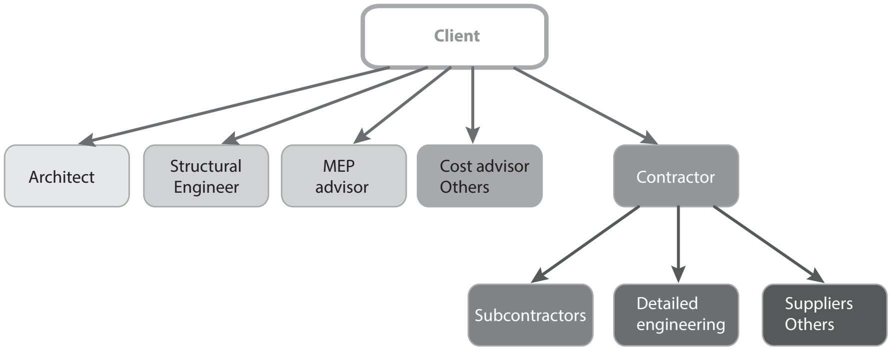


Figure 3.1 *Contractual relations among various actors in traditional form of collaboration*

In contrast with the traditional approach, various forms of integrated contracts are possible, where for instance contractors and engineers work closer together. The results of research on the influence of form of collaboration on structural safety are ambiguous. In a comparison study of the assurance of structural safety of 15 building projects the form of collaboration was not found to be of influence on the level of quality assurance (Mans et al. 2009). Other researches indicate that integrated contracts might have a positive influence on structural safety (Dijkshoorn, Terwel et al. 2013). However, as stated in subsection 1.2.2, this study will not focus on the type of contract, but on underlying issues like coordination and allocation of responsibilities which are part of every type of contract (see chapter 5 and 7).

The following subsections will describe the tasks in the design and construction phase.

3.2.3 Phases in the building process

Compendium Structural Safety (Spekkink 2011, p. 81) distinguishes the following phases in the building process: initial phase, design phase, construction phase and use phase.

In the initial phase the program of requirements will be developed and the feasibility will be assessed. The client and often an advisor are the main actors in this phase.
The design phase in the Compendium Structural Safety consists of three stages: the Preliminary design, the Detailed Design and the Technical design.

The aspects of the structural design for every design stage are, according to the Compendium:

- Preliminary design (in Dutch: 'VO: Voor(lopig) Ontwerp'): in this stage a main set up of the load bearing structure, a preliminary choice of material, a rough dimensioning of elements of the main load bearing structure and a first proposal for the foundation principles have to be made
- Detailed design (in Dutch: 'DO-Definitief Ontwerp'): a design and calculations have to be made with attention to: weights, stability, analysis of deformations and changes in geometry, definitive main set-up and global dimensions of main load bearing structure, overview of foundation or pile plan and principle detailing
- Technical design (in Dutch: 'Technisch ontwerp' or 'Besteksontwerp'): in this stage the following documents have to be prepared: structural specification drawings, main calculations, technical specifications of structures and structural elements. Usually, these are part of the contract documents.

In traditional building projects the client or his delegate and advisors (at least architect, structural engineer and technical services (MEP)) are the leading actors in the design phase.

Construction-ready technical design (in Dutch: 'Uitvoeringsgereed ontwerp') is distinguished as a separate stage between design and construction, alhough in the Compendium Structural Safety this stage is included in the construction phase. In this stage structural detailed shop drawings and calculations have to be finalized. In this phase attention has to be paid to fabrication and erection issues.

In the construction phase the structure will be built. As the design evolves, the engineers of the (sub) contractor will come to the stage and in the construction phase the contractor will take the lead. The role of the designers will be reduced and will focus on control activities, although sometimes the design engineers are hired for detailed engineering too.

In the use phase, the structure is delivered and can be used for various purposes.

For this study the following distinction will be used: design phase (preliminary, detailed and technical design), construction-ready technical design (or detailed engineering) and construction (see figure 3.2). In subsection 4.4.3 the distinction in phases is used, when the phase with the main cause is determined for various failure cases.

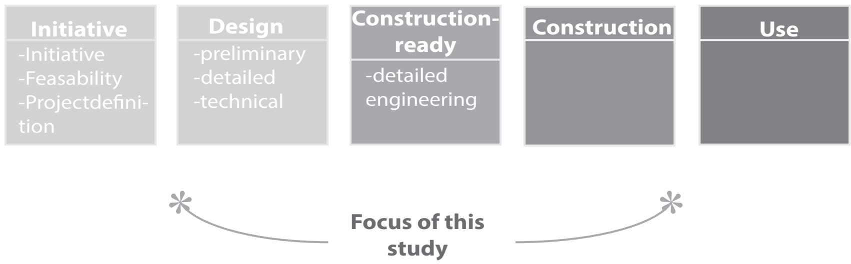


Figure 3.2 *Phases in building process and focus of this study*

This study will focus on the design and construction phase of a project, because these phases are expected to be the primary origins of structural failure (subsection 1.2.2, this assumption will be checked in chapter 4). The following subsection will elaborate on the tasks in these phases.

3.2.4 Tasks in design phase

Compendium Structural Safety (Spekkink 2011, pp. 86-90) lists several tasks for various actors in the various stages. Tasks can be regarded as formally intended activities, which indicates that there might be a difference in the formally intended tasks and the actually performed activities. Often the tasks are appointed in a procedure, which is a "specified way to carry out an activity or a process" (ISO 9000:2005, art. 3.4.5).

The tasks leading to a structural design are (Spekkink 2011, pp. 86-90):

- Making an architectural design
- Making a structural design
- Integrate designs of various disciplines (architectural, structural, technical services)
- Coordinate design changes
- Assure quality of the design, decide on second opinion
- Make, approve and distribute drawings, specifications and calculations
- Check the design with the program of requirements and regulations

Control tasks in this overview are very important. Without control in theory still a satisfying structural design is possible, if the other tasks are performed in the right way. But leaving out control will be to the detriment of safety.

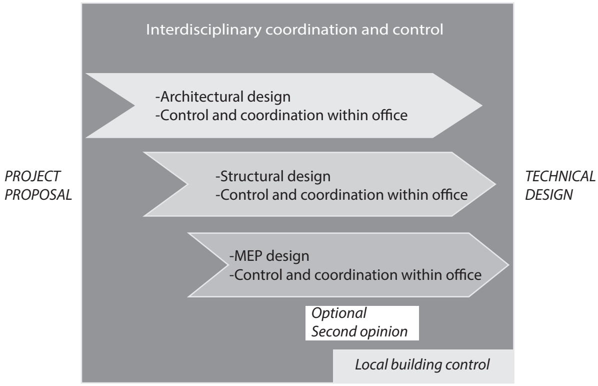


Figure 3.3 *Simplified overview of tasks in design stage (until technical design)*

Figure 3.3 presents a simplified overview of the various tasks in the design stage, resulting in a technical design. It should be noted that in practice an abundance of subtasks has to be executed, often at the same time, resulting in a complex process.

For design checking a distinction can be made between internal checking, checking by an independent consultant or checking by authorities (Stewart and Melchers 1989). In each of these forms self-checking (immediate monitoring and correction of each successive task), independent detailed design checking (checking and correction of all tasks in the design by an independent reviewer after the initial design process is completed) and overview checking (check by senior engineer without resorting to detailed calculations) may be included (Stewart and Melchers 1989).

In addition to internal control, external control can be applied. An example of external control is a Technical Inspection Service, which is a form of checking by a company that is independent from the design team. This type of checking is sometimes mandatory to receive insurance coverage and is more common in France and Belgium.
In the Netherlands, external control was usually performed by local building control, a responsibility of the municipality (see subsection 3.2.3). However, it is expected that checking by the municipality will be reduced, and the municipality will focus on system control (CUR Bouw & Infra 2011, pp. 108-109).

3.2.5 Tasks in construction-ready and construction phases

The tasks in the construction-ready phase and in the construction phase will be discussed in one subsection, because in practice these tasks are often performed at the same time. The detailed engineering tasks in the construction-ready phase have been briefly listed in subsection 3.2.3.

The construction phase is less specified in the Compendium Structural Safety. It focuses on executing the tasks to make the load bearing structures, and subsequently the finishing structures. The main tasks leading to a structure as presented in the Compendium are:

- Execute construction tasks
- Demonstrate strength, stability and stiffness of temporary structures
- Coordinating activities of suppliers and subcontractors
- Assure quality of construction and supervise construction
- Deliver finished structure
- Produce drawings 'as built'

In figure 3.4 various construction and detailed engineering tasks are presented. For clarity, the number of actors is limited. However, in practice usually a larger number of suppliers and subcontractors is present thus increasing the need for coordination (see also subsection 6.4.2).

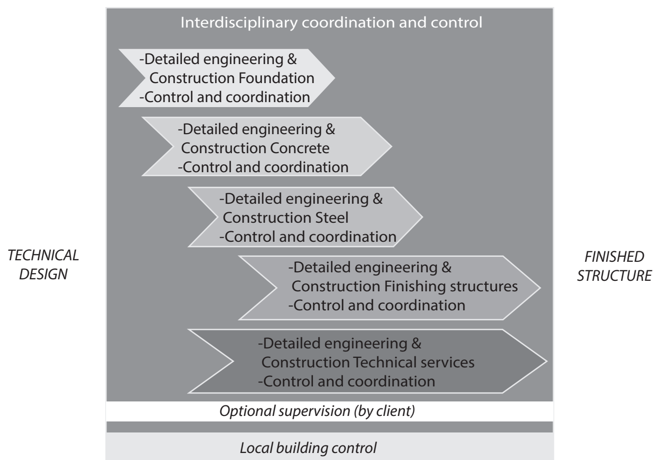


Figure 3.4 *Simplified overview of tasks in detailed engineering and construction stage*

3.2.6 Skill-based, rule-based and knowledge-based tasks

Tasks can be performed on various cognitive levels. Rasmussen (1983) makes a distinction in tasks on skill-based, rule-based and knowledge-based levels. Skill-based tasks, can be done on routine by sub-conscious behaviour. Rule-based tasks can be performed in familiar situations based on known rules which previously proved successful. Knowledge-based level is used only when the previous two are not adequate, for instance in an unfamiliar situation. In this level different options are considered and finally a sequence of actions is chosen. It can be imagined that for experienced persons many tasks can be performed on skill-based and rule-based level, while for inexperienced persons many tasks have to be done on rule-based or on knowledge-based level, because of a lack of experience with comparable situations.

3.3 Human error

When the right tasks are performed in the right way, the quality of structures will be satisfactory, unless unexpected circumstances occur. However, errors in these tasks might lead to structural failures. In every type of task or activity and in every step of a task errors can occur.

Many authors conclude that the majority of structural failures is caused by human error (Schneider and Matousek 1976; Ellingwood 1987; Fruehwald, Serrano et al. 2007). In this section the concept of human errors is explained and in section 3.6 the influence on structural failure will be elaborated.

3.3.1 Definition of human error

Within safety science the concept of human error is commonly used. Swain and Guttman (1983) use the following definition: "Any member of a set of human actions or activities that exceeds some limit of acceptability…" Stewart and Melchers (1989) provide more guidance for this 'limit of acceptability' in their definition of human error: "an event or process that departs from commonly accepted competent professional practice".

This 'commonly accepted competent professional practice' is often defined as the standard of good care: "…that level and quality of service ordinarily provided by other normally competent practitioners of good standing in that field, when providing similar services with reasonable diligence and best judgment in the same locality and the same time and under similar circumstances" (Ratay 2012).

The definitions provided by Swain and Guttman and Stewart and Melchers focus primarily on tasks themselves, while the outcome of tasks is neglected. Kletz (2001), however, defines an error as a failure to carry out a task in the way intended by the person performing it, in the way expected by other people or in a way that achieves the desired objective. This is in line with Bea's definition (1994): "A departure from acceptable or desired practice on part of an individual that can result in unacceptable or undesired results."

In this study, Bea's definition is adopted, although it is sometimes difficult to determine an acceptable or desired standard of practice.

3.3.2 Types of human error

Various authors make a distinction in various types of human errors.

Swain and Guttman (1983, pp. 2-16) distinguish errors of omission (failure to perform a task) and errors of commission (incorrect performance of a task). Errors of commission can be subdivided into selection errors, errors of sequence, time errors or qualitative errors.

Reason (1990) makes a similar distinction in two types of errors: slips/lapses and mistakes.

- Slips/lapses are "errors which result from some failure in the execution and/or storage stage of an action sequence, regardless of whether or not the plan which guided them was adequate to achieve its objective." Slips and lapses often have to do with fatigue, forgetfulness or habits (Kletz 2001). Usually they are related to skill-based tasks (see subsection 3.2.6).
- Mistakes are "deficiencies or failures in the judgmental and/or inferential processes involved in the selection of an objective or in the specification of the means to achieve it, irrespective of whether or not the actions directed by the decision-scheme run according to plan. . . ." Mistakes can be regarded as an ignorance of the correct task or the correct way to perform them (Kletz 2001). They can be rule-based or knowledge-based. Mistakes are similar to the errors of omission from Swain and Guttman.

Kletz (2001) adds to Reason's list: 'non-compliance or violations' and furthermore 'mismatches' ("an error that occurs because the task is beyond the physical or mental ability of the person asked to perform it, perhaps, beyond anyone's ability"), although the difference between a mistake and a mismatch will not always be clear. It is, however, important to recognize that it is possible that someone (generally on management level) made a mismatch and chose an incapable person to perform a task.

Bea (1994) makes a distinction in 'unknown unknowables' and 'known unknowables'. The first category appears for instance in a situation where no one could know the right task; no acceptable or desired practice was available. Within literature these situations are often described as 'Black Swans' (Taleb 2010). In chapter 4 these situations will not be categorized as a human error but as force majeure. For 'known unknowables' information exists, but this is either ignored or not/improperly used. In chapter 4 this will be categorized as a human error.

These definitions primarily focus on individuals doing a job, without taking interaction between individuals and accompanying communication errors into account. Bea's (1994) human error classification is therefore more inclusive, although sometimes his factors overlap. He lists:

- communications (transmissions of information)
- planning & preparation (program, procedures, readiness)
- slips (accidental lapses)
- selection and training (suited, educated, practiced)
- violations (infringement, transgression)
- limitations & impairment (fatigue, stress, diminished senses)
- ignorance (unawareness, unlearned)
- mistakes (cognitive errors).

In this classification it is clear that sometimes errors are made by operational personnel (e.g. communications, slips, violations, ignorance and mistakes), but that in many cases management personnel are responsible (especially with planning & preparation, selection and training, detection of limitations and impairment).

In addition, Bea pinpoints some primary factors which have resulted in individual errors, like fatigue, negligence, greed, ego, carelessness, bad judgment and laziness. His enumeration echoes the seven main sins, as listed by the Catholic Church centuries ago including greed, sloth (not making it a priority to do what we should), and pride. It can be imagined that until these vices are abandoned, structural safety will be on the threat.

From the various typologies of human errors the following conclusions can be drawn. For the prevention and detection of errors, it is relevant to know that some errors are made consciously (Kletz's violation of rules) and some unconsciously. In addition, it is important to make a distinction of errors related to the kind of task performed (Reason). Self-detection of skill-based errors is for instance easier than detection of knowledge-based errors. For the latter type external intervention is needed. Finally, it is important to consider that human errors can be made on operational level as well as on management level (Bea).

3.3.3 Human errors in the building process

Although making various sophisticated categories of human errors can be relevant and useful to apply effective measures, in this study a more pragmatic categorization of human errors will be used. In chapter 4 failure cases from Cobouw, a building construction oriented daily newspaper, are analysed (and compared with cases from other sources) and in chapter 8 less successful projects from a survey will be studied. Because the sources of these failures are generally lacking information on the background of the errors, a more straight forward distinction will be made based on the products that are produced; drawings, calculations and structural elements. The errors will be presented as failed tasks or activities.

For design errors the following classification of errors will be used in subsections 4.4.3 and 8.3.3:

- incorrect modelling or calculation error
- incorrect dimensioning on drawings
- conflicting drawing and calculation
- absence of drawing and/or calculation
- other design errors

The following classification of execution errors will be used:

- insufficient quality of materials applied
- incorrect assembling of elements on the building site
- insufficient amount of material used
- erroneous measurements on the building site
- other execution errors

A combination of errors is possible.

Furthermore, there will usually be underlying factors that stimulated the human error of individuals, like time pressure or insufficient skills to do the job. It can be seen that the classification as presented in this subsection is focused on operational level and thus on the persons who actually perform the activities of for instance calculating or assembling. However, errors on management level, like improper planning or insufficient budget, might also influence the behaviour on operational level (see subsection 3.3.2). These management errors can be classified as underlying factors.

3.3.4 Underlying factors of human error

Newspapers often highlight the presence of human errors after a major failure occurred. However, this can be criticized. Dekker (2006, p. 226), for instance, boldly states that human error is never at the root of safety problems. Human error is, in his opinion, the effect of trouble deeper in the system. Although Dekker almost completely eliminates the idea of individual errors and primarily focuses on organizational factors, his basic statement that human errors are influenced by the context, in which a person was operating before an accident occurred, will be used as a basic assumption in this thesis.

This assumption is underlined by Vrouwenvelder (2011), who recognizes the following factors as relevant for the probability of making errors:

- Professional skill
- Complexity of the task, completeness or contradiction of information
- Physical and mental conditions, including stress and time pressure
- Untried new technologies
- Adaption of technology to human beings
- Social factors and organization.

Bea (1994, p. 3) developed the concept of HOE (human and organization errors), where organization error "is a departure from acceptable or desirable practice on the part of a group of individuals that can result in unacceptable or undesirable quality. Organization errors have a pervasive influence on human errors". The organization errors are similar to the management errors, as mentioned earlier.

Dekker, Vrouwenvelder and Bea, amongst others, all assume underlying factors within the process which might influence (structural) safety. This concept of underlying factors will be used in the basic model, which will be introduced in section 3.6. In this model human errors and underlying factors are connected with structural failure. The underlying factors can range from resources and conditions (like sufficient budget) to specific activities (like checking) or to attributes (like technical skills) and will be the focus of part II of this thesis.

3.4 Structural failure

Structural failure was defined in subsection 2.3.1 as the inability of a structure or a structural member to fulfil the specified requirements. It is associated with exceedance of the resistance of (part of) a structure by the effect of the loads. In this study it is related to a structure that has been constructed.

Structural failure can manifest itself in many ways. Schneider and Matousek (1976) make a distinction between a sudden failure and unsatisfactory condition. Sudden failure can be initiated by loss of equilibrium, failure with collapse, failure without collapse or other sudden failure. An unsatisfying condition might manifest itself in excessive cracks, deformations, settlements, skewness, incorrect dimensioning or positioning and other unsatisfying conditions.

The main categories Hadipriono (1979) used make a similar distinction between sudden failure and unsatisfactory conditions with collapse or distress.
Eldukair and Ayyub (1991) distinguish collapse, loss of safety (transition mode that could lead to collapse) and loss of serviceability. Failures can occur with or without warning. Failures may be caused by rupture of sections, instability, deformation or fatigue. According to these authors, limited serviceability may be caused by deformation, cracking, local damage, displacement, vibrations or other phenomena.

For ABC registration (see chapter 1) a distinction was made in near misses without damage that were detected in time and failures that had already manifested themselves in (partial) collapse, damage (like cracking), insufficient functionality, quality and or safety, or decreased lifetime expectancy (CUR Bouw & Infra 2011).
In a failure analysis of Dutch case law the following failure categories were used: (partial) collapse, cracking, leakage, insufficient bonding, material deterioration (corrosion, rotting), deflection, instability, settlement, depravation and ageing (Boot 2010).

It can be concluded that all of these studies make a distinction in failures related to exceedance of the Ultimate Limit State and of the Serviceability Limit State. For this study it is assumed that structural failure can manifest itself in a (partial) collapse, structural damage, material deterioration, insufficient functionality or no damage.

- A collapse is defined as the (sudden) breakdown of a structure due to insufficient strength or stability. This damage is related to exceedance of the Ultimate Limit State.
- Structural damages are e.g. cracks or insufficient integrity of structures which could lead to collapse if no adequate measures would be taken. This damage is related to a reduced reliability in the Ultimate Limit State.
- Material deterioration leads to reduced performance of materials over time, which could lead to structural damage and/or reduced lifetime if no measures (like repair) are taken. This damage is related to reduced reliability in the Ultimate Limit State.

- Insufficient functionality might take the form of insufficient water tightness, too large deformations, unacceptable aesthetical cracks or deprivation. This category is related to exceedance of the Serviceability Limit State.
- Structural failure without damage is the situation where a structure cannot fulfil the specified requirements, but no damage has occurred yet. This situation is defined as a latent failure. An example is the situation where a design error is detected after completion of a structure, but no damage has occurred yet, because the full load is not present.

A near miss is a the situation where a latent failure has been detected and corrected. A special case of a near miss is a design error that was detected and corrected before the structure was constructed, and thus, before it could become a structural failure.

The predominant focus in this study will be on collapse and loss of reliability in the Ultimate Limit State (see subsection 2.3.1). Chapter 4 will focus on near misses and structural failures with the listed manifestations of damage.

3.5 Consequences

Structural failures might lead to consequences. Chryssanthopoulos et al. (2011) distinguish human, economic, environmental and social consequences, ranging from injuries to pollutant releases and loss of reputation (see table 3.1).

Table 3.1 *Consequence categories (adapted from Chryssanthopoulos, Janssens et al. (2011)*

Type	Direct	Indirect
Human	Injuries Fatalities	Injuries Fatalities Psychological damage
Economic	Repair of initial damage Replacement/repair of contents Rescue costs Clean up costs	Replacement/ repair of structure/ contents Rescue costs Clean up costs Collateral damage to surroundings Loss of functionality/ production/ business Temporary relocation Traffic delay/ management costs Regional economic effects Investigations/ compensations Infrastructure interdependancy costs
Environmental	CO2 emissions Energy use Pollutant releases	CO2 emissions Energy use Pullutant releases Environmental clean-up reversibility
Social		Loss of reputation Erosion of public confidence Undue changes in professional practice

The consequences might be limited due to warning behaviour of a structure. Often the consequences are limited to a cracked or deformed structure, after which measures can be taken. In addition, technical solutions, like a second load path might reduce the consequences after a failure.
The consequences presented in chapter 4 are limited to the number of fatalities, because these can be regarded as the most severe and usually the sources for the failure cases provide information on these consequences.

3.6 Connecting human performance and structural performance

The relationship between human errors on operational level and structural failure is not evident for various reasons. First, the number of human errors in design and construction activities will not be similar for every building project. Furthermore, these errors might lead to failure, but sometimes they are detected by control tasks. Moreover, human errors will not always significantly influence structural performance. Therefore, there is generally no deterministic relationship between human errors and structural failure. The character of this relationship will be explained in this section.

Ellingwood (1987) states that models that intend to explain the relationship between human errors and structural failures should identify likely error-causing scenarios, should include the part of errors that are detected and corrected by quality assurance activities, and should provide the probability that an error will lead to a defect and subsequently to damage or failure.

Figure 3.5 depicts an event tree which reflects the basic elements of the modelling as suggested by Ellingwood. The basic elements are presented with probabilities P. Furthermore, various types of error and failure are listed, as explained in this chapter.

The following subsections will highlight two relationships in figure 3.5: the relationship between human performance and structural performance and between risk related to human error and risk not related to human errors.

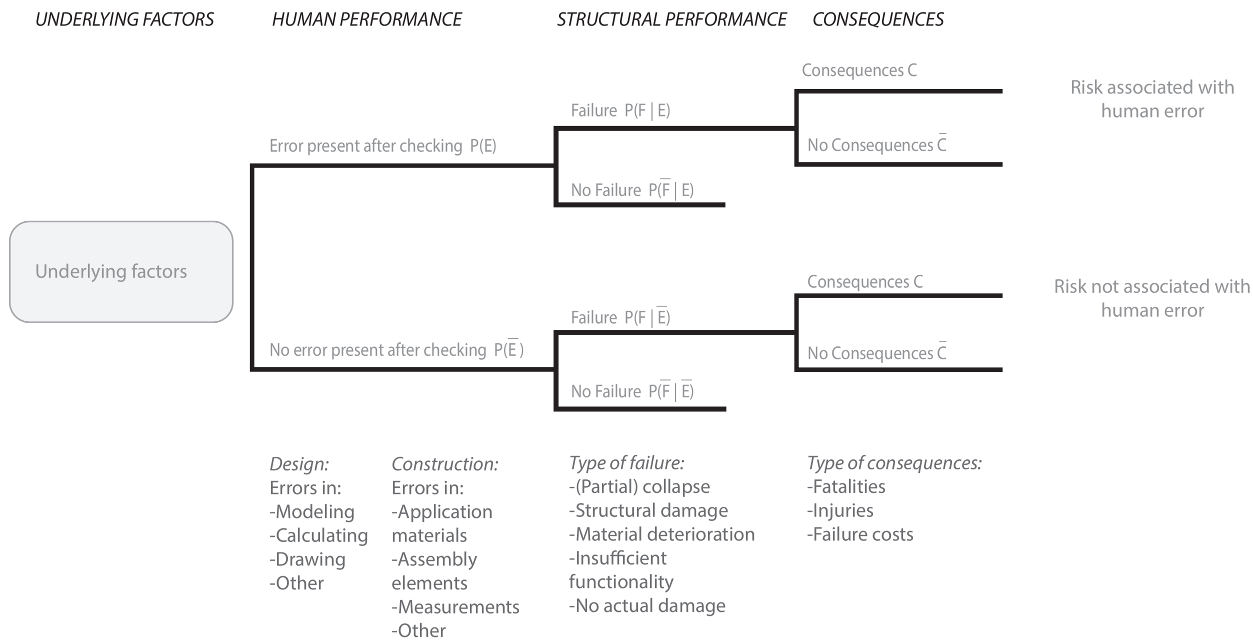


Figure 3.5 *Basic model for relationship between human performance and structural performance*

3.6.1 Relationship underlying factors, human errors and structural failures

Within the design and construction process underlying factors can influence the probability of human errors (see subsection 3.3.4). However, in many situations possible underlying factors are present, without leading to human errors and structural failure.

Several possible errors can be made in a number of different tasks, like modeling errors or erroneous application of materials. De Haan et al. (2013) provide an example of possible error scenarios in the engineering of a concrete beam (see section 10.3). For the current study the focus will be on failed tasks (as explained in subsection 3.3.3) within the building process and not on underlying typologies and psychological elements of human error (as presented in subsection 3.3.2).

Human errors can be detected and corrected by internal or external checking procedures. P(E) in figure 3.4 depicts the probability of a scenario, where an error has occurred and is still present after checking procedures. It is possible that errors are not detected or corrected in the checking procedures, or that errors are introduced in the checking procedures.

$P(\bar{E})$ in figure 3.4 depicts the probability of a scenario where no errors are present after checking procedures. It is possible that no errors are made or that errors are detected and corrected (for instance a near miss, an error that is detected in time and did not develop into damage).

Errors in design and construction tasks might lead, or at least contribute, to structural failure.

$P(F | E)$ is the probability of failure when a human error is made (and not corrected). In these situations there is stochastic variability of loads and resistance, but the failure is associated with a human error. In many situations the structure might not show damage when errors occur, because of stochastic variability of loads and resistance. When for instance the design load is much larger than the actually present load, it is possible that the structure does not even show damage, when a human error has been made. This situation is an example of a latent failure.

$P(F | \bar{E})$ is the probability of failure when no human error is present after checking procedures. This category consists of failures due to stochastic variability in the modeling of loads and resistance of the structure (see subsection 2.3.1) and due to situations which cannot be attributed to stochastic variability and human error. The latter category includes for instance situations where the structure fulfilled the requirements at the start of its lifetime, but due to growing demands (for instance increased traffic) the structure might not be reliable anymore and even show damage. This is often not related to human error, but to contextual changes where the original assumptions of stochastic variability of loads are outdated. In chapter 4 these particular situations are classified as force majeure, although in some situations it might be related to insufficient asset management.

Not all damaged structures have to be classified as unreliable structures. Those situations where failure has to be attributed to stochastic variability and small human errors might be regarded as reliable, when the actual probability of failure is smaller than the accepted probability of failure, although this is usually regarded as a hypothetical situation.
The consequences may range from failure costs to injuries and fatalities (see section 3.5).

The various steps of this basic scheme: underlying factors, human errors, structural failures and consequences will form the basic terminology of this thesis.

3.6.2 Risk related to human errors and not related to human errors

In chapter 2 it was explained that risk is the sum of the product of the probability of hazards and the consequences of various scenarios.

The total risk consists of risks related to human errors and risks not related to human errors. The risks related to human errors can be expressed as follows:

$$R = \sum_{i=1}^{n} P(E \cap F_i) \cdot C_i$$

With:
R = total risk (in this situation related to human errors)
$P(E \cap F_i)$ = probability of a failure scenario F_i when an error was present after checking
C_i = expected consequences of scenario i (for instance number of fatalities)
In these situations there is stochastic variability of loads and resistance, but the failure is associated with a human error.

In addition, there are risks not related to human errors. These risks are related to stochastic variability (uncertainties in materials, geometry, calculation models and loads, see subsection 2.3.1) and other situations which could not be classified as human errors.

This risk can be presented as:

$$R = \sum_{i=1}^{n} P(\overline{E} \cap F_i) \cdot C_i$$

where: $\overline{E}$ is the situation in which there were no human errors after checking procedures.
The calculation approach of the Eurocode primarily focuses on risks related to stochastic variability.
Chapter 4 will explore if the risks related to human errors are higher than the risks not related to human errors in the Netherlands.

3.7 Conclusions

The main aim of this chapter was to explain the relationship of human error in the building process and structural failure.

It was concluded that the building industry is different from other industries because most structures are approached as one of a kind projects. For these projects, tasks have to be performed. In practice, there often is a difference in the intended tasks and the actually performed activities.

In these activities human errors can be made. A single focus on human errors to prevent structural failure will not be beneficial. The majority of persons is believed to have the intention to perform the right tasks in the right way. Due to underlying factors, like time pressure, this might not be always possible or successful, thus resulting in so-called human errors.

Human errors can be made on operational level or on management level. Human errors on management level are usually related to underlying factors.
Human errors in operational tasks can lead to structural failure, but not necessarily. It is assumed that in every building project human errors are made. Fortunately, just a minority of these errors results in a total collapse. Some errors are too small to lead to failure, others are detected and corrected. Therefore, the relationship between human error and structural failure should not be regarded as deterministic, but this relationship is preferably expressed in probabilistic terms.

The following chapter will provide insight in the relative importance of the various elements of the basic model in figure 3.5 for the Dutch building industry and will give information on underlying factors, type of human errors, type of structural failures and consequences, based on information derived from failure cases. In addition, it will investigate if the current building stock meets the limits of acceptable individual risk.

4

Structural failures in the Netherlands[1]

4.1 Introduction

In chapters 2 and 3 the concept of structural safety was explained and the characteristics of the building process and the influence of human errors were presented. In this chapter the current state of structural safety on national level will be explored. This will be done by presenting a large number of structural incidents in the Netherlands. Structural incidents are structural failures or near misses (see 3.4 for definitions).
In this chapter the failure cases and near misses that were derived from Cobouw (a Dutch newspaper for the building sector), ABC registration (the voluntary reporting system in the Netherlands) and Dutch case law will be analysed.
First, the frequency of failures and near misses will be shown. Second, the characteristics of the incidents, like the materials involved, will be explained. Subsequently, the causes of incidents and the role of human error will be analysed. Finally, the consequences of failures will be presented. A closer analysis of the number of fatalities will be made to derive the individual risk due to structural failures and compare it with the acceptability limits of fatalities according to Eurocode.

4.2 Failure databases in the Netherlands

In the Netherlands several databases related to structural incidents have been established. Three of these recent initiatives are the subject of this chapter.

A Cobouw database was set up in 2004 by TNO (Netherlands Organisation for Applied Scientific Research) based on 230 structural failures that were reported in the Cobouw (Dieteren and Waarts 2009), a leading newspaper for the Dutch building industry.

Delft University of Technology developed a similar database, elaborating on the format used by TNO. It currently includes 401 incidents based on Cobouw articles between 1993 and 2009. The results of this database have been made available in 2012 (Terwel 2012a); more information on the set up of this database is provided in appendix II.

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[1] *This chapter is based on the paper "Structural unsafety revealed by failure databases' (Terwel, K.C. W. F. Boot and R.M.L. Nelisse (2014)), which was published by the journal 'Forensic Engineering'. Reprinted with the permission of ICE publishing.*

In 2007 ABC registration was initiated by the Platform on Structural Safety. It is a confidential reporting system of mistakes in structural design, execution, use/maintenance and demolition, which was set up by TNO (Terwel, Nelisse et al. 2012). The essence of this system is similar to CROSS in the UK. Anyone in the building industry can report mistakes through a website. These mistakes are anonymized and analysed by structural experts, who publish their results in periodic reports and newsletters. Although the latest report dates from July 2011, consideration is being given to further reports.

The Arbitration database was developed in 2010 in a master's thesis containing 151 structural and functional failures extracted from arbitration awards of the Dutch arbitration institute for construction disputes from 1992-2009 (Boot 2011). Arbitration is a common means of construction dispute resolution in the Netherlands.

The choice of boundary conditions, for instance the definition of failure and the way of categorizing failures, varied for the three studies, thus impeding a direct comparison. However, after thorough analysis and minor adjustments of some categories (for instance combining all design sub phases into one phase), usable results were obtained. Unfortunately, not all categories could be compared, as each source provided different types of data about failures. Especially categories with underlying factors varied to a large extent.

4.3 Results from incident investigations

Tables 4.1 and 4.2 present an overview of the process of data gathering and analysis and of the outcomes of the three database studies on incidents.

Table 4.1 *Information on gathering process of data*

	Cobouw	ABC registration	Dutch arbitration awards
Gathering process of data			
Source of data	(Near) failures collected by using search terms in a digital archive of newspaper Cobouw	Voluntary reports of building participants. Over 80% from local building control officers and structural engineers	Arbitration awards found by using search terms in an online database with arbitration awards
Selection criteria	Every case where the (probability of) failure of a (temporary) structure (potentially) endangers persons	Near misses without damage and failures with damage. A building mistake is defined as an error in design, execution, use or maintenance, threatening structural safety	Cases with insufficient functional or structural performance. Usually damage has occurred

Table 4.2 *Main results from databases*

	Cobouw	ABC registration	Dutch arbitration awards
Outcomes			
Number of incidents	401	189	151
Years of detection failure	<1990-2009	2000-2011	<1990-2009
Type of structures	72% buildings, 8 cases unknown	97% buildings	91% buildings, 2 cases unknown
Function of buildings	38% residential, 2 cases unknown	40% residential	43% residential, 26 cases unknown
Material	28% concrete, 31% steel/ metal, 62 cases unknown	24% concrete, 38% reinforcement	26% concrete, over 26% steel/metal, 32 cases unknown
Construction elements	24% facades, 15% floors, 1 case unknown (only buildings regarded)	23% foundations, 21% floors	19% foundations, 19% roofs, 2 cases unknown
Type of damage	51% (partial) collapse, 29% structural damage, 2 cases other	84% no damage	27% (partial) collapse, 33% structural damage, 33% insufficient functionality, 1 case other
Fatalities	43 (yearly: /17= 2,5)	0	1
Time of discovery	21% construction, 67% use, 2 cases unknown	27% design, 50% construction	25% construction, 67% use, 9 cases unknown
Phase of main cause	15% design phase, 30% construction phase, 23% use phase, 17% combination, 120 cases unknown	61% design phase, 31% construction phase	26% design phase, 30% construction phase, 19% combination, 16 cases unknown
Type of error	16% design error, 43% construction error, 16% combination, 8% use error, 17% force majeure and other, 128 cases unknown	65% design error, 35% construction error	34% design error, 33% construction error, 23% combination, 3% use error, 6% material deficit, 1% other, 15 cases unknown

4.4 Explanation of results

4.4.1 Reliability of incident investigations

The reliability of the incident investigations is determined by the reliability of the data and the reliability of the analysis process. A perfect analysis can never compensate for poor data. It appears that the reliability of the investigation of the ABC registration and Dutch arbitration awards is better than the reliability of the investigation of Cobouw cases. The main reason is that in general the reliability of the information on failure cases of the newspaper articles is expected to be limited. Terwel, Boot et al. (2013) provide a more extensive discussion of the reliability of the investigations.

4.4.2 Characteristics of cases and their damage

Number of incidents

In figure 4.1 incidents from all three studies are depicted with their date of occurrence. Fifty four of the arbitration awards are not depicted because the date of occurrence of damage is not known.

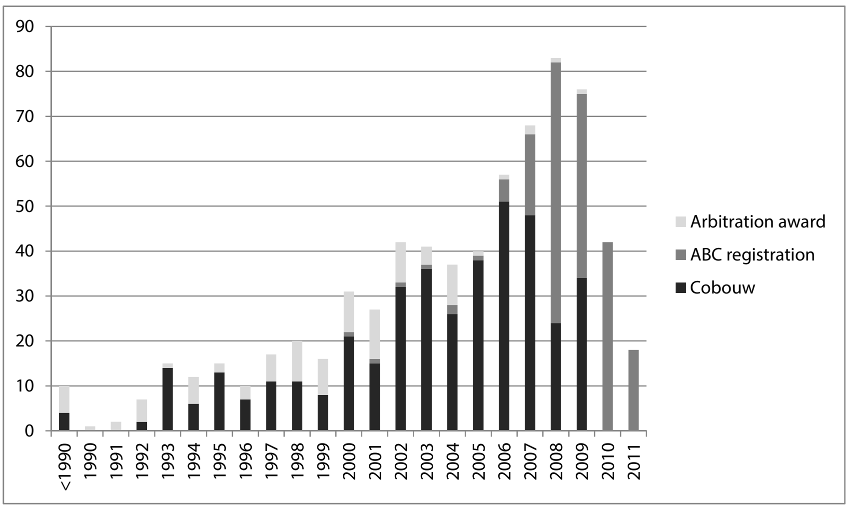


Figure 4.1 *Number of incidents of all sources depicted for the year of occurrence of damage or, if no damage resulted, for the year of the mistake*

All in all 741 cases are included in the databases for a period of over 20 years. This is a considerable number for analysis, but it should be noted that it is just a small portion of all structural incidents. It was estimated for the Dutch building industry that yearly 20.000 building mistakes occur, although not all are necessarily leading to large damage (CUR Bouw & Infra 2011, p. 20).

From the figures of the Cobouw database, an increase in number of incidents during the period 1991-2007 seems to be present. This rise in incidents over the years might be explained by an increase in media attention after major failures and a growing litigiousness. However, the increase is in line with an estimated increase of failure costs from 7.7% of the annual turnover in 2001 to 11.4% of the annual turnover in 2008 (USP Marketing Consultancy 2008).

Type and function of structures

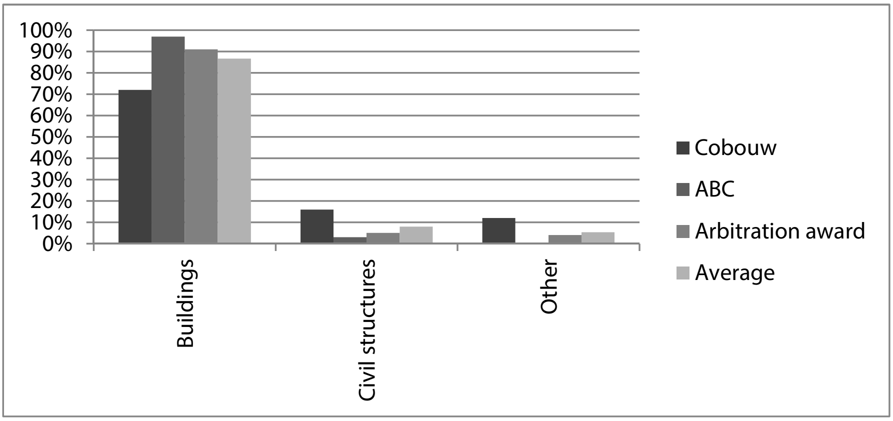


Figure 4.2 *Type of structures*

Figure 4.2 shows that approximately 85% of all incidents in the databases are related to buildings. In comparison, buildings count for approximately 74% of the annual turnover in the construction sector (EIB 2012). Assuming that the percentage of annual turnover is equivalent to the relative share of buildings in the total number of structures, this indicates that buildings might be slightly more vulnerable to structural incidents than civil structures.

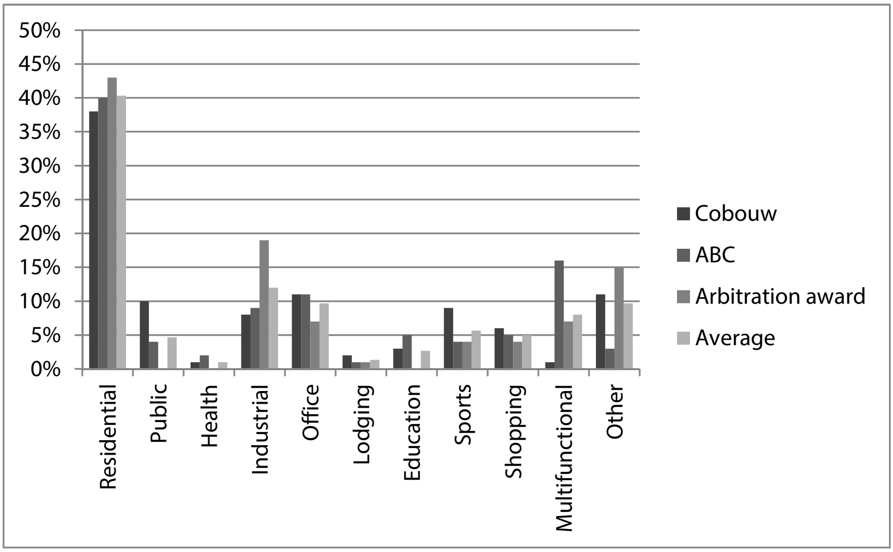


Figure 4.3 *Function of buildings*

Figure 4.3 shows that approximately 40% of the cases have a residential function. About 55-60% of the annual turnover of all new buildings in the Netherlands are on the account of residential buildings. It is possible that, because there are many small houses, structural failures of individual houses are not worthwhile mentioning in newspapers or the damage costs are too low to start an arbitration procedure. Nevertheless, it seems reasonable to draw the conclusion that residential buildings suffer relatively less often from structural failures (and near misses). This might be explained by the fact that in the Netherlands houses are often produced in series, where repetition reduces the probability of failure. In addition, due to demands on sound and heat insulation, floors and walls in residential buildings usually have larger dimensions than strictly necessary for structural reasons. This might result in a larger redundancy for housing.

Materials

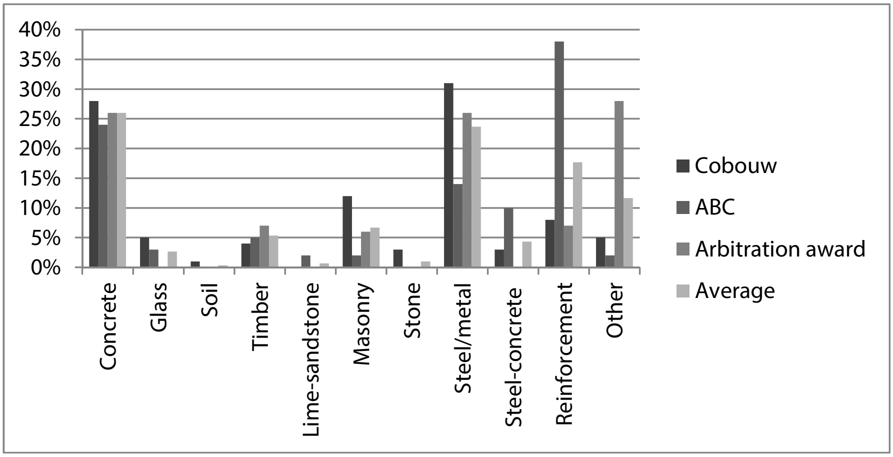


Figure 4.4 *Materials involved*

Figure 4.4 shows that the frequency of incidents with concrete and steel/metal is similar. It seems that steel structures are more prone to failure, because in the Netherlands concrete structures are more common than steel structures. However, reliable data on the exact ratio of steel and concrete structures is not available. In addition, because steel is less often used in houses and housing appears to be less prone to errors, it is possible that the assumed lower probability of failure is largely determined by the type of building and not by the type of material.

Unlike the other researches, the ABC registration recorded relatively more problems with reinforcement. It seems likely that local building control, that reported nearly 70% of the cases, more often focuses on reinforcement deviations.

Construction elements

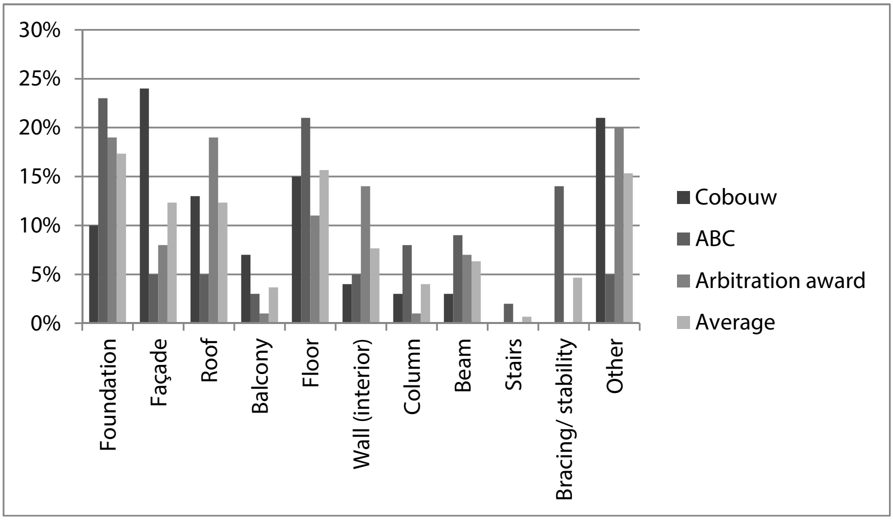


Figure 4.5 *Construction elements*

Figure 4.5 presents the construction elements that were damaged or involved. The total average share of roofs, balconies, beams and floors is 38%, while the total average share of facades, walls and columns is 24%. Assuming that a building roughly has an equal number of horizontal and vertical elements, it can be concluded that horizontal elements are more vulnerable to failures (and near misses) than vertical elements. This can be explained by the mechanical behavior; the governing forces in columns are normal forces, while the governing forces in horizontal elements are usually bending moments. The latter situation usually results in a more sophisticated structural behaviour, thus increasing the probability of failure.
Failures of foundations are also common, which is to be expected because of soft soils and erratic soil profiles in the Netherlands.

The type of damage to the construction elements ranges from (partial) collapse, material deterioration, insufficient functionality to no damage. In especially the ABC registration, over 80% of the cases had no damage, because errors were detected in time. Over 90% of the structures in the cases of Cobouw and Arbitration awards showed damage.

4.4.3 Causes

Phase with main cause

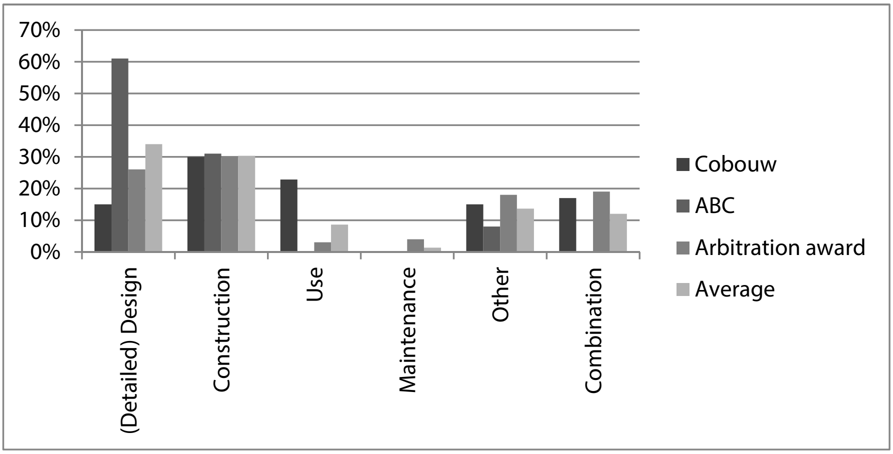


Figure 4.6 *Phase with main causes*

In figure 4.6 a remarkably large range of outcomes can be observed between the three researches, especially for the design and use phase. Because many of the errors within ABC registration are already discovered in the design phase (table 4.2), it is to be expected that the cause is more frequently found in the design phase. Within Cobouw database a relatively low number of causes is attributed to the (detailed) design phase. This might be partially explained by the characteristics of the source. Cobouw often reports within days after an incident. Usually it is easier to mention a construction error than a design error if no in depth investigation is available. In addition, in the Cobouw database various cases were included where a structure was constructed without a design. It was chosen to attribute the cause of these cases to the construction phase.

These differences indicate that the type of source influences the distribution in phases with main causes. However, the average outcomes of the phase with the main cause are within the range of international results, as presented in table 4.3.

Table 4.3 *Percentage of errors by the phase in which they were made. Adopted with modifications from Fruehwald, Serrano et al. (2007, p. 6)*

Reference	Planning & Design %	Construction %	Use/Maintenance %	Other [a] %	Total %
Matousek	37	35	5	23	98
Brand and Glatz	40	40	-	20	100
Yamamoto and Ang	36	43	21	-	100
Grunau	40	29	31[b]	-	100
Reygaertz	49	22	29[b]	-	100
Melchers et al.	55	24	21	-	100
Fraczek	55	53	-	-	108[c]
Allen	55	49	-	-	104[c]
Hadipriono	19	27	33	20	99
Average	43	36	16	7	101

[a] Includes cases where failure cannot be associated with only one factor and may be due to several of them
[b] Building materials, environmental influences, service conditions
[c] Multiple errors for single failure case

The analysis of Cobouw cases provides more insight in the type of design, construction and use errors (135 cases unknown). For design errors within the Cobouw database the following figures were derived:

- incorrect modeling or calculation error: 57%
- conflicting drawing and calculation: 2%
- absence of drawing and/or calculation: 19%
- other: 21%.

For construction errors the following figures were derived:

- incorrect quality of materials applied: 27%
- insufficient amount of material used: 14%
- incorrect assembling of elements on the building site: 27%
- erroneous measurements on the building site: 2%
- other: 30%.

For use errors the following figures were derived:

- larger load than expected: 66% (also related to force majeure)
- insufficient inspection 2%
- insufficient maintenance: 23%
- other: 10%.

The other sources used different categories, which will not be depicted.

Because this research shows that incidents are almost equally caused in both phases, engineers cannot pretend that most errors are made in the execution phase and contractors cannot claim that most failures originate in the design phase.

Only a small portion of the failures is due to force majeure. For example, in Cobouw there are some cases where inadequate stainless steel was prescribed within swimming pools, in a period that the inadequacy of this type of material was not commonly known within practice. Another example is the situation where the actual loads (due to for instance rain, snow, traffic, impact) are higher than reasonably could have been expected. It is hard to classify these situations as errors, which is the reason to classify these as force majeure (see subsection 3.3.2).

Within the investigated incidents almost no cases were found where the cause of failure was solely attributed to stochastic variability of the model assumptions (see subsection 3.6.2). It can be concluded that the majority of failures has to be attributed to human errors, and thus that $P(F \mid E) > P(F \mid \overline{E})$.

Underlying factors
All three studies mention underlying factors. Examples are the complexity of the design, number of building participants in a project, presence of warnings, role of changes, time pressure, lack of budget, underdeveloped safety culture, unclear responsibilities, insufficient communication, lack of coordination and control, inadequate codes, the quality of the engineers and workmen, and working conditions. However, comparison of these factors is difficult, because the researches did not focus on the same aspects, and often insufficient information on these aspects was available. In addition, one should be careful to attribute any safety effects to certain factors derived from failure cases, because it is usually not known to which extent these factors are also present in successful projects (see subsection 3.6.1).

From Cobouw and arbitration award research it appeared that in various cases changes were made in design or construction phase. Without these changes, the failure would not have manifested itself. For 19% of the arbitration awards changes influenced the initiation of the failure. However, in every project changes will be made which will not lead to failure. The generally accepted hypothesis is that change in a task might increase the probability of failure, because one might tend to make shortcuts in these situations. Especially in a final stage of the process, this might increase the risk of omitting thorough checking, and increases the probability of failure. However, this hypothesis cannot be tested by the available data from the failure cases, because no data is available from successful projects with and without changes.

Furthermore, from Cobouw and arbitration award research it is known that in many cases prior warnings were given by persons, after control or inspection, or by the structure itself, resulting in cracks or exceptional deformations. In the Cobouw database at least 168 cases were found, where physical signs could be observed before failure occurred to the full extent. However, it is not always certain if cracks and deformations are actually warnings before structural damage occurs to the full extent; in many situations it is just normal structural behavior. Therefore, appropriate knowledge of physical signs which should be classified as warnings and adequate response to them needs more attention.

4.4.4 Consequences: fatalities

Only Cobouw database provides sufficient data to analyse the number of fatalities due to structural failures. For the period of 17 years in total 43 fatalities were counted. Thirty eight of them occurred during (re)construction phase and only five after completion of a building project. Arbitration awards only mention one fatality in their collection of cases, ABC registration does not list any fatalities.

These figures can be compared with those from the so-called Storybuilder database. This database was set up by an international consortium (Ale, Baksteen et al. 2008) and uses reports of the Dutch Labour Inspectorate on job related accidents within various sectors. This publicly available database is based on the safety concept of bow-ties (see appendix II), with on the left side of the undesired event the actions and failed barriers leading to the accident and on the right side the consequences of the undesired event. Currently the database contains approximately 23,000 Dutch cases for the period 1998-2009 (RIVM), from which approximately 5600 are related to the building industry. The cases related to failure of temporary or permanent structures have been selected (see appendix III for selection procedure). Examples are falls due to failure of scaffolding and impact due to contact with falling objects like beams, slabs or walls that were not adequately connected or stabilized.

According to Storybuilder on average 5.3 fatalities occurred each year in the Netherlands due to structural failures during work (job related accidents in all considered sectors). The building sector is responsible for 3.7 fatalities yearly, while in the other sectors only 1.6 fatalities are counted yearly due to structural failures. When considering that in the building industry nearly 0.5 million persons are working compared to 8.3 million in the other sectors, it can be concluded that the building sector is a dangerous place to work, with respect to structural failures.

Cobouw mentions a smaller number of fatalities during construction, although it is in the same order of magnitude (38 fatalities in 17 year = 2.2 per year, compared to 3.7 per year in Storybuilder). On the other hand, Cobouw records fatalities during work in other sectors very seldom (2/17=0.12 per year, compared to 1.6 per year according to Storybuilder). Fatalities due to structural failure for residential end-users are fortunately low. Cobouw mentions only three fatalities among residential end-users in 17 years, which is 0.18 fatality per year.

Table 4.4 *Probability of death due to structural failures for various populations*

	Population (average for period 1998-2009 (CBS)	Storybuilder (per year)	Cobouw (per year)	Probability of dying (per year)
Workers in building sector	493000	3.7	2.2	3.7/493000= $7.5*10^{-6}$
Workers in other sectors	8.3 million	1.6	0.12	1.6/8.3 million= $1.9*10^{-7}$
Residential end-users	16.1 million	-	0.18	0.18/16.1 million= $1.1*10^{-8}$

Table 4.4 depicts the probability of death per year due to structural failure.

The exact numbers are rather sensitive to selection of cases in Storybuilder and should be considered with care. Furthermore, there might be some other deviations in these figures. CBS (Central organization for statistics in the Netherlands) for instance mentions approximately 25 fatalities per year in the period 1998-2009 in the building sector, while Storybuilder only records approximately 18 fatalities per year in the same period. It seems that not every accident is reported to the Labour Inspection and/or included in the Story-builder database. From these 18 fatalities only 3.7 are attributed to structural failures. Other job related accidents are related to falling of persons (without structural inadequa-cies) and accidents due to explosions, fire, chemical exposure, car collisions, etc.

Although there might be some deviations from the actual figures, table 4.4 gives a clear indication of the order of magnitude for the yearly probability of death due to structural failures. For workers in the building sector this is 10^{-5}-10^{-6}, for workers in other sectors this is 10^{-6}-10^{-7} and for citizens outside working circumstances this is 10^{-7}-10^{-8}.
Especially the average risk for residential end-users introduced by structures is low, compared to the (questionable) acceptable limit of 10^{-5} per year. This acceptable limit for residential end-users, is a basis for calculation according to the Eurocode approach for existing buildings in the Netherlands (see chapter 2).

These conclusions should be drawn with care, because a single catastrophe with a low probability of occurrence and high consequences, which did not occur in the observed period, could strongly influence the outcomes. Furthermore, safety within a country is related to the sum of all persons in a population and the number of fatalities in a given period. However, it is possible that when a building collapses, resulting in failure costs and fatalities, the risk on country level might stay within limits, when this was the only failure in a long period, but the risk of this individual structure was not within acceptable limits. Hence, conclusions on country level cannot be transferred directly to individual projects.

Nevertheless, the conclusion of individual risk is in line with for instance the CIRIA research as cited by Madsen et al. (2006, p. 7) which concludes that the risk of death per 10^4 exposed persons per year due to structural failures is 0.001, which is equivalent to an individual risk of 10^{-7} per year.

4.5 Discussion of the current Eurocode approach

These outcomes might fuel a discussion of the current two-way Eurocode approach as explained in chapter 2. The first way is the approach with structural calculations based on a probabilistic philosophy. The second way is the quality assurance approach, with for instance suggested control procedures, to deal with human errors.

From the current study it appeared that about 90% of the failures (see table 4.2, type of error, average for Cobouw and Arbitration award) are caused by human errors (during design, construction and use), although human error is not included in the probabilistic approach for calculations in the Eurocode. However, the yearly probability of death as a resident due to structural failures stays within limits for the observed time interval, although no catastrophe with low probability and high consequences did occur in the observed period.
This seems to be a paradox, but can be explained.

- Real structures are stronger than on paper. It is supposed that structures behave stronger than calculated due to redistribution of forces and better material properties than taken into account in calculations. For concrete structures the compressive strength for instance usually increases during its life time.
- Warning behaviour limits consequences. An example of this phenomenon is the case of the Bos & Lommer plaza in the Netherlands (Priemus and Ale 2010). After some major cracks in the concrete deck, the adjacent shops, houses and offices were evacuated. Investigations uncovered serious flaws in the structure of the deck and of the adjacent multipurpose building. Adequate structural measures were taken, thus limiting the financial consequences.

In the current two-way Eurocode approach the structural calculations based on probabilistic principles generally lead to safe, but usually conservative structures (with regard to the number of fatalities), by underestimating the influence of overcapacity and warning behaviour.

4.6 Conclusions

This chapter aims to explore the current state of structural safety within the Dutch buiding industry. Four sources with failure cases and near misses were used for this exploration: newspaper articles from Cobouw, files from Dutch case law, reports from the confidential failure reporting system ABC registration and job related accident reports from the Dutch Labour Inspectorate (Storybuilder). The sources and analyses differed in reliability.

Acceptable level of structural safety

Despite the reliability issues and differences in definitions and presentation of data, the results show resemblances and therefore some general conclusions can be drawn.

This chapter concluded that the annual number of fatalities among residents due to structural failures meets the limits of individual risk according to Eurocode approach. Hence, the building stock within the Netherlands can be regarded in average as structurally safe, regarding individual risks.

However, it remains indispensable to work on improvement of structural safety. The number of fatalities and injuries should be as low as reasonably possible (see chapter 2). Furthermore, consequences are not limited to fatalities. Failure costs of more than 10% of the yearly turnover are unacceptable. Structural safety according to Eurocode is also related to an acceptable level of damage of structures. With this in mind, the current level of structural safety might be inadequate.

Moreover, the current situation might be satisfactory, but structural safety should be assured in the future. Several trends have been observed, like financial cuts in education and research, increased use of computers, deregulation and an increase in multiple use of space, that might be a threat for structural safety (Terwel and Mans 2011).

Therefore, it is worthwhile to search for improvement of structural safety. To suggest measures for improvement it is necessary to know what factors are influencing structural safety of projects.

Cause of failure

The main outcomes of this chapter, which are related to the basic model of chapter 3, are depicted in figure 4.7.

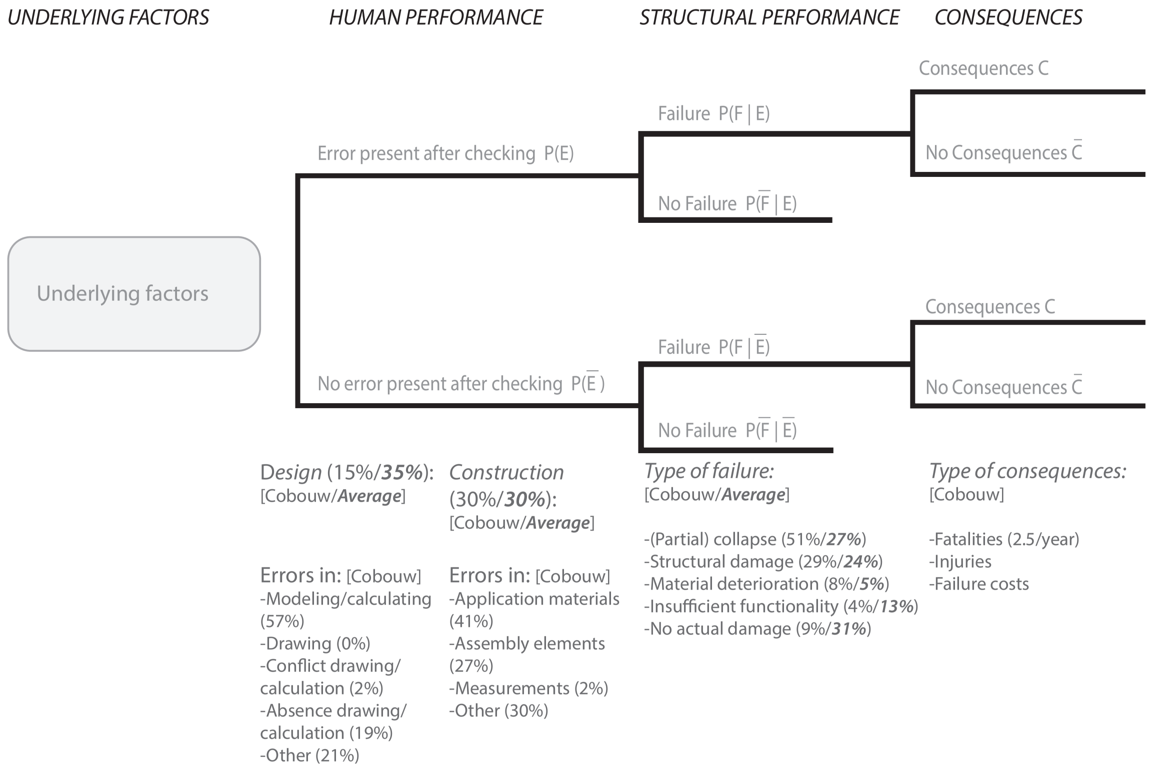


Figure 4.7 *Main outcomes database research depicted in basic model*

Regarding the cause of failure it was concluded that about 90% can be attributed to human errors during design, construction and use, while about 80-85% can be attributed to design and construction errors (see table 4.2, type of errors). Human errors are usually influenced by underlying factors. This means that the current quality assurance approach of the Eurocode is not satisfactory.
Hence, it can be concluded that the number of failures associated with human errors exceeds the number of failures not related to human errors.

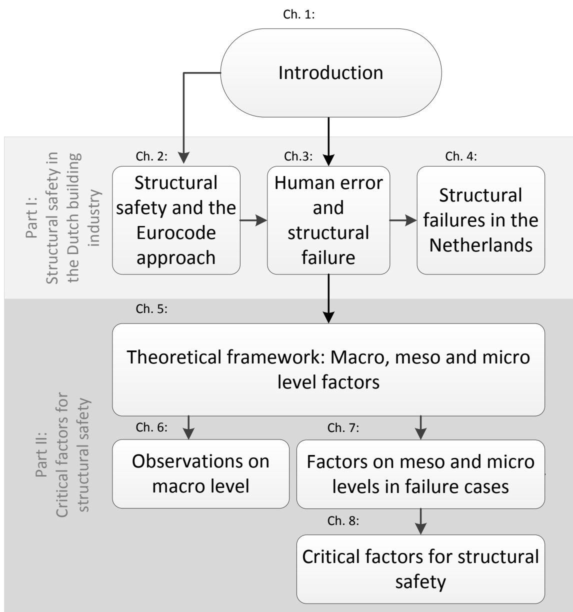
Furthermore, it was concluded that the cause of origin of structural failure (including near misses) is approximately 35% in the design phase, approximately 30% in the construction phase and less often in the use and maintenance phase (approximately 10%). A reasonable number of cases (over 10%) have a combination of design and construction errors. Therefore, special attention is needed for the design and construction phase, to reduce the number of failures.

Finally, the proneness of errors might range depending on for instance the type of structure, material and type of element. When searching for improvement of structural safety, this should be taken into account.

From the study of underlying factors it is concluded that every source used different categories. A consistent framework with underlying factors, would be helpful to make comparison between databases easier.

Part I of this thesis explained the current Eurocode approach to assure structural safety and investigated the current level of structural safety. This final chapter of part I revealed that structured knowledge on underlying factors within the building industry is currently lacking, while these factors are expected to be of major importance in the occurrence of structural failures. Therefore, the underlying factors within the design and construction process which are expected to influence structural safety, will be the main focus of part II of this thesis.

PART II:



CRITICAL FACTORS FOR STRUCTURAL SAFETY

“Human error is not the cause of failure, but the effect of trouble deeper inside your system”
S. Dekker

5

Theoretical framework for macro, meso and micro level factors[1]

5.1 Introduction

In chapter 3 a basic model was introduced in which underlying factors and human errors were related to structural failure. Chapter 4 revealed that about 80-85% of the structural failures in the Netherlands were caused by human errors during design and construction, which might have been influenced by underlying factors. However, the descriptions of the majority of cases did not include extensive information on the underlying factors. In addition, limiting to information from failure cases will not provide adequate answers on the criticality of factors, because the factors might also be equally present in successful projects. If, for instance, a primary contributing factor of the collapse of a structure seemed to be changes in the design, it is possible that in successful projects an equal number of changes is present.

Therefore, part II of this study will focus on deriving the underlying factors within design and construction process that are critical for structural safety. Critical factors are expected to make a difference between a successful and less successful project regarding structural safety.
This chapter will present the results of a literature study on management theory and safety science, with the aim to comprehensively list factors within the process that might influence safety. The results will be presented as an initial theoretical framework for the underlying process factors.

Subsequent chapters will investigate in what way these factors can influence structural safety in the building industry (chapters 6 and 7) and which of the factors are critical for structural safety (chapter 8).

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[1] *This chapter is based on a conference paper 'Critical Structural Safety Factors' for the ASCE Forensic Engineering Conference in San Francisco (Terwel, K. C. and J. N. J. A. Vambersky (2012)) and on a paper 'Critical factors for structural safety in the design and construction phase' (Terwel, K.C. and S.J.T. Jansen) which was accepted by the 'Journal of Performance of Constructed Facilities' for publication. Used with permission from ASCE.*

In this chapter the approach for developing the framework is explained first. In addition, the structure of the framework is presented, based on the multidisciplinary literature study. This framework makes a distinction in macro level with external factors, in meso level with organizational factors and micro level with human factors. Finally, for every level possible influencing factors are listed.

5.2 Multidisciplinary approach

5.2.1 General approach for developing the theoretical framework

The list of possible underlying factors is based on a literature study, which focused on factors that might influence safety or quality in the building industry and other industries. The framework was developed in various iterations. First, an initial list with possible influencing factors was used, based on a review paper of a number of studies of Critical Success Factors (Chan, Scott et al. 2004, see subsection 5.2.2). This initial list was amended based on the results of a number of studies from management literature, with a focus on factors influencing project success. Quality can be regarded as an element of success. Furthermore, the initial list was compared with a selection of literature from safety science, with a focus on factors influencing safety (see figure 5.1).

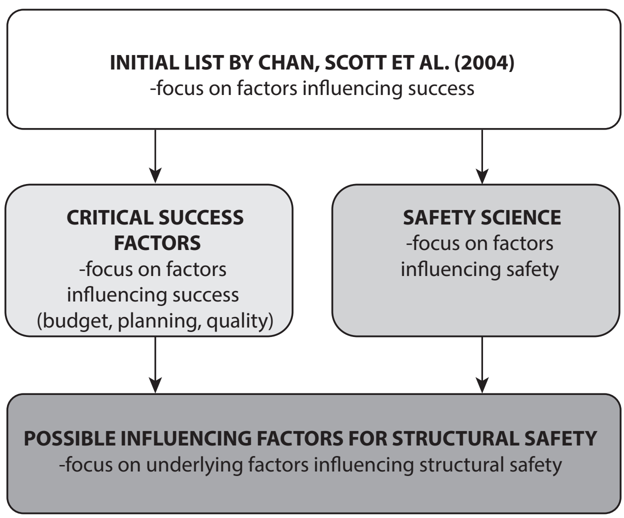

Figure 5.1 *Sources for possible underlying factors on structural safety from various disciplines*

Only those factors were selected, that are expected to be likely to influence structural safety. The final framework was discussed with some experts from building industry to check if any trivial factors were lacking in their opinion.

5.2.2 Critical Success Factors

The review of management literature has focused on the concept of Critical Success Factors (CSFs). CSFs are usually defined as "those few key areas of activity, in which favorable results are absolutely necessary for a particular manager to reach his/her goals" (Rockart 1982). Although many definitions of success have been suggested, a satisfactory performance on time, cost and quality is predominant. Since structural safety can be regarded as an essential aspect of the quality of a structure (see chapter 2), the concept of CSFs could be useful as a source of inspiration. Furthermore, in chapter 8 an approach will be used to derive critical factors, which has been used in the reviewed literature to derive CSFs.

As a starting point for this thesis the conceptual framework by Chan, Scott et al. (2004) is used, which will be named Ref 1. These authors performed a structured review on literature related to CSFs in seven major highly rated management journals. Forty three journal articles were finally selected which formed the basis for a conceptual framework for factors affecting project success. The authors distinguish factors in five categories, see table 5.1.

Table 5.1 *Initial list of underlying factors, based on Chan, Scott et al. (2004)*

External environment	Project-related factors	Project procedures	Project management actions	Human-related factors
-Economic environment -Social environment -Political environment -Physical environment -Industrial relations environment -Technology advanced	-Type of project -Nature of project -Number of floors -Complexity of project -Size of project	-Procurement method -Tendering method	-Communication system -Control mechanism -Feedback capabilities -Planning effort -Appropriate organization structure -Effective safety program -Effective quality assurance system -Control of subcontractors -Overall managerial actions	-Client's experience -Nature of client -Size of client's organization -Client's emphasis on cost, high quality or quick construction -Client's ability to brief, make decisions, define roles -Client's contribution to design or construction -Project team leaders' experience -Technical, planning, organizing, coordinating, motivating skills of the project team leaders -Project team leaders' commitment to meet cost, time and quality/ early and continued involvement/ adaptability to changes/ working relationship -Support and provision of resources from project team leaders' parent company

The initial list of Chan, Scott et al. was compared with the outcomes of a list of 10 CSF publications and where necessary amended. The CSF publications were selected by Favie (2010) from research in which CSFs were quantitatively derived on building projects.

These references 2-11 are briefly discussed in appendix IV.
Ref 2 = (Ashley, Lurie et al. 1987)
Ref 3 = (Belassi and Tukel 1996)
Ref 4 = (Chan, Ho et al. 2001)
Ref 5 = (Chua, Kog et al. 1999)
Ref 6 = (Jaselskis and Ashley 1991)
Ref 7 = (Lam, Chan et al. 2008)
Ref 8 = (Ling 2004)
Ref 9 = (Sanvido, Grobler et al. 1992)
Ref 10 = (Songer and Molenaar 1997)
Ref 11 = (Favie 2010)

However, CSF literature usually focused on performance on time, budget and quality and not specifically on safety. Therefore, literature from safety science was included to adjust the initial list of Chan, Scott et al.

5.2.3 Safety Science

Within safety science numerous publications are available that focus on factors influencing safety in various industries. From this abundance of literature five sources have been selected, which provided useable lists of influencing factors.

Groeneweg (1992, ref. 12) developed the TRIPOD method, based on chaos and fractal theory. This method distinguishes 11 General Failures Types: hardware defects, inappropriate design, poor maintenance management, poor operating procedures, error enforcing conditions, poor housekeeping, incompatible goals, communication failures, organizational failures, inadequate training and inadequate defenses. The General Failure Types were derived on the basis of 1500 possible indicators for safety, which were collected in an extensive case study within petrochemical industry. This method has been selected because of its thorough set up and long term application in various industries.

Ref. 13 (Guldenmund, Hale et al. 2006) explains the ARAMIS method, an audit technique to rate safety performance. In this model the following factors are included: 1. Risk (scenario) identification, barrier selection and specification, 2. Monitoring, feedback, learning and change management, 3. Design specification, purchase, construction installation, interface design/layout and spares, 4. Inspection, testing, performance monitoring, maintenance and repair, 5. Procedures, plans, rules and goals, 6. Availability and manpower planning, 7. Competence and suitability, 8. Commitment and conflict resolution and 9. Coordination and communication. ARAMIS has been selected because it includes the outcomes of I-risk. I-risk was an international project to design a risk assessment tool, which was also the basis for the management deliveries in Storybuilder (see chapter 4 and appendix III).

However, in TRIPOD and ARAMIS explicit cultural factors remain underexposed. Ref. 14 (Fleming 2000) highlights these factors in his Safety Culture Maturity model with factors management commitment and visibility, communication, production versus safety, learning organization, safety resources, participation, shared perceptions about safety, trust, industrial relations and job satisfaction and training.

TRIPOD, ARAMIS and the Safety Culture Maturity model predominantly focus on organizational factors influencing safety. Safety science, however, also produced an abundance of Human Reliability Assessment (HRA) methods used for error identification, quantification and reduction within processes, with a primary focus on individual behaviour. A typical HRA method is the Cognitive Reliability Error Analysis Method (CREAM), as explained in Ref. 15 (Hollnagel 1998). This method consists of a task analysis, context description, specification of initiating events and error prediction. Within this method Common Performance Conditions are distinguished: adequacy of organization, working conditions, adequacy of MMI and operational support, availability of procedures and plan, number of simultaneous goals, available time, time of the day, adequacy of training and expertise and crew collaboration quality.

Ref. 16 (Toriizuka 2001) derives Performance Shaping Factors (PSFs) for maintenance, based on a broad literature review. These PSFs are similar to the Common Performance Conditions within CREAM, although Toriizuka's selection includes the influence of physical and mental pressure on individuals. These PSFs consist of the categories: judgmental load, physical load, mental load, information and confirmation, indication and communication, machinery and tools, environment and work space.

The selected possible underlying factors are explained in the following section.

5.3 Possible underlying factors

5.3.1 Categories and factors in the framework

Van Duin (1992) suggests a categorization with factors on three levels: sector/country level (macro level), organizational factors (meso level) and human factors (micro level). Similar categorizations are found in CSF literature (e.g. the five categories of Chan, Scott et al. in section 5.2). In this study this categorization is adopted with modifications.

For selection of factors, the initial list of Chan, Scott et al. was amended with the factors that were presented in ref. 2-16. Some factors were combined. Others were excluded when it seemed evident that the factors would not be relevant for structural safety in the building industry.

Figure 5.2 gives the final overview of the relevant factors that have been derived from the selected literature in section 5.2 on macro, meso and micro level.

On macro level possible underlying external factors are listed. These factors are related to the situation in which a project exists and they are usually hard to influence by any of the project participants.
On meso level project factors, company factors, and project characteristics are distinguished. Project factors are related to the collaboration of several parties within a project. Company factors take into account that every company brings his own features, like organization, culture, working conditions and habits in a project. The factors that might play a role within companies, might be similar to the factors on project level. Project characteristics are related to type and complexity of the project and the phase of a project.
On micro level possible underlying human factors are mentioned.

MACRO

EXTERNAL FACTORS
Cultural factors
Socio-political factors
Economic factors
Technical factors
Legal factors
Physical factors

MESO

COMPANY/ PROJECT FACTORS
Safety goals
Safety culture
Allocation of responsibilities
Risk analysis and allocation
Control mechanisms
Protocols
Communication
Collaboration
Planning and budget
Knowledge infrastructure
Working conditions
Instrumens

PROJECT CHARACTERISTICS
Complexity of the project
Complexity of the process
Phase within the building process

MICRO

HUMAN FACTORS
Technical competencies
Management skills
Social-communicative skills
Attitude
Mental resilience
Physical resilience

Figure 5.2 *Overview of possible underlying factors (adopted from Terwel and Vambersky (2012)*

In the following sections the various possible underlying factors are explained with a listing of the references which mentioned these factors. Only those factors are presented, that are expected to be likely to influence structural safety. Sometimes the listed sources did not provide a definition. In these situations a definition is suggested by the author or derived from other sources.

5.3.2 Macro level: External factors

Culture is the collective mental programming that distinguishes between the members of a group or category and other members (Hofstede 1991). The safety culture of a country or sector might be of importance in the way safety is approached (Fleming 2000).

Socio-political factors can be political or religious movements, political conditions and public opinion (Morris and Hough 1987; Hadipriono and Chang 1988). Pressure from the public with regard to structural safety might stimulate legislation and increase attention for structural safety. In addition to these social factors, political factors might play a role. The way and extent a government is involved in the building industry might affect the level of structural safety.

Economic factors are defined as factors related to the current state of the economy (recession or boom), inflation, interest rate variations, exchange rate fluctuations, current state of the market (available supply of labour, materials, equipment and level of competition) and tax level (Morris and Hough 1987; Hadipriono and Chang 1988; Songer and Molenaar 1997). Scarcity might be a thread towards structural safety, because designs will be developed on the edges to the detriment of redundancy.

Technical factors are described as the current state of technology within a country (available structural systems, building technologies, quality of materials, level of education and transfer of knowledge). Usually, these factors are mentioned on project level (Ashley, Lurie et al. 1987; Songer and Molenaar 1997; Chua, Kog et al. 1999), but the national situation might play a role as well. The state of technology in a country determines the extent to which the project or process is regarded as complex and the possibilities for design and construction of project participants. It is widely believed that in developed countries the current state of technology is on a higher level, resulting in a lower probability of failures.

Legal factors are the entirety of laws and rules issued by the government to assure structural safety. Included are the quality of codes, the level of penalties for breaking laws or rules and the way public control has been established. Ashley, Lury et al. (1987) mention the legal-political environment, with special reference to favourable governmental agency involvement and minimal legal restrictions. Li, Akintoye et al. (2005) highlight the government as issuer of laws. Diekmann and Girard (1995) mention the role of permits and regulations and Arditi and Gunaydin (1998) mention codes and standards in the design phase.

Physical factors are the natural circumstances of a location, such as the ground conditions (Long, Ogunlana et al. 2004), groundwater level (fluctuations), climate (temperature, humidity, wind, rain) (Hadipriono and Chang 1988), existence of earthquakes and organic situation (deterioration by insects or micro-organisms). Often these factors differ locally, but they are categorized as external factors, for project participants have no influence on these situations.

It should be noted that all external factors can change over time.

Table 5.2 provides additional information on references that list possible external factors.

Table 5.2 *External factors possibly influencing structural safety*

External factors	References
Cultural	Ref 14
Socio-political	Ref 1, 2, 3, 5, 7
Economic	Ref 1, 2, 3, 5, 7, 10, 11
Technical	Ref 1, 2, 3, 5, 8, 10, 11
Legal	Ref 2
Physical	Ref 1, 3, 4, 5, 7, 9

5.3.3 Meso level: Project Characteristics

Complexity can be defined as "the complicated nature of something" (Rundell et al. 2007). The concept of complexity is ambiguous. Johansen and Rausand (2012) define complexity as: "a state of difficulty in determining the output of a system based on knowledge about individual inputs and given our current knowledge base." Because the knowledge and experience of individuals will differ, the assessment whether a project or process is complex, is dependent on the assessor and makes the variable 'complexity' hard to operationalize.

Complexity of the project can be defined as the extent to which the design and final appearance of the building or structure is regarded to have a complicated nature. Forensic engineering literature often distinguishes between the function of a project (a nuclear reactor is usually more complex than a residential building), nature of the project (structural load-bearing system), material use (use of innovative materials often gives more complexity and proneness to errors) and size of the project (a large building might have the advantage of a lot of repetition when modularization (Chua, Kog et al. 1999) is used, but gives greater demands on communication and coordination). It can be concluded that various features of a structure might influence the complexity of a structure.

Complexity of the building process can be defined as the extent to which the design and construction process is regarded to have a complicated nature. The complexity of the organization, with for instance a large number of subcontractors, is pointed out by

Akinsola, Potts et al. (1997). The number of times a team changes ('team turnover rate') is mentioned by Chua, Kog et al. (1999). Complexity of activities, like constructability of a project, is mentioned by various authors (e.g. Diekmann and Girard 1995).

The *phase within the building process* is a limited period between the initiation of the project and the delivery of the structure. In every stage of the building process other risks and threats are present. As stated in chapter 1, this thesis will focus on the design and construction phase.

Pinto and Covin (1989) argue that for different type of projects and in various phases different success factors may play a role. Therefore the project characteristics might be presented as potential influencing factors, but moreover they do influence the relative importance of other influencing factors. A very complex construction method for instance might make the structure more vulnerable to failures. However, it might also increase the importance of control processes (possible factor on meso level) or technical competencies (possible factor on micro level).

Table 5.3 provides additional information on references that list possible project characteristics.

Table 5.3 *Project characteristics possibly influencing structural safety*

Project characteristics	References
Complexity of project	Ref 1, 2, 3, 5, 6, 7, 8, 9, 10, 11
Complexity of building process	Ref 3, 4, 5, 6, 8, 10, 11
Phase within the building process	Ref 11

5.3.4 Meso Level: Project and Company factors

Safety goals are objectives with regard to structural safety.
The importance of clear goals is outlined by Ashley, Lurie et al. (1987), amongst others. In safety literature the risk of incompatible goals is mentioned, for instance with productivity versus safety goals (Groeneweg 1992; Fleming 2000). In this regard management commitment to safety is often mentioned, for instance by Fleming (2000). When the (top) management is not motivated to improve safety, they will not make any funds and time available to improve safety. For other persons in the company it will be very hard to stay committed to safety in this situation.

Safety culture has been defined in various ways (see Guldenmund 2010, p. 25). For this study it is regarded as the total of practices, conventions and habits that affect the way the organization is dealing with risks. Fleming (2000) lists 10 aspects of safety culture (see subsection 5.2.3). Straight forward it can be defined as 'The way we do things around here' (Guldenmund 2010).

Safety culture is often regarded as a layered concept. Schein (2010) makes a distinction in artifacts, espoused values and basic assumptions.
Artifacts are the phenomena within a group you can see, hear and feel.
Espoused values are the ideals, goals, values and aspirations of a group. They may, or may not be in line with behavior and other artifacts. The espoused values might be regarded as the sum of attitudes of various individuals (Guldenmund 2010). The espoused values can be defined as safety climate (Guldenmund 2010).
Basic underlying assumptions are non negotiable, unconscious, taken-for granted beliefs and values. These assumptions will determine behavior, perception thought and feeling, but are not directly observable (Schein 2010).

Safety culture is a broad concept that might sometimes overlap with several other factors. For example, the explicit stating of safety goals can be part of safety culture (or more specifically, they might be a form of espoused values (Schein 2010)) within an organization. However, the current study choses to separately mention safety culture, to pay attention to safety climate issues that are not entirely covered by others factors.
This factor might be of importance on sector level as well as on project and company level.

Allocation of responsibilities is the amount or share of responsibility that is given to a person or organization (based on Rundell et al. (2007)). A good allocation of responsibilities can be described as a project organization suited to size, complexity and urgency of a project with a clear and suitable assignment of responsibilities (Diekmann and Girard 1995; Chan, Scott et al. 2004). Several authors point out that the project organization is of importance for project success and an inadequate project organization might threaten safety (e.g. Groeneweg 1992). In the present study it is recognized that the type of project organization might be of importance, especially for process complexity. This organization can be determined by the procurement method. However, in the present study the focus will be on the allocation of responsibilities, because every tendering form should be able to lead to safe structures.
With regard to the allocation of responsibilities some authors mention the role of a project champion (central responsible person) (Morris 1989; Belassi and Tukel 1996) .

Risk analysis and allocation stands for the identification and assignment of risks, associated with structural safety of the building product and the building process. It is mentioned by various authors (e.g. Ashley, Lurie et al. 1987; Guldenmund, Hale et al. 2006). The combination of risk analysis and risk allocation is part of risk management. Risk management is usually regarded as an integral approach to deal with risks. Hubbard (2009) defines risk management as the identification, assessment, and prioritization of risks followed by coordinated and economical application of resources to minimize, monitor and control the probability and/or impact of unfortunate events.

Control mechanisms are defined as ways to keep something at the right level/limit (after Rundell et al. (2007)). For structures this might be in the form of monitoring, warning systems or checking (Schneider 1997, p. 22). This study will focus on control in the form of checking, because this is commonly regarded as an important way to detect mistakes already made. This factor is therefore accepted by numerous authors (e.g. Chan, Scott et al. 2004). Checking is an essential part of quality management, because the basis of quality management is to avoid mistakes and to detect and recover already made mistakes (see chapter 2). In addition, checking can be based on risk analysis.

(Change) *protocols* can be regarded as the rules describing the way tasks should be performed. They are related to procedures that are specified ways to carry out an activity or process (ISO 9000, art. 3.4.5). It is believed that when working in conformity with established procedures the probability of mistakes will be reduced. ISO 9001 procedures are based on this assumption (see chapter 2).

Communication is exchange of information within a company or among the various project partners. This factor is mentioned in almost every relevant source as influencing factor (e.g. Chan, Scott et al. 2004; Guldenmund, Hale et al. 2006). If information about the structure is not adequately shared among the various partners, structural safety will be questionable. Communication can be written, for instance in contracts, minutes, protocols, reports, letters, emails or faxes. In addition, it can be oral, by telephone or face-to-face, or non-verbal.

Several sources mention coordination, but this factor will not be separately listed, because it can be regarded as a combination of communication, collaboration and control on the interfaces of various disciplines or tasks.

Collaboration can be defined as the way various project partners cooperate with each other. In the literature this factor has often been mentioned in relation to aspects like trust (Fleming 2000) and atmosphere in the sense of harmonious working relationships among project team members (Lam, Chan et al. 2008). Good cooperation is believed to improve the quality of a building project.

Planning and budget can be defined as a the amount of available hours and budget to deliver a product. In the literature planning effort is often mentioned. Belassi and Tukel (1996) for instance mention the importance of effective planning and scheduling. For structural safety the following reasoning can be posed: if the planning is too tight, the risk of rushing through tasks with accompanying mistakes is possible.
Various authors highlight the importance of adequacy of budget (e.g. Chua, Kog et al. 1999). However, a reasonable budget made available by the client does not always result in a reasonable amount of time that is truly devoted to the project by the project team members.

If a *knowledge infrastructure* is developed, technical as well as process knowledge of relevant solutions will be present and available. Aspects like years of education (Chua, Kog et al. 1999), experience (various authors), training (various authors) and learning from failures (Ashley, Lurie et al. 1987) might play a role. The cumulative technical competencies (see subsection 5.3.5) of project participants are included in the knowledge infrastructure, but knowledge infrastructure can also consist of written knowledge in databases and books/reports of for instance past projects.

Working conditions entail the influence of the environment on the performance of work. Toriizuka (2001) describes environment and workspace as performance shaping factors. Hollnagel (1998) mentions working conditions, time of the day, adequacy of MMI (man machine interface) and operational support as influencing factors.

Instruments are the provided tools (software or equipment) that are necessary to perform the tasks properly. This is mentioned by some authors (e.g. Toriizuka 2001). If no adequate tools are available to craftsmen, this might lead to a lower level of quality and safety.

Each of the listed factors can be relevant on project level (with regard to collaboration of the project partners) or on company level (with regard to the internal organization of every project partner). Control processes for instance are important within a single company as well as between various project partners.
Sometimes, it will not be easy to distinct the company level and the project level from each other; the safety culture of single companies, for instance, can influence the safety culture of the entire project.
On the other hand, it should be stressed that factors might be different on project and company level. The quality of human resources might be good on average for a project, although there can be one company in the team with inadequately skilled personnel. The overall project budget might be sufficient, while specific subcontractors have to deal with a suboptimal budget.
Furthermore, a difference in importance of factors on project level compared to factors on company level might be present. It is possible that, for instance, tools are more important on company level, because on project level there is only a small number of shared tools.

Some possible factors like the type of client and the size or experience of companies are not listed. These aspects can be related to a successful performance on structural safety. However, it is believed that the possible successful performance of for instance companies with relevant experience is covered by underlying factors like knowledge infrastructure or technical competencies.

Table 5.4 provides additional information on references which list possible project or company factors.

Table 5.4 *Project and company factors possibly influencing structural safety*

Project and company related factors	References
(Safety) goals	Ref 1, 2, 4, 5, 6, 7, 8, 10, 11, 12, 14, 15
Safety culture	Ref 1, 2, 3, 5, 7, 9, 14
Allocation of responsibilities	Ref 1, 2, 3, 4, 5, 6, 7, 12
Risk Management	Ref 2, 5, 11, 13
Control Mechanisms	Ref 1, 2, 3, 4, 5, 6, 7, 8, 11, 13
Protocols	Ref 2, 4, 5, 8, 9, 10, 12, 13, 15
Communication	Ref 1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 12, 13, 14, 16
Collaboration	Ref 2, 4, 5, 6, 7, 8, 14, 15
Planning and budget	Ref 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13, 14, 15
Knowledge infrastructure	Ref 2, 12, 13, 14, 15
Working conditions	Ref 11, 15, 16
Instruments	Ref 3, 8, 12, 13, 15, 16

5.3.5 Micro level: Human factors

Technical competencies are the demonstrated abilities to apply knowledge and skills for the design and construction of a structure (ISO 9000, art. 3.1.6). More knowledge will not automatically lead to better skills. Knowledge of possible solutions, for instance, is no guarantee for the ability of successful application of these solutions.
The importance of competencies is often mentioned. Chan, Scott et al. (2004) for instance highlight the importance of the technical skills of project team leaders. With regard to skills and knowledge, Chua, Kog et al. (1999) state that an engineer should include the constructability of a project in his design (constructability program).

Management skills are the skills to lead oneself and others. Aspects are the ability to plan and decide (Ashley, Lurie et al. 1987), organize (Belassi and Tukel 1996) and motivate (Chua, Kog et al. 1999). If a project is not managed properly (e.g. no adequate team arranged for engineering a project) this might lead to inattentive work and mistakes.

Social-communicative skills are the abilities with regard to interpersonal communication. In CSF literature this factor is repeatedly mentioned, for instance by Chan, Scott et al. (2004). It is believed that when people within a team do not feel recognized and appreciated for their effort, they are not motivated to deliver quality.

Attitude is defined as "someone's opinions or feelings about something" (Rundell et al. 2007). For this study a positive attitude is regarded as a constructive position and commitment towards safety by the various participants of the project. Ashley, Lurie et al. (1987) for instance mention the project managers' goals commitment and involvement. A positive attitude and motivation might lead to more conscious behavior and less failures.

Mental resilience is the way in which an individual can cope with stress. This factor is for instance suggested by Toriizuka (2001). When a person cannot cope with the pressure of a project, health problems (like lack of sleep) might occur, resulting in a declining quality of the person's work.

Physical resilience is the way in which an individual can cope with long term and heavy physical loading (Toriizuka 2001). When a craftsman is loaded above his capacity, he might develop health problems and the quality of the work will be under pressure.

Table 5.5 provides additional information on references that list human factors.

Table 5.5 *Human factors possibly influencing structural safety*

Human factors	
Technical competencies	Ref 1, 2, 3, 4, 5, 6, 7, 8, 9, 16
Management skills	Ref 1, 2, 3, 4, 5, 6, 7, 8
Social-communicative skills	Ref 1, 3
Attitude	Ref 1, 2, 3, 5, 7, 8, 13
Mental resilience	Ref 16
Physical resilience	Ref 16

5.4 Relationships between factors

Without giving a comprehensive overview of all possible relationships between levels and tasks, some examples will be provided for the influence of higher levels on lower levels, of factors on the same level, of lower levels on higher levels and between underlying factors and tasks and activities.

It is plausible that higher levels might influence lower levels. Macro level can influence meso level or micro level. Some examples are given. The culture in a country (macro level) can influence safety culture of a project (meso level) and the attitude of individuals (micro level). Economic factors (macro level) can influence the availability of budget (meso level). In addition, meso level can influence micro level. For instance, the safety culture of a project can influence the attitude of individuals.

Furthermore, factors on the same level can influence each other. Some examples are provided for macro, meso and micro levels. Technical factors, like a high level of industry, can influence economic factors (macro level). Culture is an all encompassing term which can include socio-political, economic, technical, legal and physical factors (macro level).
Risk analysis can determine the aspects that have to be checked (meso level). Safety culture is a broad term which might include factors like safety goals, allocation of responsibilities, risk analysis, communication and collaboration.
On micro level, mental resilience can influence technical competencies.

Moreover, lower levels can influence higher levels. Micro level can influence meso level and meso level can influence macro level. The influence of micro level on macro level is less obvious.
Management skills (micro level) are expected to have a high influence on meso level factors like allocation of responsibilities, development of risk analysis and allocation, availability of protocols, available planning and budget, working conditions and instruments. Safety culture of projects (meso level) influences the culture in a sector.

Finally, underlying factors are expected to influence tasks and activities. Macro level is usually not directly influencing tasks and activities (like drawing, calculating and assembling). However, meso level can directly influence the performed tasks and activities. When for instance allocation of responsibilities is poor, some tasks might be omitted. When risk analysis or control mechanisms are not well developed, control tasks might be performed in an ineffective way. When planning is poor, this might result in insufficient performance of tasks.
Micro level is also expected to directly influence tasks and activities in the building process. Technical competencies or attitude can directly influence the ability to perform tasks in the right way. However, management skills usually will influence tasks and activities like drawing and assembling through the meso level (planning and budget, allocation of responsibilities, etcetera).

From this brief discussion, it can be concluded that there is an abundance of relationships between various levels and between underlying factors and tasks and activities.

Within the CATS-model (Lin 2011) various relationships between meso and micro levels have been tried to quantify. This resulted in a very complex model. Because for structural safety the influencing variables have not been derived yet, the primary focus of this study will be on determining these variables, with brief attention to the relationship between the variables. In chapter 8, for instance, it will be checked if there are large correlationships between factors on meso and micro level.

5.5 Conclusions

By using concepts from management literature and safety science, possible underlying factors could be derived, which might influence the performance of a structure within the design and construction process. Hence, a start is made by exploring the underlying process factors influencing structural safety, as introduced in subsection 3.3.4.

It appears that in the studied literature factors on meso and micro level are mentioned most often. These are especially safety goals, allocation of responsibilities, control mechanisms, communication, collaboration, planning and budget and knowledge infrastructure respectively technical competencies and management skills. However, no reliable conclusions can be drawn about the relative influence of the various factors based on this initial literature study yet.

Chapters 6 and 7 will explore to what extent the various levels can influence structural safety in the Dutch building industry.

6

Observations on macro level

6.1 Introduction

In chapter 5 possible underlying factors of structural safety of buildings were derived from safety and management literature. It was assumed that the selected factors are also applicable for structural safety in the building industry.
This chapter will explore in what way the suggested underlying factors on macro level are expected to influence structural safety within the current Dutch building industry. The suggested factors on macro level are: cultural, socio-political, economic, technical, legal or physical. The exploration is based on a selection of literature, which focuses on the building industry in the Netherlands.
The factors that are expected to have an obvious negative impact within the current building industry will be highlighted as main observed threats.

6.2 Approach: literature review

Relevant Dutch literature on structural safety was selected and reviewed on the macro factors that might influence structural safety. The information within selected publications was extracted, the information was compiled per factor and the relevant outcomes are presented in this chapter.
Literature is considered to be relevant when it is often cited (e.g. professional journal articles), when it is written by an acknowledged authority, like the Dutch Safety Board or the Platform on Structural Safety (see chapter 1) or when it is peer reviewed.

A brief description of the relevant literature is provided in appendix V.

6.3 Presence of factors in selected publications

Table 6.1 shows the presence of factors on macro level in the selected publications, usually negatively related to structural safety. The English translation of Dutch sources is provided in appendix V. Sources 1-15 are general publications regarding structural safety in the Netherlands. Sources 16-25 are focused on Dutch failure cases. To prevent overlap, when failure cases are covered in summarizing reports, the original public failure case reports were not included.

Table 6.1 *Presence of macro level factors in selected publications*

	Name of source	Cultural (15)	Socio-political (5)	Economic (7)	Technical (17)	Legal (24)	Physical (9)
1	'De tikkende tijdbom onder de bouw' (Vambersky and Sagel 1997a; Vambersky and Sagel 1997b; Vambersky and Sagel 1997c)	•				•	
2*	'De 'juridische constructeur" (Boot, Terwel et al. 2011; Boot, Terwel et al. 2012a; Boot, Terwel et al. 2012b)					•	
3	'Kasteel of kaartenhuis?' (Inspectorate of Housing 2007; VROM-inspectie 2007)	•		•	•	•	
4	'Weg met de zwakke schakels' (Inspectorate of Housing 2007; VROM-inspectie 2007)	•			•	•	
5	'Borging van de constructieve veiligheid in 15 projecten' (KplusV 2007; VROM-inspectie 2008a; Mans et al. 2009)	•			•	•	
6	'Compendium aanpak constructieve veiligheid' (VROM-inspectie et al. 2006; Spekkink 2011)				•	•	
7	'Gedragscode constructieve veiligheid' (NEPROM 2008)	•				•	
8	'Constructieve veiligheid in juridisch perspectief' (Gambon 2008)				•	•	
9*	'Constructieve veiligheid van bouwwerken en het rapport commissie Dekker' (Vambersky and Terwel 2009)	•	•	•	•	•	•
10	'Over constructieve veiligheid en het belang van interactief communiceren in bouwnetwerken' (Gulijk 2011)	•				•	
11	'Construction safety, an analysis of systems failure' (Priemus and Ale 2010)	•		•	•	•	
12*	'Trends in the Dutch building industry: potential threats for structural safety' (Terwel and Mans 2011)	•	•	•	•	•	
13*	'Learning from safety in other industries' (Terwel and Zwaard 2012)	•			•	•	•
14*	'Comparison of structural performance of Dutch and Spanish Building industry' (Mendez Safont and Terwel 2012)		•			•	
15*	'An initial survey of forensic engineering practices in some European countries and the USA' (Terwel et al. 2012)					•	
16	'Falende constructies' (CUR Bouw & Infra 2010a)	•			•	•	•
17	'Leren van geotechnisch falen' (CUR Bouw & Infra 2010b)	•	•		•	•	•
18*	'ABC meldpunt: een constructieve verbetering?' (CUR Bouw & Infra 2011; Terwel, Nelisse et al. 2012)	•			•	•	•
19	'Veiligheidsproblemen met gevelconstructies' (Onderzoeksraad voor Veiligheid 2006)			•	•	•	•
20	'Bezwijken torenkraan Rotterdam' (Onderzoeksraad voor Veiligheid 2008)				•	•	
21	'Instorting verdiepingsvloer B-tower Rotterdam' (Onderzoeksraad voor Veiligheid 2012b)	•			•	•	•
22	'Instorten van het dak van de aanbouw van het stadion van FC Twente, te Enschede' (Onderzoeksraad voor Veiligheid 2012a)					•	
23	'Leren van instortingen' (Van Herwijnen 2009)	•		•	•	•	•
24	'Storybuilder analyse van meldingsplichtige ongevallen over 2007 t/m 2009' (Beek and Dijkshoorn 2011)						
25*	'Constructieve schade – een analyse van oorzaken aan de hand van jurisprudentie' (Boot 2010; Boot and Terwel 2010; Boot 2011b)		•	•	•	•	•

It can be noticed that the author of this thesis regularly was one of the authors of the listed publications, together with various co-authors. This was due to the fact that he was one of the few authors who recently published about structural safety in the Dutch building industry in an international context. However, care should be taken by biasing the analysis with the results from a single source/author. Therefore, these publications are marked (*) in table 6.1.

From this table it can be concluded that all macro level factors from the theoretical framework are present in the selected literature regarding structural safety. The literature primarily mentioned cultural, legal and technical factors.

In the following sections the possible (negative) influence per factor is explained, based on the selected literature. The main observed threats will be highlighted.

6.4 Cultural factors

Culture was defined as the mental programming that distinguishes the members of a group or category from other members. Culture can be observed as a multi-layered concept, with visible expressions of culture and underlying structures and beliefs (Schein 2010).

In literature on structural safety in the Netherlands often aspects of culture influencing safety are mentioned, like: a focus on lowest price and time, fragmentation of the sector and a reactive and anti-authoritative culture. In the following subsections these four aspects, their influence on structural safety and their probable relationship with other factors will be explained.

6.4.1 Focus on lowest price and time

In the current Dutch society a primary focus on economic values can be observed. In the literature a focus on lowest price and time are often mentioned (e.g. VROM-inspectie 2007, p. 17). Developers often select advisors and contractors based on the lowest price, and so do contractors with subcontractors. Where time is considered to be the equivalent of money, tight schedules are proposed often with accompanying penalty clauses (VROM-inspectie 2007, p. 18). It is evident when the budgets and schedules for building projects are too tight, time will be lacking to pay sufficient attention to assure quality. By limiting the budget, engineers and contractors are forced to limit the time spent on the project (VROM-inspectie 2007, p. 11). Sometimes (coordination and control) tasks are eliminated from the contract, to reduce the fee.

Hence, focus on lowest price and time can have a relationship with the availability of time and budget on meso level. The availability of time and budget can influence for instance the amount of control, tools, communication, safety culture, technical skills and attitude. Attitude can also be directly influenced by the sector's culture of a focus on lowest price and time. Even when a project has ample budget, team members can get used to taking shortcuts and deliver deficient work, because this has become common practice. Focus on lowest price and time is regarded to be a main threat.

6.4.2 Fragmentation in the building sector

Many building participants point out that the current building industry is characterized by fragmentation with a low level of coordination, which is a threat to structural safety (for instance (CUR Bouw & Infra 2011, pp. 90, 102, 112). Fragmentation is considered to be present when a large number of building participants are involved in a project, who are all responsible for a part or an aspect of the project.

This can be illustrated if in figure 3.3 the primary task of constructing the main load bearing structure of a small industrial building (with prefab ground floor and steel structure for frame) is divided in many subtasks of constructing building components by different subcontractors and suppliers (see figure 6.1). Figure 6.1 indicates the increasing number of subcontractors and relationships between contractors even for a small industrial building, let alone a more complex multifunctional building. The number of subcontractors often exceeds comparable numbers in other industries like process industry (Terwel and Zwaard 2012). Similar reasoning applies for the design phase.

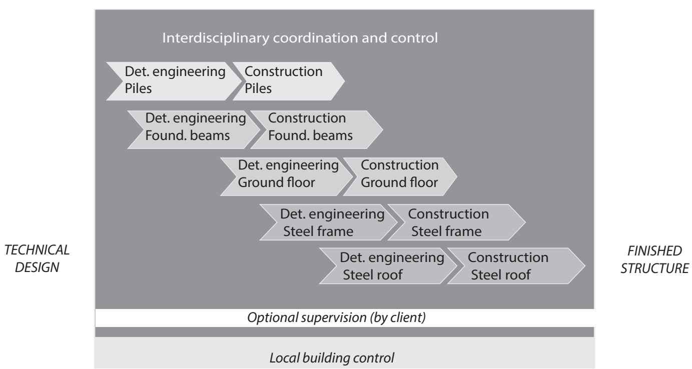

Figure 6.1 *Example of fragmented tasks in construction stage for a small project*

A low level of coordination can be observed on sector level, where many parties are involved in finding solutions to improve structural safety, but no single party has the authority to take the lead and impose changes.

The low level of coordination on sector level resulted in a lack of a common strategy on structural safety (VROM-inspectie 2008a, p. 21). The low level of coordination is also observed on project level, resulting in discussions about the necessity to employ an engineer of record (coordinating structural engineer) (Vambersky and Terwel 2009).

Several reasons for fragmentation and lack of coordination can be mentioned.
First, due to a trend of individualism, many persons opt to start their own companies, resulting in a number of small companies (Terwel and Mans 2011).
Second, because high quality products are demanded by a highly developed society, it is necessary to specialize to be able to meet the high standards, thus resulting in a high number of specialized companies (Vambersky and Terwel 2009).
Finally, contractors want to reduce their financial risks, just keeping a small number of own personnel and hiring other parties when the work demands this (Vambersky and Terwel 2009).

Fragmentation within the building sector inevitably raises the need for a strict allocation of responsibilities. In addition, extra coordination and control effort should be exerted in a fragmented building process. Every party will have its own interests, which might hamper collaboration. Fragmentation of the building sector is regarded to be a main threat.

6.4.3 Reactive culture

A reactive culture can be observed on sector and on project level (Terwel and Zwaard 2012). On sector level initiatives to improve structural safety are usually taken only after a major incident. Figure 1.1 illustrated this by showing all reports that have been issued only after failures had occurred; a reactive approach. This reactive culture becomes more clear when the way of working is compared with other safety related industries. In the building industry often mistakes, that are discovered after control, are 'fixed' (solved), which is a reactive way of working (Gulijk 2011).
In a comparison of the assurance of structural safety in 15 different projects it was observed that clients from safety related industries paid explicit and proactive attention to structural safety in their building projects, thus resulting in a better performance on the assurance of structural safety (Mans et al. 2009). A reactive culture is regarded to be a main threat.

6.4.4 Anti-authoritative behaviour

Since societal changes in the 1960's, anti-authoritative behaviour within the Dutch society can be easily observed. Although often a demand for extra control can be heard, actually many Dutch persons do not like to control and do not like to be controlled; many are control averse, probably due to their anti-authoritative attitude (personal communication with P. van Boom, July 21st 2011). Therefore, building control with accompanying enforcement is sometimes a tough task (VROM-inspectie 2007, p. 17). In other countries, like Germany with the prüf-ingenieur, the role of control and the position of controllers is more prominent (Boot 2011a). It is questionable if this system would be suitable for the Dutch situation.
This behaviour might influence the attitude of project team members towards control procedures and protocols and towards coordinators and managers. Anti-authoritative behaviour is regarded to be a main threat.

Many more aspects of Dutch culture could be mentioned, like a possible blame and shame culture, consensus culture with a lot of consultation or a tendency of straightforward and blunt communication. However, the description will be limited to the earlier mentioned aspects, because the main focus of this thesis will not be an exhaustive and complete description of cultural factors influencing structural safety.

In the following sections socio-political factors, economic factors, legal factors and technical factors will be discussed, which might be considered as specific forms of cultural factors.

6.5 Socio-political factors

Socio-political factors can be political or religious movements, political conditions and public opinion. The Dutch political situation can be regarded as relatively stable, a probable reason why this factor is not often highlighted within the selected literature. However, three possibly threatening aspects are mentioned: increasing individualism within society, reticent government and finally the dense population in the Netherlands.

6.5.1 Increasing individualism

Increasing individualism within society has been mentioned in the selected literature (Terwel and Mans 2011). As stated with cultural factors, this stimulated the emerging of many single person companies, one of the reasons of a fragmented building industry. It might also influence the way of collaboration within building projects and might influence the attitude of individuals.
In addition, related to individualism, clients are more aware of their personal demands, resulting in an increase of non-professional, private clients (Terwel and Mans 2011). Lack of professionalism might lead to a lack of complete allocation of responsibilities, and insufficient awareness of the importance of control. However, the majority of projects is still not initiated by non-professional individuals. Therefore, this possible threat will not be classified as a main threat.

6.5.2 Reticent government

A political development possibly influencing structural safety is a reticent government in combination with deregulation (Vambersky and Terwel 2009).
First, the government is reticent, because the role of building control is reduced by financial cuts, In addition, alternative ways of private building control are investigated (Van der Heijden 2009). This might influence the attitude of persons in the building process, because they are increasingly aware that they cannot rely on building control as an extra quality assuring measure (VROM-inspectie 2007, p. 14; CUR Bouw & Infra 2011, p. 105).
Second, deregulation tries to reduce the amount of legislation. When rules that are assuring structural safety are abandoned, this is a threat. In a transformation period from public building control towards private building control there might be an increased risk for safety when quality within the process is not adequately assured, because new proce-

dures still have to be developed. It is believed that this threat will be temporary, until a new equilibrium has been settled.

6.5.3 Densely populated

A social demographic factor that might influence structural safety is the fact that the Netherlands is one of the most densely populated countries in the world. This induces the necessity of a multiple use of space, which increases the complexity of building projects (Terwel and Mans 2011; Mendez Safont and Terwel 2012). It should be noticed that this is not a unique phenomenon; in other countries, cities with higher densities than in the Netherlands can be observed.

6.6 Economic factors

Economic factors are defined as factors related to the current state of the economy (recession or boom), inflation, interest rate variations, exchange rate fluctuations, current state of the market (available supply of labour, materials, equipment and level of competition) and tax level. Little attention is paid to this factor in the selected literature.

In the Dutch literature the most important economic aspects mentioned are the focus on lowest price and time, influence of recession or economic booming period and a high level of welfare in the Netherlands. Because the focus on lowest price and time has been described in the section on cultural factors, only the latter two aspects will be explained here.

6.6.1 Economic recession and increasing market

In a recession, like the situation in large parts of Europe in 2012, there might be too little budget available to do projects; in a booming economy there might be a shortage of time and skilled personnel (VROM-inspectie 2007, p. 8). The influence of the state of economy is therefore ambiguous (Vambersky and Terwel 2009).

6.6.2 Welfare

The Netherlands is recognized as a developed country with a high level of welfare. Compared to other countries the remunerations are high. As stated with 'cultural factors' it stimulates contractors to employ labourers from third parties to reduce the risks of entrepreneurship, resulting in a fragmentation of the building industry (Vambersky and Terwel 2009; Terwel and Mans 2011).

A second influence of a high level of welfare is the demand for special and unique, high quality building design, resulting in an increased level of complexity of building projects (Terwel and Mans 2011). Finally, a high level of welfare gives higher demands on working conditions. The building industry suffers from the 3D syndrome; working in the building sector is Dirty, Dangerous and Difficult (Vambersky and Terwel 2009). This might decrease the popularity of working in the building sector, thus reducing the number of available skilled workers (Terwel and Mans 2011). During current recession (2013) this is not a problem, but when economy rises this might be a threat.

6.7 Technical factors

Technical factors are described as the current state of technology within a country, like available structural systems, building technologies, quality of materials, level of education and transfer of knowledge. These aspects are mentioned by numerous authors in the selected literature on structural safety. However, problems with this factor in the Netherlands usually are not related to the quality of available materials, but generally with the availability of technical knowledge.

6.7.1 Knowledge infrastructure

The current state of technology is dependent on the knowledge infrastructure within a sector: the level of knowledge within a country and the availability of this knowledge (Terwel and Zwaard 2012). In the first place extensive knowledge of existing materials and building methods should be available and in addition, research should be done on new materials and building methods.

In the Netherlands extensive knowledge of existing materials and building methods is available, although from failure investigation in the Cobouw (chapter 4) it is known that through the years some similar failures occurred due to a lack of knowledge. Examples are a lack of knowledge on alkali-silica reactions in concrete, misuse of stainless steel in swimming pools and insufficient awareness of the possibility of breaking of double layered tempered glass due to nickel sulfide inclusions (Terwel 2012a).

The adequacy of the knowledge infrastructure is dependent on the quality of research, the quality of education and application of available knowledge.

6.7.2 Quality of research

Cost cutting on research has been mentioned as a possible threat towards structural safety (Terwel and Mans 2011). Although a lack of research might not directly influence safety of projects, the knowledge infrastructure of a country might decline with negative influences on the long term.

6.7.3 Quality of education

Quality of education has been mentioned by numerous authors. It is widely believed that the quality of education in structural engineering is on the decline (VROM-inspectie 2007; VROM-inspectie 2008b). Recent research discovered that in general technical universities deliver structural students that can easily start as engineers, although the quality of structural students from Higher Education stays far from the expected level of the engineering companies (Mastenbroek and Teunissen 2012; Terwel and Hermens 2012). In addition, it is mentioned that lifelong learning is no common practice within Dutch building industry (VROM-inspectie 2007, p. 19). It is evident that the level of education directly influences the technical skills of engineers and craftsmen. A decrease in the quality of higher education is regarded to be a main threat.

6.7.4 Application of available knowledge

Although the level of knowledge in the Netherlands is expected to be good, a lack of knowledge of an individual might be a determining cause for failure (CUR Bouw & Infra 2010a, p. 22).

Availability of knowledge in a sector is necessary to update the knowledge of individuals. Professional organizations can play an important role (Onderzoeksraad voor Veiligheid 2008). In addition, it is often mentioned that the building sector should learn from its mistakes by sharing information on failures. An important tool to achieve this is the ABC registration, as mentioned in the introduction. Evaluation of this reporting system revealed that cases were predominantly reported by officers from building control. However, the influence and implementation of this reporting system is considered to be limited (CUR Bouw & Infra 2011; Terwel, Nelisse et al. 2012). More generally, the application of available knowledge is often lacking.
Therefore, numerous authors plead for the improvement of the knowledge infrastructure of the building sector; the availability and/or use of knowledge and the learning ability can be increased (VROM-inspectie 2007; VROM-inspectie 2008b; CUR Bouw & Infra 2010a; Priemus and Ale 2010). Insufficient application of available knowledge is regarded to be a main threat.

6.8 Legal factors

Legal factors are the entirety of laws and rules issued by the government to secure structural safety. Legal factors are included in almost all of the selected publications in table 6.1.

In chapter 2 the legal framework regarding structural safety has been discussed. It was concluded that the codes in general are of good quality, although sometimes too complex.
In this section the focus will be on private law, with attention for contracts, liability and insurance. In addition, some non-legal regulations will be discussed that were issued in the Dutch building industry with regard to safety.

6.8.1 Contracts and liability

Within building projects contracts are generally used between for instance the client and advisors or builders. In the contracts usually standard conditions are made applicable. The UAV (in Dutch: 'Uniforme Algemene Voorwaarden') are the general conditions for builders and the DNR (in Dutch: 'De Nieuwe Regeling') are the general conditions for advisors.
An important aspect of the DNR is the limitation of liability. In DNR 2005 it was limited to the fee of the advisor. Because this limitation was too strict, especially when compared to other countries, many clients did not accept this limitation and asked for extra guarantees. In DNR 2011 there is an option to enlarge the limitation to 2,5 million euro. It is usually possible to cover liability with insurance (Boot, Terwel et al. 2012b).

It is suggested that a limitation of liability will reduce the incentive to deliver qualitative work (VROM-inspectie 2007, p. 19).

However, currently the level of accountability of advisors is regarded to be low. In an international comparison with seven other western countries the accountability of structural engineers proved to be the lowest in the Netherlands (Terwel et al. 2012). In addition, from arbitration award investigation it appeared that clients were accountable in 27% of the cases, contractors in 55% and engineers in only 1-2% (Boot 2011b). In 16% of the cases shared accountability was established. From these figures it can be concluded that the level of accountability of engineers is low in the current situation, if it is considered that more than 30% of the failures is due to design errors (chapter 4), even when part of the (detailed) design errors can be ascribed to contractors. A low level of accountability of advisors is regarded to be a main threat.

6.8.2 Non-legal regulations

In addition to laws and regulations issued by the government, the building industry issued non-legal regulations to improve structural safety.
First, several parties within the building industry have tried to state a common strategy towards safety. NEPROM issued their own code of conduct (see subsection 6.2.3), with which NEPROM members are expected to comply.
In October 2012 a declaration of intent was signed by various large contractors, public clients and some other parties to develop a governance code to improve safety culture and to apply a uniform way of working on safety management. The focus will be on the chain of participants in the building industry, standardization and uniformity and education and knowledge sharing. This might have a relationship with safety culture, attitude and technical skills.

In 2008 the Dutch associations for steel and for concrete structures initiated the 'Constructeursregister' (in English: 'Register for structural engineers'). Experienced engineers can apply for this register. Depending on education, past experience and current activities one can apply for registered engineer or registered designer. The demands on the latter are more strict. By applying for the register, engineers conform to the code of good governance, which states that activities shall be carefully done in an integer way, that efforts will be made to assure structural safety, that the boundaries of expertise and responsibilities shall be recognized and that professional knowledge and skills shall be constantly developed (Constructeursregister 2013). This is expected to have a positive influence on attitude and technical competencies.

Furthermore, Compendium Structural Safety (see chapter 2 and subsection 6.2.3), DNR-STB, and Demarcation list for tasks prefab structures (KIWA 2012) can be mentioned as non-legal regulations, which focus on a demarcation of responsibilities. The DNR-STB (Dutch: 'De Nieuwe Regeling – Standaard Taakbeschrijving') is a list of necessary tasks

within the building process for structural engineers. The Demarcation list prefab structures consists of six categories. Every category represents a demarcation of tasks, related to detailed engineering of prefab structures, between the client (or coordinating engineer) and certification holder (detailed engineer). It is remarkable that the demarcation list for tasks prefab structures is not provided for other materials like timber or steel.
In this regard, numerous authors underline the importance of a full commission for the structural engineer, where all the tasks, including coordination and control, can be fulfilled (VROM-inspectie 2007, p. 19; NEPROM 2008; Spekkink 2011, p. 14).

It can be concluded that various promising measures were issued in non-legal regulations. A drawback of these regulations is that they are often not enforced.

6.9 Physical factors

Physical factors are the natural circumstances of a location, such as the ground conditions, groundwater level (fluctuations), climate (temperature, humidity, wind, rain), existence of earthquakes and organic situation (deterioration by insects or micro-organisms).

In the Dutch literature this factor is not often mentioned, but most attention is paid to climate, soil conditions, and recently to earthquakes.

6.9.1 Climate

Climate influences the working conditions during construction of a building (Vambersky and Terwel 2009). Sun radiation, temperature differences, frost and wind might affect the behaviour of building materials, thus influencing structural safety.
Climate determines the severity of natural loads, like snow, rain and wind (Van Herwijnen 2009, pp. 14-20). The values for natural loads are included in the building codes (legal factor). The Dutch climate is temperate. Hurricanes and tornadoes are very rare and snow loads and rain loads are moderate compared to other countries. In some areas flooding is a potential risk, thus influencing the complexity of the design.

6.9.2 Soil conditions

Soil conditions in the Netherlands vary per area. They are commonly poorer in the western part of the Netherlands than in the eastern part. Insufficient care with regard to soil conditions has frequently caused structural damage and failures (CUR Bouw & Infra 2010b). However, the risk of this factor can be limited to a large extent when adequate risk management for geo-engineering is applied (Van Staveren 2011).

6.9.3 Earthquakes

Until recently, earthquakes were no significant issue in the Netherlands. They were rare and usually not severe. However, after an increasing number of minor shocks in Groningen, probably related to drilling for natural gas, this topic deserves attention. It is expected that regulations will follow.

6.10 Conclusions

This chapter explored the way macro level (cultural, socio-political, economic, technical, legal and physical factors) is expected to influence structural safety. It was made plausible that the suggested underlying factors on macro level can influence structural safety. There was no need to add other factors to the theoretical framework.

The majority of these factors are expected to be adequately covered in the current situation; the political situation is relatively stable (socio-political), the level of welfare is high (economic), the legal framework and level of technical knowledge are generally of good quality (legal and technical), and the Netherlands has a temperate climate (physical).

Some of the characteristics of current Dutch building sector are especially expected to negatively influence structural safety; these are called the main observed threats.
The main observed threats for structural safety are expected to be caused by some specific cultural, legal and technical factors, because within the selected literature (table 6.1) these categories attract the highest amount of attention. They were mentioned more than 10 times, while the others were mentioned less often. An elaborate validation of these observed threats will not be included in this thesis.

The main observed threats associated with these factors were highlighted in the various subsections, and are listed in figure 6.2.

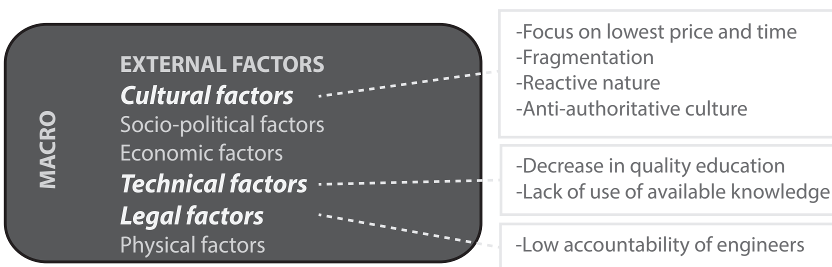

Figure 6.2 *Observed main threats for structural safety on macro level*

From the explanation of the various factors it can be concluded that the main observed threats can influence every project within the Dutch building industry, which indicates systemic problems that might impede improvements within building industry. In sections 8.5 and 9.10 attention is paid to this issue.

In the following chapter the way meso and micro levels are expected to influence structural safety will be explored, by a description of the assumed contribution of these factors in three failure cases.

7

Factors on meso and micro levels in failure cases

7.1 Introduction

In chapter 6 the main observed threats on macro level have been selected from literature. In chapter 5 it was assumed that the meso and micro level factors as determined by the international literature study are relevant for the Dutch building industry. However, it is not known yet in what way these levels can actually influence structural safety. Therefore, this chapter will illustrate in what way the underlying factors on meso and micro level can influence structural safety, by a cross case analysis of underlying factors in failure cases. In chapter 4 it was concluded that for the majority of cases, with publicly available documents, information on possible influencing factors is lacking. Therefore, in this chapter three well-documented failure cases will be investigated. Only one of these cases (Bos & Lommer) was included in the Cobouw database, the others occurred outside the selected period of the Cobouw database.

7.2 Three major structural failures in the Netherlands

To gain insight in the influence of factors, three well-documented failure cases will be discussed: the cracking of a concrete roof of the parking garage of the Bos & Lommer plaza and the subsequent evacuation of the surrounding buildings in 2006 (de Boer et al. 2007), the collapse of a concrete floor during casting of the concrete at the B-tower in Rotterdam in 2010 (Onderzoeksraad voor Veiligheid 2012b) and the collapse of a roof structure for a new extension of the FC Twente stadium in 2011 (Onderzoeksraad voor Veiligheid 2012a). Bos & Lommer was a case that was a wakeup call for the building industry, showing that the problems revealed by the collapse of the balconies in Maastricht were no incidents (see chapter 1). The cases of B-tower and FC Twente are cases that are focused on safety during construction. In the B-tower case a temporary structure collapsed during construction. In the FC Twente case part of an unfinished final structure collapsed. Chapter 4 concludes that the construction phase is the most dangerous phase within the building process, which indicates the relevance of including these cases. These cases can be classified as *typical* cases (Yin 2009, p. 48).

The description of the cases will be based on the publicly available reports from independent investigation organizations (Committee de Boer for Bos & Lommer and Dutch Safety Board for B-tower and FC Twente stadium). They used multiple sources to draw their conclusions.

The analyses in this chapter are directly based on the original sources and no additional research or external opinions were included. Therefore, this chapter can be regarded as a cross case analysis , where the individual case studies have previously been conducted as independent research studies (similar to cross case synthesis, see: Yin 2009, p. 156).

7.2.1 Bos & Lommer plaza (de Boer et al. 2007; Priemus and Ale 2010)

The multifunctional Bos & Lommer plaza complex in Amsterdam was delivered in 2004 (see figure 7.1). It consisted of 96 appartments, businesses and shops, a two-storey parking lot for more than 500 cars and a market place. In 2006 an 11 ton truck drove on the market place, which was the roof of the parking garage, and caused structural damage. A part of the load bearing structure underneath the deck had failed. Residents of apartments were evacuated until the deck was strutted and a maximum load on the deck was introduced and enforced.

Figure 7.1 *Recovery activities at Bos & Lommer Plaza (photo: Dick Hordijk)*

Investigations into the causes were started. It was concluded that the detailing of the reinforcement was questionable and the amount of reinforcement was insufficient. Furthermore, at a number of locations the actual reinforcement differed from the reinforcement prescribed by drawings. Finally, further checking of the total project showed that the design of a 1 m thick transfer floor was erroneous. The authorities were compelled to evacuate the area until measures were taken.
An investigation committee was established that extensively studied the underlying factors of this case. The committee concluded that the multifunctional program of the project was very complex with multiple use of space. In addition, the building process had been complex with many changes in the functional program, with a project that was split up into three components, with many parties (two developers, three architectural firms, two structural engineering companies, over 50 subcontractors) and a difficult loca-

tion in a city. The safety culture within the building process was not well developed with: heavily economizing on costs and very tight planning, preparations that were not internally supervised, fragmentation and no clear all-encompassing final responsibility. There appeared to be no risk analysis and there was no evidence of independent internal or external checking. The main contractor was ISO 9001 certified, but the committee could not observe any added value of this certification. Communication was sometimes poor and collaboration was characterized by extremely tough price competition. Sometimes the working conditions were hard, with a very small building site. Insufficient technical competencies were suggested, because of problems related to structural modeling.

7.2.2 B-tower (Onderzoeksraad voor Veiligheid 2012b)

In October 2010 the 70 m high B-tower was being erected in the city centre of Rotterdam. The tower consisted of three layers of shops, two layers with parking and 15 storeys with housing. The floors of the first five storeys are made as precast composite plank floors; prefab concrete planks are used as formwork for the cast in situ upper part of the floors. During casting, the concrete planks cannot bear the total weight of the floors, which necessitates a temporary support structure. For this temporary structure scaffolding was used. On October 21st the third floor was being cast. Because a void was positioned underneath this floor, the scaffolding had a height of approximately 11.50 m. During casting of the floor, the temporary structure collapsed, resulting in 5 injuries among the construction workers (see figure 7.2).

Figure 7.2 *Top view of collapsed floor B-tower (photo: Karel Terwel)*

Investigation by the Dutch Safety Board revealed that the assembling team worked with just one part of the structural drawing of the scaffolding. This resulted in the omittance of a large number of stability braces in one direction. An advisor from the supplier noticed this and warned, but this did not result in amendments. The structure was checked by three different members from the contractor with checklists, but they did not notice the absence of the bracings. A final check was omitted. The main contractor asked a supplier to do this. The advisor of the supplier was not able to do it, but the responsible construction manager from the main contractor was not adequately informed and he thought that the checking had been done. During the casting of the concrete, the structure lost stability, because of the absence of the bracings, thus resulting in the collapse. Underlying factors of this case are a lack of technical competencies of the assembly team, unclear responsibilities regarding structures (the advisor from the supplier with adequate knowledge had no formal responsibilities, while the others were counting on him), insufficient risk management for the temporary structure and inadequate checking (several checks did not reveal the absence of braces). It was concluded that no party seemed to take final responsibility for the quality of the supporting structure.

7.2.3 Roof stadium FC Twente (Onderzoeksraad voor Veiligheid 2012a)

In 2011 the roof of an extension for the FC Twente stadium collapsed during construction, resulting in two fatalities and nine injuries (see figure 7.3). The roof structure consisted of a cantilevering steel structure with steel sheeting, which was stabilized by bracings. In addition to the usual loads, the roof structure had to bear some heavy video screens.

This extension was constructed by the same combination of (sub)contractors that successfully constructed an earlier extension in 2008, thus resulting in great confidence between parties involved.

Figure 7.3. *Roof of FC Twente stadium after collapse. Reproduced by permission of the Netherlands Police Agency, Air support and Aviation Police*

Investigation by the independent Dutch Safety Board showed that the the main load bearing structure was not completed and stabilized when the finishing structure was

applied. Essential connecting bars of the final structure were not in place and temporary bracings were removed to apply safety nets. At the moment of collapse, the roof was already loaded with hanging bridges, labourers, stacked roof sheets and the video screen. Furthermore, the structure deviated from the intended dimensions.
According to the investigation report, these aspects contributed to the collapse of the roof. Influencing factors for the incident were the tight planning resulting in a suboptimal construction sequence and unclear boundaries between the various phases during construction, a design with too little attention for the way of execution, unjustified trust resulting in insufficient coordination and control and insufficient allocation of responsibilities resulting in a failure to execute tasks.

7.2.4 Observed influence of underlying factors in three cases

Table 7.1 *Observed influence of factors in the cases Bos & Lommer, B-tower and FC Twente*

	Project characteristics			**MESO**												**MICRO**					
	Complexity of the project	*Complexity of the building process*	*Phase within the building process*	*Safety goals*	*Safety culture*	*Allocation of responsibilities*	*Risk management*	*Control mechanisms*	*Protocols*	*Communication*	*Collaboration*	*Planning and budget*	*Knowledge infrastructure*	*Working conditions*	*Instruments*	*Technical competencies*	*Management skills*	*Social-communicative skills*	*Attitude*	*Mental resilience*	*Physical resilience*
Bos & Lommer	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•	•		•		
B-tower		•	•	•	•	•	•	•	•	•	•	•	•			•	•		•		
FC Twente	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•		•		

Table 7.1 presents the observed (negative) influence of underlying factors on the technical cause of failure per case. The table reveals that almost every underlying factor is assumed to contribute to the failure of the selected cases, although the magnitude of the influence is not determined. It should be highlighted that absence of an assumed relationship in table 7.1 is no proof of a specific factor not influencing the failure, but this influence was not presented in the used sources.
In the following sections an explanation will be given in what way the factors were expected to influence the failure. The main aim is to give examples of how various factors were expected to influence structural safety in the three failure cases, and not to blame individual persons or companies.

7.3 Meso level: Project characteristics

For project characteristics relevant examples of the three cases for complexity of the structure, complexity of the building process and phase in the building process will be listed.

7.3.1 Complexity of the structure

Bos & Lommer is a case where complexity of the project was of major importance. It was a large project with multiple functions. The program consisted of 395 houses, 24,000 m^2 offices, 6000 m^2 central functions and 3500 m^2 socio-cultural amenities. In addition the program was complex with an apartment building on top of shops and a market plaza on top of a parking garage.
This latter kind of complexity is supposed to be one of the contributing factors of the structural problems that were revealed in the appartment building of the Bos & Lommer complex (Priemus and Ale 2010). A different grid size for the retail on the ground floor was chosen in comparison with the grid for the residential part on top of it. A conceptual error was made in the structural design of the redistributing floor on the second level, thus resulting in a structure with questionable safety.

The extension of the FC Twente stadium was also regarded to be complex, although a similar extension had been constructed before. Complexity made it hard to understand the behaviour of the structure for the labourers.

The scaffold of the B-tower is classified as non-complex; it is a relatively standard structure, although relatively high. This case shows that complexity is no requirement for failure.

7.3.2 Complexity of the building process

Various aspects of complexity of the process that might have influenced the failure have been observed in the three cases: fragmentation, number of changes, location of project and function of structure.

First, the Dutch safety board gives a clear example of *fragmentation* in the description of the failure of a temporary supporting structure for the B-tower in Rotterdam. Many parties were involved, like a main contractor, a subcontractor for the casting of the concrete of the floor, a supplier for the temporary structure with their own structural consultant among others. Every party was partly responsible, but according to the Dutch safety board no party was taking final responsibility (Onderzoeksraad voor Veiligheid 2012b, fig. 8 on p. 32 and p. 4). In the case of Bos & Lommer over 50 subcontractors were involved, thus making coordination a hard task (Priemus and Ale 2010).

Second, complexity of the building process increases when *the number of changes* increases, especially when they are made during the construction phase. In the case of Bos & Lommer, many deviations in actual reinforcement were reported in comparison to the drawings (de Boer et al. 2007, Table V.2 on p. 154). Sometimes this was due to limited availability of the right size of reinforcement bars, which necessitated improvised solutions with alternative sizes. Hence, checking of the actually applied reinforcement was impeded.

Third, the *location of a project* might increase the complexity of the building process. Many projects are situated in city centres, like for instance the B-tower in the centre of Rotterdam. This impedes the supply of building materials, because of transportation limitations and scarcely available space for storage, thus influencing logistics in the building process (Onderzoeksraad voor Veiligheid 2012b, p. 13). However, it is not expected that this actually did influence the failure.

Fourth, the *function of a structure* might increase complexity of the process. The available time for the extension of the FC Twente stadium was reduced, because of extra international games that had to be hosted, resulting in a shift from sequential towards simultaneous activities. This was mentioned as a contributing factor of the failure of the roof of this stadium during construction (Onderzoeksraad voor Veiligheid 2012a, p. 6).

7.3.3 Phase within the building process

In the three failure cases contributing factors differed for the various stages during the building process. Working conditions for instance were not mentioned for the design phase, but specifically for the construction phase (see subsection 7.4.11).

The transition between phases is believed to be of major importance for dissemination of project information. In the case of Bos & Lommer every transition between phases was regarded to be a barrier within the building process, where mistakes could be detected by the new parties that were showing up in the process (Priemus and Ale 2010). The authors explain that all the barriers were breached: "the design was inadequate, the construction not according to the design, the permitting and monitoring were insufficient".

For the B-tower it was also reported that formal delivery moments were deemed necessary, although in practice this was not systematically assured (Onderzoeksraad voor Veiligheid 2012b, pp. 54-55). In a formal delivery moment it can be checked if the delivered structure is adequately built in accordance with drawings.

7.4 Meso level: company and project factors

On meso level the factors safety goals, safety culture, allocation of responsibilities, risk management, control mechanisms, protocols, communication and feedback, collaboration, reasonable planning and budget, knowledge infrastructure, working conditions and instruments will be discussed. These factors might play a role on company level and on project level (in the interaction between companies).

7.4.1 Safety goals

When the Dutch safety board examines failures, it specifically assesses the presence of safety goals within a project organization (Onderzoeksraad voor Veiligheid 2012a,b). In the case of Bos & Lommer the investigation board concluded that the main contractor pretended to have a well developed safety and quality approach, although adequate proof of implementation of this approach was lacking (de Boer et al. 2007, pp. 64, 67).

In the failure case of the B-tower a lacking collective safety approach among the building participants was observed. Common safety goals might enable such a safety approach (Onderzoeksraad voor Veiligheid 2012b, p. 4).

In the case of FC Twente it was suggested that in general clients manage on functionality, time and costs and less on safety assurance. For the FC Twente case the board observed a lack of collective safety approach too (Onderzoeksraad voor Veiligheid 2012a, p. 6).

7.4.2 Safety culture

Safety culture is not easy to operationalize and measure. It shows the way safety is actually assured and it can consist of several factors.

In the case of Bos & Lommer safety culture was not explicitly defined, although the aspects of a poor safety culture were listed: heavily economizing on costs, preparations not internally supervised, fragmentation and no al-encompassing final responsibility (Priemus and Ale 2010).

For the B-Tower the Dutch safety board observed a lack of collective safety approach (see subsection 7.4.1). An example is that after signaling the possible threat of structural collapse of temporary structures and suggesting measures, no attention seemed to be paid to the actual implementation of these measures during the construction process. In addition, no one of the individual parties seemed to feel final responsibility for structural safety (Onderzoeksraad voor Veiligheid 2012b, p. 5). The Dutch safety board highlights the importance of a proactive attitude, with traceable accountabilities within the building sector. The board criticizes the reactive, legal-driven behaviour of the various parties after the collapse of the temporary structure of the B-tower (Onderzoeksraad voor Veiligheid 2012b, pp. 7-8).

The safety culture of the FC Twente stadium was characterized by unjustified trust (Onderzoeksraad voor Veiligheid 2012a, p. 30). Because of earlier collaboration (Onderzoeksraad voor Veiligheid 2012a, p. 4) the parties trusted each other's competencies, to the detriment of thorough checking. Misplaced trust was also reported for the Bos & Lommer case, where inspectorate staff trusted too much in the quality of the main contractor and his subcontractors (Priemus and Ale 2010).
It is expected that unhealthy safety cultures contributed to the failures.

7.4.3 Allocation of responsibilities

The cases provide examples of situations where an unclear allocation of responsibilities might have stimulated the failure.

In the case of Bos & Lommer there were two developers, three architectural firms, two different lead engineers (one for the apartment building and another for the other structures), one main contractor and around 50 sub-contractors (Priemus and Ale 2010). Final responsibility seemed to be unclear and it is expected that this has contributed to the failure.

For the B-tower an unclear and incomplete allocation of responsibilities was reported (Onderzoeksraad voor Veiligheid 2012b, pp. 4-5). An example is that the foreman of the assembly team was of the opinion that checking of the scaffolding on conformity with the design was the responsibility of the advisor of the supplier (Onderzoeksraad voor Veiligheid 2012b, p. 48). The main contractor and others, thus ,seemed to be leaning on the expertise of the advisor of the supplier (Onderzoeksraad voor Veiligheid 2012b, pp. 50, 52), although no project specific appointments of checking with the supplier of the scaffolding were made (Onderzoeksraad voor Veiligheid 2012b, p. 50). The informally expected responsibilities seemed to deviate from the formal responsibilities.

In the case of the FC Twente stadium the same project team was working on the failed project as on the successful first extension of the stadium (see subsection 7.4.2). Nevertheless, the allocation of responsibilities was not sufficient and was one of the contributing factors of the roof collapse. Pre-arranged tasks, like the measurement of the concrete structure, were not allocated to individuals within organizations and were not executed or communicated (Onderzoeksraad voor Veiligheid 2012a, pp. 5, 37). Structural inspections were included in the contract of the structural engineer, but the kind of inspections was not clear (Onderzoeksraad voor Veiligheid 2012a, p. 22). All in all, it was concluded that the client did not settle all responsibilities and tasks of the members of the team in an agreement with the various parties (Onderzoeksraad voor Veiligheid 2012a, pp. 38, 44).

7.4.4 Risk analysis and allocation

The three cases provide examples of situations where risk analysis of the product or of the process might have revealed hazards.

Risks in the product

An example of a structure that was inherently risky was the temporary supporting structure of the floor for the B-tower. It was reported that these supports were very slender and that the structure was vulnerable to instability (Onderzoeksraad voor Veiligheid 2012b, p. 41). Risk analysis of the structure might have revealed this vulnerability. Although some risks were identified, risk management of the temporary supporting structure was lacking (Onderzoeksraad voor Veiligheid 2012b, p. 53). In addition, control was not based on a risk analysis (Onderzoeksraad voor Veiligheid 2012b, p. 5).

Risk in the process
For Bos & Lommer it was stated that no explicit risk analyses were performed focusing on structural safety (Priemus and Ale 2010).

In the case of the B-tower, an advisor of the supplier of the temporary structure was expected to play an important role in assuring the safety. However, it was not clear what his exact responsibilities were (Onderzoeksraad voor Veiligheid 2012b, p. 50). Risk analysis of the process might have revealed this inconsistency in responsibilities.

For the Twente case no information on risk management was provided, but it can be assumed that adequate risk analysis of the process would have revealed the hazards of abandoning the original planning and the simultaneous execution of tasks.

7.4.5 Control mechanisms

Control is commonly regarded as an effective measure to reduce failures; in each of the failure cases a lack of control was established as contributing factor for the failure.

This is stated very clearly for the Bos & Lommer case: "There is no evidence that an independent inspection was performed either internally or externally" (Priemus and Ale 2010), indicating a general lack of control.

In the situation of the B-tower, three independent checks of the temporary structure with use of checklists did not reveal that some bracings were left out; there seemed to be sufficient control, but it was not adequate (Onderzoeksraad voor Veiligheid 2012b, p. 16). Moreover, it was also reported that the insufficient number of braces was noticed by one of the persons involved, but no follow-up was given to this information (Onderzoeksraad voor Veiligheid 2012b, pp. 4, 16). The warnings in the process were not adequately addressed (see also subsection 4.4.3).

The case of FC Twente revealed various deficiencies in the control processes. For instance, the sequence and method of construction was not checked by the main contractor (Onderzoeksraad voor Veiligheid 2012a, p. 5). This lack of control was explained by stating that the main contractor was of the opinion that he was not qualified to control the specialized steelwork (Onderzoeksraad voor Veiligheid 2012a, p. 34).

It can be concluded that a lack of control might be the result of three possibilities: it was insufficiently included in the contracts (see subsection 7.4.3 for B-tower and FC Twente), actual performance was omitted (Bos & Lommer), or it was performed inadequately (B-tower). In general, checking is sometimes associated with lengthy delays and, moreover, workforce can be more engaged in productive 'doing' when checking is omitted (Reason 1997, p. 48). Hence, there might be a gap between the procedures (intended checking) and the work-as-actually-done.

7.4.6 Protocols

In many failure cases parties involved were certified, which did not prevent them from making mistakes. In the Bos & Lommer case the main contractor was certified in conformity with ISO 9001. However, after investigation it was concluded that the project developer and contractor primarily focused on making profit. The contractor did not seem to maintain an adequate quality assurance system (Priemus and Ale 2010). In the Bos & Lommer report this is explained by citing R. Spruit, who stated that in general ISO certification holders often use it as a marketing instrument and try to do as little as possible to fulfil the minimum requirements for the certification. In addition, the broad applicability of this certification in various sectors leaves room for personal interpretation, which might impede effectiveness (de Boer et al. 2007, p. 66).

In addition, the Bos & Lommer case provides some examples why in practice procedures might not always work. The fixing of the reinforcement procedures seemed to be clear, but a lot of improvising was needed due to: stolen reinforcement, bankruptcy of a company, some labourers were engaged that were unable to read drawings, some could barely speak Dutch, and available reinforcement bars were not always available in the right size (de Boer et al. 2007, p. 68).

For the B-tower case a number of regulations was listed that included procedures for safe construction. However, the legal obligation to apply these regulations are debatable. The main contractor was ISO 9001 certified, but his procedure manual did not cover temporary structures (Onderzoeksraad voor Veiligheid 2012b, p. 29). Therefore, insufficient protocols might have contributed to the failure, although it is not sure if temporary structures would have been included in the manual, the failure would have been avoided.

In the case of FC Twente, the assembly plan was based on an earlier extension. However, this procedure was incomplete. There was no attention for strength and stability during construction (Onderzoeksraad voor Veiligheid 2012a, p. 5) and it did not provide adequate guidance for the sequence of the assembling of stability bracings (Onderzoeksraad voor Veiligheid 2012a, p. 31).

It can be concluded that protocols might be lacking, inappropriate or application might be ommitted.

7.4.7 Communication

In the investigated cases various examples of problems with communication are mentioned. A few examples will be presented.

Language problems, because of the presence of foreign labourers, were reported for the Bos & Lommer case, although a direct relationship with the failure has not been made. In this case, the communication between steel-fixer and main contractor was not adequate

(Priemus and Ale 2010). Furthermore, there was inadequate coordination between main contractor, concrete pourer and steel fixer.

When essential information on structures is not shared between parties, this is a risk for structural safety. In the case of the B-tower the team that had to assemble the supporting structure was provided with a partial drawing, where one view with stability bracings was missing. As a result, many bracings were not placed, which was not revealed by some of the inspections (Onderzoeksraad voor Veiligheid 2012b, p. 16). For this case, it was also reported that the main responsible person from the contractor was not informed that the final check had not been performed (Onderzoeksraad voor Veiligheid 2012b, p. 18).

For the FC Twente case it was reported that some forms of communication were indirect. There was, for instance, no direct communication between structural engineer and steel contractor. Direct communication might have been beneficial to avoid the structural problems (Onderzoeksraad voor Veiligheid 2012a, p. 31). Sometimes the communication seemed to be unclear. The steel contractor was convinced that the main contractor agreed to an adapted assembly plan, while the main contractor stated that he did not order changes in assembly sequence and did not demand to leave out structural parts (Onderzoeksraad voor Veiligheid 2012a, p. 32).

It can be concluded that in failure cases with multiple parties, communication problems between companies are often at the root of the incident.

7.4.8 Collaboration

Communication always takes place in the collaboration between various persons or parties and was of importance in every case. Therefore, collaboration is assumed to be of influence for all three cases.

For the Bos & Lommer case it was reported that 'the relationship between the main contractor and the sub-contractors was characterized by extremely tough price competition' (Priemus and Ale 2010).

As stated earlier, the relationships between the participants of the FC Twente stadium could be characterized by unjustified trust.

7.4.9 Planning and budget

Planning and budget are often related, although not always. The failure cases all suffered from time pressure.

In the case of Bos & Lommer there was a strong emphasis on cutting costs, with a strict time table for pouring the concrete, resulting in a huge pressure on the assembly of the reinforcement (Priemus and Ale 2010).

For the B-tower it was reported that the assembly of the scaffolding did not go fast enough according to the main contractor (Onderzoeksraad voor Veiligheid 2012b, p. 16). Prefab beams were already placed before the scaffold structure was ready. A direct relationship of time pressure with the failure is not proved, but is a reasonable possibility.

In the case of the FC Twente stadium the planning had to be condensed because of the schedule of soccer games (Onderzoeksraad voor Veiligheid 2012a, pp. 6, 30). This resulted in time pressure and a simultaneous execution of tasks. The steel contractor had planned to apply the steel structure in six weeks, whereas the main contractor had only reserved two weeks in the planning (Onderzoeksraad voor Veiligheid 2012a, p. 30).

7.4.10 Knowledge infrastructure

Exchange of knowledge is a part of communication. The failure cases provide some examples related to this issue.
In the case of the B-tower, the persons that assembled the temporary structure, were insufficiently aware of the design starting points, thus failing to apply the required number of stability braces (Onderzoeksraad voor Veiligheid 2012b, p. 44). Furthermore, in this case it was explained that knowledge within the sector of temporary supporting structures is not sufficiently available on execution level (Onderzoeksraad voor Veiligheid 2012b, p. 6).

A lack of knowledge transfer between structural engineer and steel contractor concerning strength and stability during construction is assumed in the FC Twente case, because the assembly plan seemed to lack an analysis of structural safety during construction (Onderzoeksraad voor Veiligheid 2012a, p. 5) and there was no direct contact between structural engineer and steel contractor (see subsection 7.4.7).

7.4.11 Working conditions

In the cases sometimes a relationship between working conditions and safety is suggested.

In the case of Bos & Lommer a limited building site was reported, which impeded logistics and construction. In addition, there was not enough security, which resulted in the stealing of reinforcement from the building site. This resulted in improvising in the choice of reinforcement bars, which impeded checking of the reinforcement (de Boer et al. 2007, pp. 68, 154). This might have influenced the failure.

The case of the B-tower is strongly related to labour safety. An employer should provide his employees with stable and safe working conditions (Onderzoeksraad voor Veiligheid 2012b, p. 23). However, the employees that were on top of the collapsed floor were not provided with stable and safe working conditions. Labour safety and structural safety are closely related in this type of situations although a causal relationship with the technical failure is not assumed.

Sometimes occupational safety and health has a negative impact on structural safety. In the case of the collapse of the stadium roof of FC Twente it was reported that labourers removed a stability brace to be able to assemble safety nets for roof workers (Onderzoeksraad voor Veiligheid 2012a, p. 28). However, it is questionable, if this removal actually influenced the collapse of the roof structure.

7.4.12 Instruments

Problems with software or equipment were scarcely mentioned in the studied cases.

In the Bos & Lommer case for the situation with the floor between shops and apartment building it was suggested that to adequately model the materials, it would have been better to use a finite element program, instead of simplified modeling as used. A modeling error is assumed in the investigation report (de Boer et al. 2007, pp. 83-84).

7.5 Micro level factors

7.5.1 Technical competencies

The relevance of technical competencies is highlighted in all three failure cases.

In the Bos & Lommer case a lack of technical competencies was assumed for some structural engineering companies, because of erroneous modelling of the transfer floor between shops and apartments and the structure underneath the plaza floor (de Boer et al. 2007, p. 86). It should be noted that the engineering companies involved not always agreed upon the assumed modelling errors. Furthermore, some steel fixers were not able to read drawings and, thus, were lacking technical skills (Priemus and Ale 2010).

Technical competencies of the labourers were questioned at construction of the B-tower too, where assembly personnel did not recognize that for stability the temporary supporting structure should be braced in two directions (Onderzoeksraad voor Veiligheid 2012b, pp. 44, 49).

In the FC Twente case, the risk of removing the bracings to apply safety nets (Onderzoeksraad voor Veiligheid 2012a, p. 28) and to make assembling of the roof sheets easier (Onderzoeksraad voor Veiligheid 2012a, p. 32) was not adequately addressed, nor was the risk of leaving out essential elements to avoid problems with the crane (Onderzoeksraad voor Veiligheid 2012a, p. 31). The removal of bracings was approved, because the stability bracing was not under tension (Onderzoeksraad voor Veiligheid 2012a, p.28). This indicates a lack of technical skills, although it is questionable if this has lead to the actual failure. In this case, there was too little insight in strength and stability during construction, which might indicate a lack of technical skills.

7.5.2 Management skills

Management skills can be used to improve structural safety (Onderzoeksraad voor Veiligheid 2008, p. 34). On the contrary, they can also be used to serve competing goals like maximizing profit. Although a lack of management skills of individuals is not explicitly mentioned in the reports, it can be assumed in all three situations.

The management of the Bos & Lommer project was believed to focus on profits to the detriment of safety (Priemus and Ale 2010). This indicates underdeveloped skills to chose the right priorities.

In the B-tower case the assembly company could not prove that the assembly team was skilled. This can be regarded as a management failure (Onderzoeksraad voor Veiligheid 2012b, p. 49). Similar examples can be given for the other cases where for instance insufficiently skilled workers were hired.

In the FC Twente case the choice to abandon the original planning and work simultaneously, without analysing possible consequences, might indicate insufficient management skills.

7.5.3 Social-communicative skills

Social-communicative skills are necessary for communication. For the Bos & Lommer case it was reported that some labourers had problems with Dutch language (see subsection 7.4.7). However, it is hard to directly relate this to the technical failure.

7.5.4 Attitude

In the case descriptions it is not always easy to distinct between the safety culture within companies and the attitude of individuals. In the Bos- en Lommer case it is highlighted that within a failed project not all involved parties should have a negative attitude, by observing a professional and serious attitude for several of the interviewed persons (de Boer 2007, p. 107).

Two examples are given of an unhealthy attitude for B-tower and FC Twente.
In the case of the B-tower no one seemed to feel final responsibility for structural safety (Onderzoeksraad voor Veiligheid 2012b, p. 5). In this regard the Dutch Safety Board states that structural safety depends on the attitude of individuals (Onderzoeksraad voor Veiligheid 2012b, p. 6).

In the case of the roof of the FC Twente stadium the various parties had an unjustified trust in each other, resulting in loosening necessary checks in the process (see subsection 7.4.2 and 7.4.8).

7.5.5 Mental resilience

Mental resilience was not explicitly mentioned in the three failure cases.

In general, within Dutch building industry, the phenomenon 'structural engineers' illness' is known, which means that structural engineers cannot sleep because they are concerned about the structural safety of their projects (Wiltjer 2007). This is a common phenomenon for responsible professionals, although it might be problematic when this stress becomes epidemic and structural. Under too much stress the judgment of individuals will be reduced and the probability of errors will increase.

It is reported that an officer of the building control in Almere committed suicide after he discovered structural problems and did not know how to cope with it (Visscher and Meijer 2006). Enforcement of legislation often requires a firm attitude based on authority for municipality officers in their communication with private parties (VROM-inspectie 2007).

7.5.6 Physical resilience

Physical resilience was not mentioned as an influencing factor in the three failure cases. This might be explained by strict occupational safety and health requirements. A person is not allowed to carry more than 25 kg and there are limitations on the maximum daily and weekly hours of work. These requirements stimulated the design of lifting tools and promoted working in shifts.

Therefore, physical resilience will seldom make a difference in the structural performance of projects in the Netherlands. However, internationally it might be a factor of influence.

7.6 Limitations case studies

By presenting examples from the case studies the way underlying factors on meso and micro level can influence structural safety is illustrated. Validity and reliability of the original sources in general can be regarded as good, while every study used a thorough research approach and multiple sources of evidence. However, the case study approach has some limitations.

First, only three cases were investigated, which limits the generalization of the outcomes. In addition, the case studies were merely related to larger projects, which are not representative for all building projects in the Netherlands. However, appendix VI shows that all factors on meso and micro levels are mentioned in the selected literature from chapter 6, except for physical resilience. Therefore, it is expected that the listed factors on meso and micro level can influence structural safety within Dutch building industry.

Second, for every case one major source is used. Although these sources were from independent investigation boards, that used various sources to draw their conclusions, there were no second opinions and additional interviews included in the current study.

Third, the analysis of the cases is subjective. The original investigators might have their personal opinions, and also for the analysis of this report choices have been made. It is known that in failure investigations, especially with legal consequences, various positions are taken towards the influencing factors of the failure. Persons involved in the three cases might have other opinions on the contributing factors than presented here.

Finally, the focus has been on lacking factors. However, sometimes it appeared that a certain factor was judged positively, although a failure occurred (for instance positive attitude of some of the participants). To know if a factor was really influencing the outcome of the process, and the performance of the structure, it is necessary to work with a control group where no failure occurred.
To overcome the problems of the absence of a control group, in chapter 8 a study will be done on the presence of factors in successful and in less successful projects.

7.7 Conclusions

In this chapter the possible influence of the derived underlying factors was illustrated with examples from three failure cases. It appeared that for every case, there were just a limited number of technical causes of failure, but a relatively large number of underlying factors which were expected to contribute to the technical failure. The magnitude of the possible contribution has not been determined for the various factors.

The theoretical framework proved to be adequate in listing the factors, because no information in the case descriptions was given on underlying causes, that could not be attributed to the suggested theoretical framework.

It should be noted that all three cases focus on relatively large projects. The outcomes are therefore not completely representative for the complete building industry. In addition, no distinction has been made in possible factors on company level and on project level.

However, the possible influence of the various factors is explained and it is concluded that the majority of factors of the theoretical framework can be of influence for the initiation of the structural failures.

Figure 7.4 shows the factors that might influence structural safety. In this figure it is highlighted that factors on meso level might influence factors on micro level and vice versa, as was shown in the failure cases.

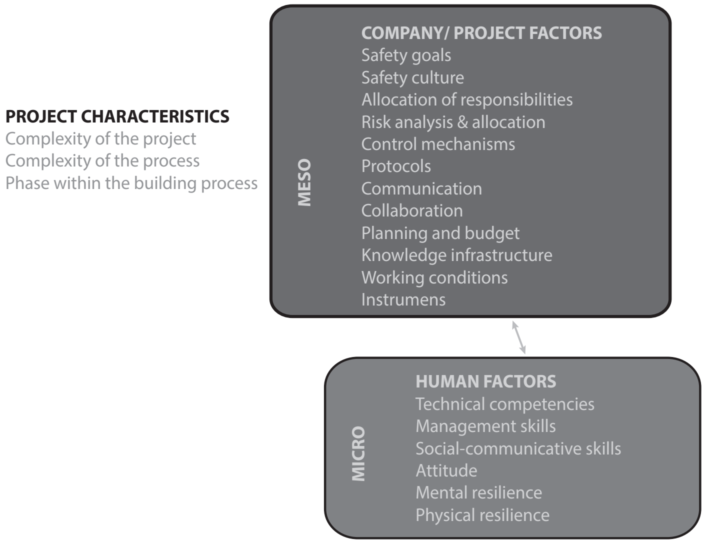

Figure 7.4 *Possibly influencing factors on meso and micro levels*

It was explained that the presence of factors in failure cases sometimes indicates the contribution to failure. However, the presence is no absolute proof of the influence on structural safety, because these factors might be present in successful projects too.

At this point, it is expected that the theoretical framework with the possible underlying factors is relevant for the assurance of structural safety. However, it is still unknown which factors in the Netherlands are critical, related to the assurance of structural safety. Therefore, in the following chapter it will be investigated which meso and micro factors actually make the difference between less successful and successful projects in the Dutch building industry, regarding structural safety.

8

Critical factors for structural safety[1]

8.1 Introduction

After exploring the possible underlying factors for the building industry in chapters 6 and 7, it is necessary to determine what factors in the design and construction process are critical for the assurance of structural safety. In chapter 1 critical factors with respect to structural safety were defined as those few key areas, in which favourable results are absolutely necessary to assure structural safety. For this chapter the approach of the 'Wheel of Science' is used (see chapter 1). This wheel will start on meso and micro level with the possible influencing factors from the theoretical framework and with the assumption that critical factors for structural safety can be derived.
A set of hypotheses is used. For every possible influencing factor on meso and micro levels the hypothesis is tested that the specific factor from the theoretical framework on meso and micro levels is critical for the assurance of structural safety.
This test is done by comparing successful and less successful projects with regard to structural safety, resulting in delta scores. The most determining factors in the current situation, with the highest delta scores, will be called critical factors for structural safety. It will be checked if the critical factors are actually the factors that need improvement, by comparing them with the top rated factors from direct judgement. The information of the projects and the opinion of building participants was collected in a survey, within the Dutch building industry. A second validation of the critical factors is performed by discussing the results of the survey with experts from building industry.

The final step of the 'Wheel of Science' is empirical generalization. This will be done by reflecting on representiveness of the respondents and by comparing the results with an international study.
In this chapter, first, the methodology of the study will be explained. Subsequently, the results will be presented and discussed.

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[1] *This chapter is based on the paper 'Critical factors for structural safety in the design and construction phase' (Terwel, K.C. and S.J.T. Jansen) which was accepted by the 'Journal of Performance of Constructed Facilities' for publication. Used with permission from ASCE.*

8.2 Method

8.2.1 Design of questionnaire

To gain insight into the central research question of this chapter ("*What factors in the design and construction process are critical for the assurance of structural safety in the Dutch building industry?*") a web-based questionnaire was set up. The precondition for the questionnaire was to include less successful as well as successful projects, because, as explained in chapter 1, solving problems related to factors that have an impact on less successful projects might not necessarily lead to successful projects.

The respondents were asked to think of a personally experienced successful project and a less successful project with regard to structural safety and to evaluate these projects on a number of relevant aspects.

Because structural safety cannot be measured directly (see chapter 2), for this survey it was chosen to operationalize structural safety by defining a successful project and a less successful project.
In a successful project structural safety was well assured and during the building process a relatively small amount of structural hazards was present. In a successful project no damage has been observed. In addition, no incidents were known, for which measures were necessary to avoid damage. Respondents were convinced that no hidden design or construction errors were present.
In a less successful project structural safety was assured to a lesser extent and during the building process or after delivery a relatively large number of hazards was observed. Damage was present, or could have easily arisen.

It should be noted that absence of structural damage and of errors is no absolute proof of structural safety, as defined in chapter 2, but gives an indication. When no damage occurs, it is still possible that a structure is unreliable, without manifesting failure in damage. However, when failure with accompanying damage occurs, this is usually not due to acceptable stochastic variability, but due to gross human errors (see chapter 4). It is reasonable to assume that when a gross human error has been made, for instance resulting in an insufficient amount of reinforcement, in the majority of cases the structure cannot be regarded reliable nor safe anymore. When no human errors have been made, the probability of failure and the accompanying risk will be reduced, usually within acceptable limits, thus resulting in a safe structure.
Hence, in the survey a structure in a situation with human error and damage (failure) is assumed to be unsafe and a structure in a situation without human error and damage is assumed to be sufficiently safe.

The order - successful project first or less successful project first - was randomly determined by the digital software. Respondents were asked to rate the level of presence of

39 underlying factors (see chapter 5) on a 5-point Likert scale (totally disagree – totally agree). In addition, respondents were asked for a direct listing of the factors that they perceived to have the largest impact on structural safety from a list of 13 factors on meso level. A selection of factors on meso level was made, because otherwise the burden of choosing from 39 factors would have been too high.

To test the questionnaire, a pilot study was performed in 2012 at a large Dutch contractor with 61 respondents (Dijkshoorn, Terwel et al. 2013). The questionnaire proved to be useable. Some minor adjustments were made, after which the questionnaire was programmed within an internet-environment. Finally, it was tested by a panel of four experienced building professionals. The questionnaire is presented in appendix VII.

8.2.2 Method of analysis

First, the data was explored using a descriptive analysis, resulting in an impression of the respondents and their projects.
Subsequently, two different approaches were used to determine the factors that are critical for structural safety. First, the delta approach was used. In this approach the difference (delta) between the rating of factors on successful and less successful projects with regard to structural safety is calculated. A large difference between the perceived presence of a factor in a successful and a less successful project, is considered to be an indication of the impact on structural safety. A similar method with a comparison of average and outstanding projects was used to derive CSFs by Ashley, Lurie et al. (1987). Second, direct judgement was used, in which the number of times that a particular factor was selected by the respondents was calculated. A large score on a factor is a proof of the relevance of the factor, according to the respondents. Similar methods are generally used to derive CSFs, often in combination with regression methods (e.g. Belassi and Tukel 1996; Arditi and Gunaydin 1998; Chan, Lam et al. 2010).

The factors with a delta score larger than 1.0 will be classified as critical factors. It will be checked if these factors are also among the 'top' factors from the direct judgement.
By combining the two methods to derive the critical factors it is expected that reliability of the analysis is improved and that the critical factors are actually the factors that need improvement.

Dr. S.J.T. Jansen, methodologist and head of fieldwork at department OTB of Delft University of Technology, has been consulted for the set up of the questionnaire and execution of the statistical analysis.

8.2.3 Respondents

Based on the planned statistical analyses, it was determined beforehand that at least 200 respondents were needed.
Furthermore, to give a realistic representation of the Dutch building sector, the respond-

ents should be a mix of structural engineers, contractors and other parties and they should be directly involved in the building process. For this reason, organizations of contractors and structural engineers were asked to mobilize their members by newsletters. The questionnaire was open for 6 weeks.

8.3 Results

8.3.1 Respondents

In total 340 respondents started the questionnaire, of which 226 (66%) completed it. A relatively large number of respondents (n =36) quitted the questionnaire after the first two questions and before evaluating the presence of the 39 factors. The percentage of quitting was not influenced by the order of the questionnaire, i.e. whether or not they started with a successful or less successful project.

Seventy-six (34%) respondents were structural engineers, 90 (40%) were contractors (including the engineering departments of contractors) and 60 (26%) were from local building control, clients, architects and others. Although structural engineers form a relatively large part of the respondents, compared to the total population of structural engineers and contractors, this distribution of respondents is expected to be a useful representation of the actors within the building process.
A hundred sixty (71%) respondents were working at a company of over 51 employees. This is remarkable, because in the Dutch building sector there are more persons working at small companies than at larger companies. Probably, larger companies have more time available for participation in researches like this. On the other hand, it is also possible that managing the process to improve quality is more relevant to them. Furthermore, in some of the larger companies, management stimulated employees to fill in the questionnaire. Over 90% of the respondents were rather experienced, by working in the building sector for more than 10 years. The average age of the respondents was 48, and the average experience 26 years.

8.3.2 Characteristics of projects

At the start of the questionnaire, respondents were asked to grade their project on a scale ranging from 1-10, where '1' reflects a project that is 'structurally very unsafe and '10' reflects a project that is 'structurally very safe'. The higher the mark, the more confident respondents are that no structural damage occurred and that there were no (hidden) design and construction errors.
The average score for less successful projects was a 5.8 and for successful projects an 8.3. It is remarkable that less successful projects on average receive an almost 'passing' mark (>6 = pass in the Netherlands). This indicates that although the process was suboptimal, most of the projects passed the requirements for minimal safety in the view of the respondents.

The respondents were asked to indicate the function of the project they evaluated. Table 8.1 depicts these functions for successful and less successful projects. It can be seen from this table that almost half of the respondents evaluated a utility project. However, in the Netherlands more residential projects are executed than utility projects. Thus, in this study utility projects are over represented. A possible explanation is that the relatively large companies that are involved in the survey more often deal with civil structures and (multidisciplinary) utility buildings.

Table 8.1 *Function of project*

	Residential	Utility (offices, leisure, etc.)	Civil structures (bridges, tunnels, etc.)	Other
Less successful project	80 (28%)	131 (47%)	55 (20%)	14 (5%)
Successful project	69 (24%)	139 (48%)	74 (25%)	10 (3%)

Civil structures are mentioned somewhat more often in successful projects than in less successful projects. This is in line with a common opinion within Dutch building industry that structural safety is on a higher level for civil structures than for buildings, because with civil structures there is more attention for quality assurance of the building process (CUR Bouw & Infra 2011, p. 103).

The finding that residential buildings are somewhat more often less successful is remarkable, because other research points out that residential buildings are relatively less prone to errors (see chapter 4). A possible explanation is that in general larger companies in this study have less experience in small scale residential projects and therefore the risk of less successful projects might be increased. However, the project experience of a company, if defined as the accumulated experience of all individuals within the company, was not included in this research.

8.3.3 Type of errors for less successful projects

First, the types of errors for the less successful project are depicted. These figures are compared with the outcomes of the Cobouw database (see chapter 4) to check to what extent the project data from the survey are representative for the Dutch building industry.

Figure 8.1 presents the outcomes where the main problem was in the design phase, figure 8.2 for the detailed engineering phase and figure 8.3 for the construction phase.

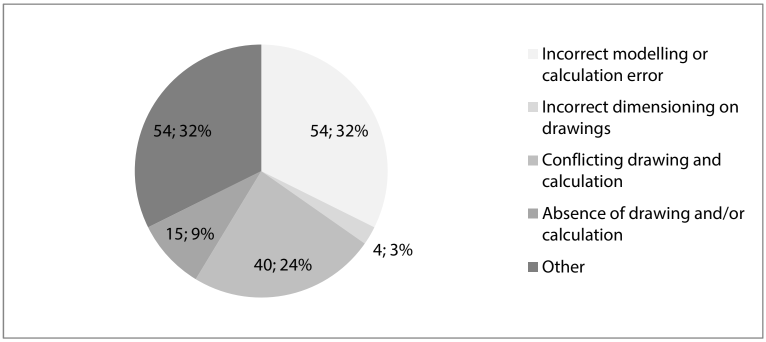


Fig. 8.1 *Type of errors when largest risk is in the design phase (depicted: number of respondents; percentage)*

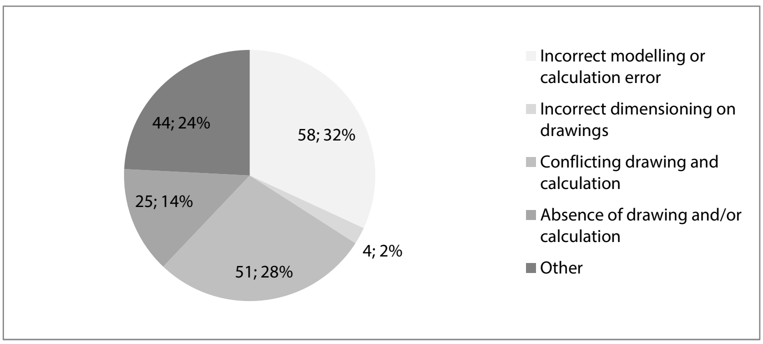


Fig. 8.2 *Type of errors when largest risk is in the detailed engineering phase*

For design errors within the Cobouw database the following figures were derived (see subsection 4.4.3): incorrect modeling or calculation error: 57%, conflicting drawing and calculation: 2%, absence of drawing and/or calculation: 19% and other: 21% (see chapter 4).

When these figures are compared, it seems that Cobouw more often shows 'simple' modeling or calculation errors. Within the survey more often problems in communication and coordination are perceived with a relatively high number of conflicting drawings and calculations. In addition, in the category 'other', respondents mentioned relatively often communication and coordination problems, together with insufficient inclusion of the construction phase in the structural design.

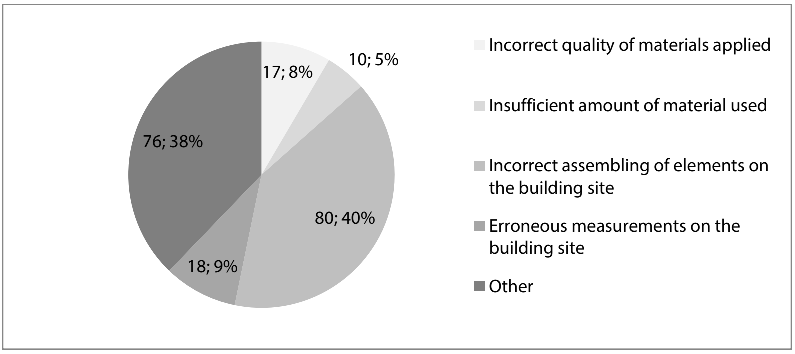


Fig. 8.3 *Type of errors when largest risk is in the construction phase.*

For construction errors within the Cobouw database the following figures were derived: incorrect quality of materials applied: 27%, insufficient amount of material used: 14%, incorrect assembling of elements on the building site: 27%, erroneous measurements on the building site: 2% and other: 30%. A comparison shows that the survey relatively often gives incorrect assembling of elements on the building site and the category 'other'. Within the category 'other', many factors were mentioned that could be categorized within one of the other categories, or underlying factors, which makes a comparison difficult.

From the comparison of the figures of the survey and the Cobouw database the impression is that the survey relatively often focuses on more complex projects with communication and coordination problems. This can be explained by the relatively high number of respondents from larger companies. The outcomes of the survey are therefore relevant for similar large, multidisciplinary projects, but are not completely representative for the Dutch building industry, especially not for smaller projects (see also subsection 8.4).

8.3.4 Delta approach

Respondents were asked to rate the level of presence of various factors within their successful (light gray) and less successful (dark gray) projects. The results of all respondents (n=216 to 276) are presented in figure 8.4. A 5-point Likert scale is used (1=totally disagree, 5=totally agree)

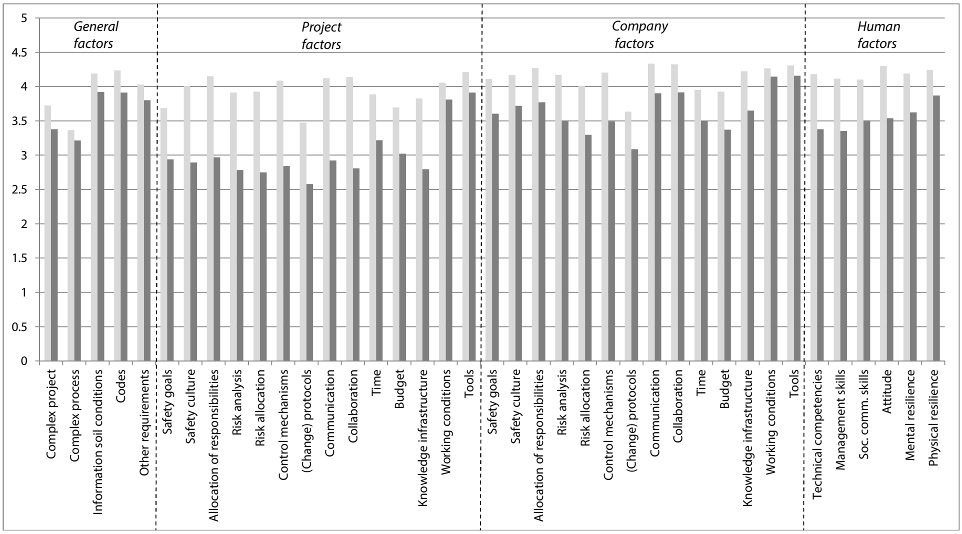


Figure 8.4 *The average level of presence per factor for successful (light gray) and less successful (dark grey) projects*

All propositions were formulated in such a way that a positive evaluation would have a positive effect on the performance of the project, with regard to structural safety. The average score for all the factors is 4.0 for a successful project (largely agree that the factor is present) and 3.4 for a less successful project (between neutral and largely agree). This indicates that, in general, the factors are perceived to be more frequently present in a successful project than in a less successful project.

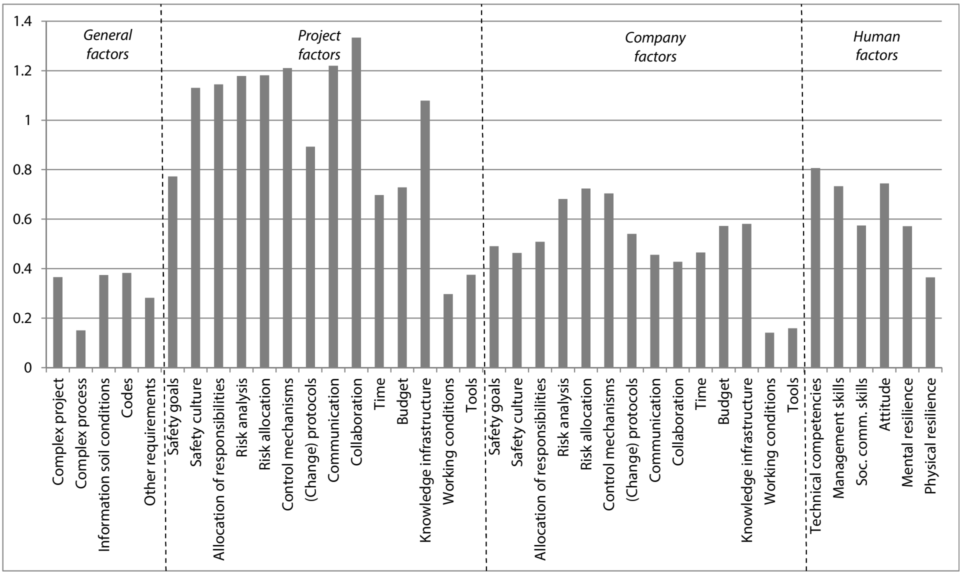


Figure 8.5 *Delta score for all factors*

Figure 8.5 depicts the differences in scores for all factors. This is the difference in scores from figure 8.4, although in figure 8.5 only the factors are used for the respondents that have given scores for both factors (n=202 to 227). Thus, for each respondent the difference in presence of each factor is calculated and the mean differences are presented in figure 8.5. The figure shows that the highest mean difference is found for the factor collaboration. The lowest score is found for working conditions.

Table 8.2 *Factors with highest delta scores*

Factor	Delta score	Level
1. Collaboration	1.33	Project
2. Communication	1.22	Project
3. Control	1.21	Project
4. Risk allocation	1.18	Project
5. Risk analysis	1.18	Project
6. Allocation of responsibilities	1.14	Project
7. Safety culture	1.13	Project
8. Knowledge infrastructure	1.08	Project
9. (Change) protocols	0.89	Project
10. Technical competencies	0.81	Human

An overview of the ten factors with the largest difference in mean scores between a successful and a less successful project is enumerated in table 8.2. These are the factors that are expected to have the highest influence on the assurance of structural safety.
From figure 8.5 and table 8.2 it can be concluded that the most influencing factors are on project level, which is in the interaction between the building parties. The outcomes for the various levels will be briefly explained.

General factors
Delta scores of general factors are relatively low. However, analyses with the use of a Wilcoxon signed-rank test showed that all delta scores are significant ($p<0.05$) except for the score of the complexity of the process. This means that all of these factors, except for complexity of the process, are more frequently present in successful projects than in unsuccessful projects.
It is remarkable that the mean score for the factor 'complexity of the project' is higher for successful projects than for less successful projects. This can be explained by stricter requirements on this kind of structures. According to Eurocode, designs in a higher consequence class, which can often be regarded as complex structures, have stricter partial safety factors and will need a higer level of control in design and construction. The Convenant high rise, a convenant with additional requirements for high rise structures in the Netherlands, suggests an increased level of quality insurance with extra control and demands on the skills of engineering companies for high rise structures (Terwel, Wijte et al. 2011). Furthermore, the outcome is in line with Wood (2005), who assumes that ICU (innovative, complex and unusual) projects do not necessarily suffer more often from failures, because of the extra care that is taken, provided that there will be adequate budgets available.

Project factors
All delta scores of project factors are statistically significant. They are also among the factors with the highest mean differences (see table 8.2).

Company factors
Company factors show smaller delta scores than project and human factors. An explanation can be that fluctuation of quality within a company will usually be smaller than fluctuation of the quality of partners within building projects, because every new project is usually performed with new, different parties. All delta scores on company level, except for working conditions ($p=0.06$), are statistically significant.

Human factors
Human factors show larger delta scores than the company factors. Especially technical competencies, management skills and attitude give delta scores of over 0.6. All delta scores on micro level are significant.

Differences between groups of respondents

The respondents were divided into three groups: structural engineers, contractors/suppliers and "other professions". A Kruskall-Wallis test was used to test whether these three groups differ with regard to the delta scores for the 39 factors. It appeared that the only significant difference is the evaluation of safety culture. The delta scores for safety culture are statistically significantly smaller ($p<0.05$) in the contractor group than in the other two groups (score is 0.84 versus 1.31 and 1.37). Many respondents of contractors are working at large contractors. Several of them actively try to improve safety culture, with programs like: WAVE: Wees Alert Veiligheid eerst ('be alert, safety first", (Van Hattum en Blankevoort 2013)). Therefore, differences in safety culture might be smaller among contractors for various projects.

8.3.5 Direct judgement

Results from direct judgement

In addition to the delta scores approach, an analysis based on direct judgement was performed. The respondents were asked to select three organizational factors that they deemed most important for the assurance of structural safety from a list of 13. It was possible to add other factors.

Table 8.3 *Rank of factors based on cumulative scores from direct judgement*

Rank of factor	Direct judgement score
1. Risk analysis	115
2. Control	93
3. Allocation of responsibilities	89
4. Safety culture	71
5. Collaboration	64
6. Budget	50
7. Knowledge infrastructure	42
8. Time	38
9. Safety goals	37
10. Communication	36
11. Protocols	13
12. Instruments	7
13. Working conditions	1
14. Other	22

The frequency with which the factors have been selected by the respondents (n = 226) is presented in table 8.3. Each respondent could allocate three votes, resulting in a total number of 678 votes. The factor structural risk analysis has been selected most often by the respondents (115 times, thus by 51% of respondents) and the factor working conditions the least often (only one time). Twenty two respondents suggested a factor outside the list. An example is the appointment of a coordinating engineer of record. However, the additional factors could usually be classified into one of the other categories; two of them are related to allocation of responsibilities and seven to control and coordination. In this study, coordination is regarded as a combination of allocation of responsibilities (who is responsible for the coordination task?), control (the work of other project team members has to be checked for clashes), and collaboration and communication (the possible clashes should be discussed).

Different judgement between groups

A comparison of the ranking of the factors between the three groups of respondents (structural engineers, contractors/suppliers and "other professions") shows that the factors safety culture, risk analysis and budget differ between the groups. Contractors selected the factor structural risk analysis statistically significantly more often than the other groups. In contrast, structural engineers selected the factor budget more often than the other groups. A possible explanation is that budget for structural engineers is directly related to the amount of attention an engineer can pay to a project, whereas contractors have more and other opportunities to cut costs. First, a contractor's budget is much higher and second, they can cut costs in their own hours, in the cost of subcontractors and in the cost of materials.

Finally, contractors and "other professions" selected a safety culture more often than structural engineers. This is remarkable, because in the delta approach this factor showed smaller differences (and thus less impact) for the contractors. It is possible that the contractors have learned from their past projects that safety culture was an important lacking factor, and that they currently are of the opinion that safety culture is of high importance.

8.3.6 Comparison delta approach and direct judgement on meso level

Table 8.4 compares the results obtained with the delta approach and the direct judgement. It should be emphasized that in the direct approach only the meso level has been included. In this comparison for the delta approach factors outside the meso level (like technical competencies) are left out.

Table 8.4 *Top ranking delta approach versus direct judgement on meso level*

Rank	Delta approach (delta score)	Direct judgement (cumulative score)
1.	Collaboration (1.33)	Risk analysis (115)
2.	Communication (1.22)	Control (93)
3.	Control (1.21)	Allocation of responsibilities (89)
4.	Risk analysis and allocation (1.18)	Safety culture (71)
5.	Allocation of responsibilities (1.14)	Collaboration (64)
6.	Safety culture (1.13)	Budget (50)
7.	Knowledge infrastructure (1.08)	Knowledge infrastructure (42)
8.	(Change) protocols (0.89)	Time (38)
9.	Safety goals (0.77)	Safety goals (37)
10.	Budget (0.73)	Communication (36)
11.	Time (0.70)	Protocols (13)
12.	Instruments (0.38)	Instruments (7)
13.	Working conditions (0.30)	Working conditions (1)

The top 5 in both approaches is almost equivalent in the factors listed, although the ranking differs. Communication is ranked second in the delta approach and 10th in the direct judgment approach, whereas direct judgement lists safety culture in the top 5, which is ranked 6th in the delta approach.
It is remarkable that in the delta approach 'soft factors' like collaboration and communication are derived as the most important factors. However, when the respondents were directly asked for their opinion on the most important factors, 'harder' factors like risk analysis, control mechanisms and allocation of responsibilities are valued as most important. In the opinion of the respondents time and budget are more important than concluded from the delta approach.

8.3.7 Correlation

The relationship between the various factors is analyzed using the non-parametric Spearman rank test. Table 8.5 shows the correlations of factors with a coefficient over 0.7, which indicates a strong relationship.

Table 8.5 *Spearman rank coefficients > 0.7*

Factor 1	Factor 2	Spearman rank coefficient
Risk analysis (project level)	Risk allocation (project level)	0.729
Communication (project level)	Collaboration (project level)	0.874
Working conditions (project level)	Instruments (project level)	0.822
Safety goals (company level)	Safety culture (company level)	0.776
Communication (company level)	Collaboration (company level)	0.867
Working conditions (company level)	Instruments (company level)	0.874
Social Communicative skills (individual level)	Attitude (individual level)	0.712
Attitude (individual level)	Mental resilience (individual level)	0.713
Mental resilience (individual level)	Physical resilience (individual level)	0.815

These correlations can be partially explained because some aspects are closely interrelated; risk analysis and risk allocation are both part of risk management, communication is necessary for collaboration, safety goals are a part of safety culture and a positive attitude is easier revealed when social communicative skills are present.

In the list of critical factors in the following subsection the strongly correlated factors will be combined.

8.3.8 Critical factors

To list critical factors for structural safety, the factors with a delta score larger than 1.0 are selected. It appears that the selected factors based on this criterion are similar to the top factors based on the direct judgement approach.
Critical factors for structural safety within current building industry are found on project level with:

- communication and collaboration
- control mechanisms
- allocation of responsibilities
- structural risk management
- safety culture
- knowledge infrastructure.

These factors were recognized by a number of experts from building industry as the factors that need improvement in current building industry (see appendix VIII).
Hence, the critical factors for structural safety are determined.

8.3.9 Empirical generalization

The critical factors have been derived for the Dutch building industry, especially for larger projects (see also section 8.4 on representativeness of respondents). However, it is possible that the critical factors are not limited to the Dutch situation and are applicable for various building industries. Cormie (2013, pp. 61-62) lists key deficiencies leading to structural failure, after the comparison of some international failure cases (with the critical factors from the present study between brackets):

- lack of information flow (communication)
- lack of clarity and design responsibility (allocation of responsibilities)
- lack of knowledge (knowledge infrastructure)
- lack of quality management (risk management and control mechanisms). This often results from a straightforward failure to adhere to agreed quality standards, perhaps due to cost or time pressures (safety culture)
- lack of proper inspection and maintenance strategy (control mechanisms)

A general agreement between both studies can be observed. It can be concluded that the derived critical factors do not have to be limited to the Netherlands.

8.4 Limitations of outcomes of survey

Although the outcomes of the survey are very relevant, it is necessary to point out some limitations of this study.

1. The method of a questionnaire knows some drawbacks and Guldenmund (2010) warns to not solely rely on questionnaires. In the interpretation of the results one should be aware of the HALO-effect. When a person is good looking, one tends to attribute positive properties, like intelligence to this person (Clifford and Walster 1973). Similar reasoning is relevant for this research; when a project is regarded as successful, respondents tend to rate various factors in a more positive way. This might explain why the average mean score for the presence of the 39 factors was higher for successful projects (mean = 4.0) than for less successful projects (mean = 3.4). However, by using a theoretical framework from a broad range of literature and discussing it with experts, by testing this framework on structural failure cases, by using two independent ways of analysis, and by discussing the outcomes with a group of experts, it is believed that these drawbacks have been tackled to a large extent. Furthermore, the delta approach examines the differences between successful and less successful projects within the 39 factors. Even in the case when the factors regarding the successful projects were upwardly biased by the HALO effect, this effect is likely to occur for all 39 factors to the same extent. Thus, the comparison between the 39 factors is still reliable.
2. There are limitations to the inclusiveness of this study. The influences of project characteristics, like size, use of materials, type of structure and form of tendering process, are not directly investigated. Although some of these factors might be included in project complexity or process complexity, the actual influence of these separate

factors is not clear from this study. Additional research is necessary for an inclusive determination of these project characteristics.

3. The representativeness of the respondents raises questions. Most respondents are working at large companies, and thus the number of small companies is underrepresented. The results of this study therefore are expected to be appropriate for larger projects with several project partners. For very small and simple projects, like the building of a bus shelter, the results will almost entirely be dependent on the availability of materials and technical competencies; only one or two parties are involved in this kind of projects, resulting in an elimination of the project factors. Although some of the results were slightly different for engineers, contractors and others, the majority of results did not differ between occupation groups. It is therefore believed that another composition of the types of respondents will not largely influence the main outcomes.
4. The critical factors can change over time.The selected factors are believed to have the largest impact on structural safety in the current situation. However, when special attention is paid to these factors, it is possible that other factors remain underexposed and in the future other factors will be critical.
5. Chosing a limit for the delta score of 1.0 is questionable. However, between the factors with a delta score of 1.0 and the ones with a smaller deltascore there was a relatively large difference. In addition, chosing this limit has resulted in a limited list of six factors, that were supported by the outcomes of the direct judgement.
6. The discussion of the questionable limit of 1.0 for the critical factors, indicates that the other factors can not be neglected. A minimum level for other factors than the derived factors is essential. For example, time and budget can be mentioned. Almost every project suffers from pressure on budget and planning; this might be the reason why these factors are not appointed as critical factors. However, it is evident that a realistic budget and planning is necessary to make a building of satisfying quality.
7. This study reveals six areas (the critical factors), that need extra attention. These areas are still very broadly defined. Further investigation and specification of these areas is needed, and experiences of effective practices within these areas should be shared to be actually able to improve the building process. A start will be made with exploring improvements in chapter 9.

8.5 Conclusions

Critical factors

The central question to be answered in this chapter was: "*What factors in the design and construction process are critical for the assurance of structural safety?*" The hypothesis to be tested was for every possible underlying factor from the theoretical framework on meso and micro levels that it was critical for the assurance of structural safety.

The two methods that were used agreed that the most important process factors to assure structural safety are project factors; the interaction between the various project partners often determines the outcome of the project. According to respondents the most important factors are communication and collaboration, control mechanisms, allocation of responsibilities, structural risk management, safety culture and knowledge infrastructure. These can be called the critical factors for structural safety. Because of the agreement of different approaches, it is expected that the critical factors are actually the factors that need improvement in the current building industry.
In addition, a comparison with an international study showed that the results are expected to be applicable for building industries similar to the Dutch situation.

Main observed threats and critical factors
When the results of the survey and the main observed threats from chapter 6 are included in the basic model with the relationship between human performance and structural performance from chapter 3, this results in figure 8.6 .

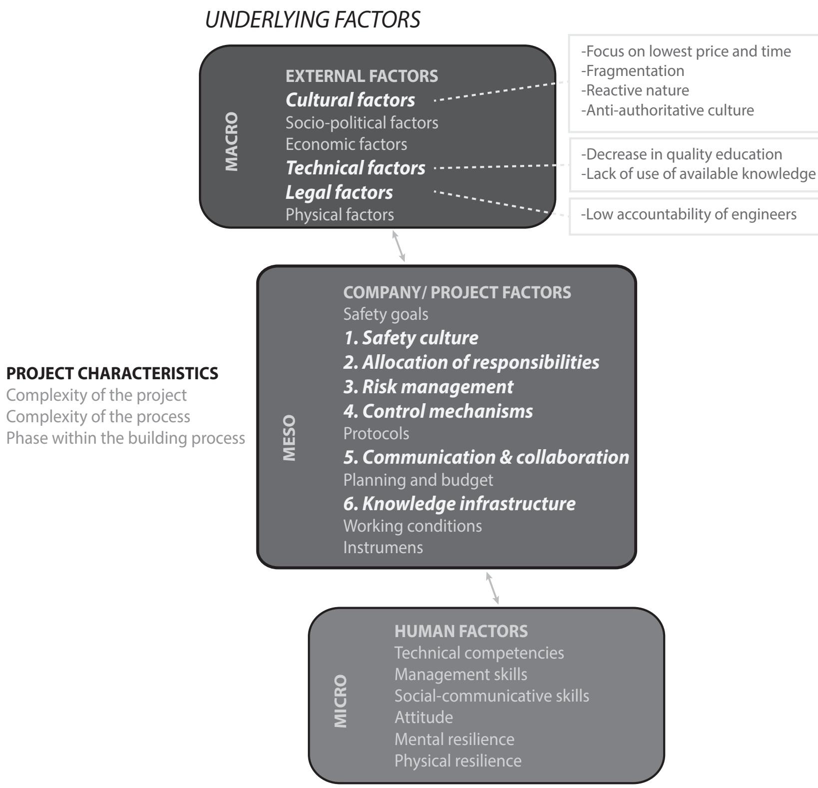


Figure 8.6 *Critical factors for structural safety and main observed threats (highlighed in bold)*

The figure shows that factors on macro level, like the main observed threats (depicted in bold), can influence factors on meso level. These factors can directly influence tasks within the building process, when for instance the allocation of responsibilities is poor and tasks are omitted. In addition, the factors on meso level can influence micro level, when for instance due to a lack of time the mental resilience of employees is under pressure, which might lead to the occurrence of human errors. The critical factors on project level are numbered and highlighted in bold.

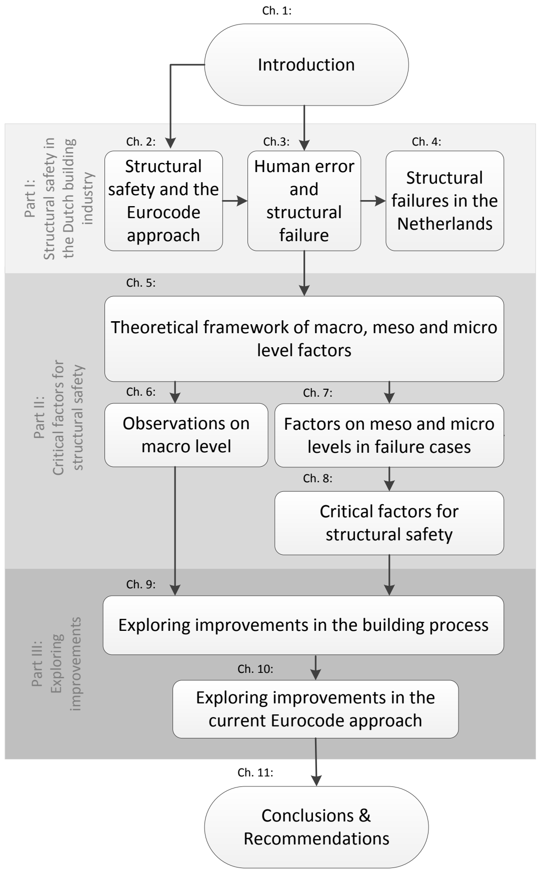
Relationships in figure 8.6 are simplified; it is for instance possible that factors on macro level are directly influencing micro level, factors on meso level might be related to each other, like various factors that might be part of a company's safety culture. Furthermore, factors on micro level, like management skills, might influence factors on meso level, like the allocation of responsibilities (see also section 5.4). Therefore, the relationship between the levels of underlying factors and the tasks within the building process is expected to be more complex than depicted in figure 8.6.

In section 6.10 and in figure 8.6 it is suggested that various critical factors can be negatively influenced by observed threats on macro level. This might impede improvements of the critical factors, because negative influences are deeply rooted within national culture.

Part II of this thesis derived underlying factors for structural safety. The most important underlying factors for the current building industry are expected to be the main threats on macro level and critical factors on meso and micro levels for structural safety.

Part III of this thesis will explore improvements in the building industry and in the Eurocode approach. First, in chapter 9, attention will be paid to improvements of single factors within building projects, but also to system change of the building industry.

PART III:



EXPLORING IMPROVEMENTS

"Prediction is difficult, especially for the future"
N. Bohr

9

Exploring improvements in the building process

9.1 Introduction

Part I of this study explained the current Eurocode approach to assure structural safety and investigated the current state of structural safety in the Netherlands.
Part II of this study derived main observed threats on macro level and critical factors on meso and micro levels for structural safety in the Dutch building industry.
This final part will focus on improvements in the building industry and in the Eurocode approach.

Figure 9.1 combines the outcomes of parts I and II of this thesis. This figure shows that the main possibilities to improve structural safety are on meso and macro levels with the critical factors and main observed threats.
Therefore, in this chapter non-structural measures to improve the critical factors on project level will be presented. Non-structural measures are focused on adjustments in the building process (see chapter 2). Structural measures, like increased robustness, are not included.
In addition to individual measures on project level, it will be necessary to enforce some measures on sector level. Therefore, measures will be suggested that are supposed to neutralize the observed main cultural, technical and legal threats of the sector that affect every project. By improvements on macro level, it is expected that the critical factors on project level will be enhanced too.

Finally, a proposed transformation of the building sector will be presented, which might improve structural safety in projects.

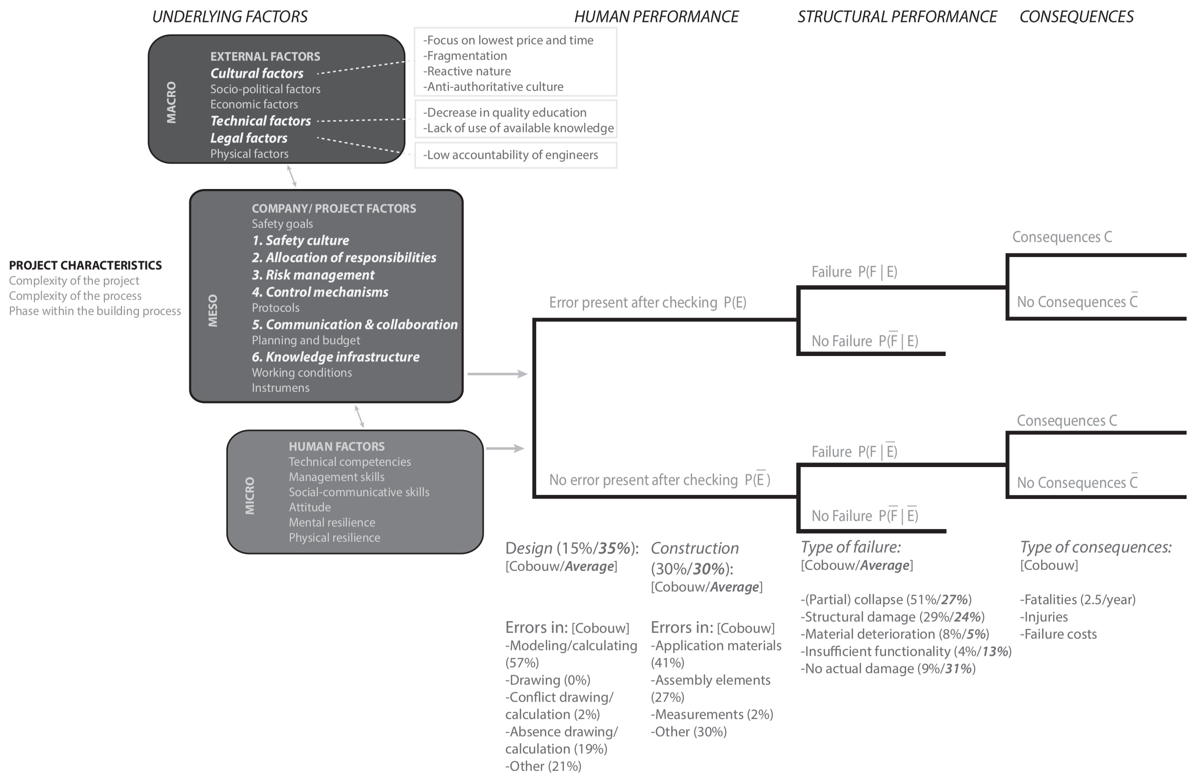


Figure 9.1 *Observed main threats on macro level and critical factors for structural safety on project level in relation to structural performance (depicted in bold-italic) within Dutch building projects*

9.2 Overview of measures

Table 9.1 presents a list of measures to improve the critical factors for structural safety on project level: safety culture, allocation of responsibilities, risk management, control, communication and collaboration and knowledge infrastructure (see fig. 9.1).

The sources of the suggested measures are:
[1] Eurocode
[2] Convenant Highrise
[3] Neprom Code of Conduct Structural Safety
[4] Compendium Structural Safety
[5] Interviews with experts from the building industry who suggested measures for improvement.
[6] Comparison with other industries as presented in (Terwel and Zwaard 2012)

The selection is a combination of legal regulations (Eurocode) and non-legal regulations (Convenant Highrise, Neproms code of Conduct and Compendium Structural Safety, for a description see appendix V). In addition, the outcomes of interviews with some participants from industry are included. In these interviews ideas and best practices for improving structural safety were shared. Six interviews were conducted for the evaluation of ABC registration and four interviews for evaluating the national survey in chapter 8 (see headlines in appendix VIII). Finally, ideas from other safety related industries were included.

The measures are categorized as legal (L), organizational (O) or behavioural measures (B). It should be noted that legal measures usually will need involvement from government on national level, while the other measures usually can be applied within a project.
In table 9.1 organizational measures on national level are marked *.

In section 11.3 the suggested measures are summarized for Dutch government, clients and projectmanagement and management of building companies.

Table 9.1 *Possible measures to improve critical factors in the Dutch building industry*

Critical factors (project level)	Possible measures	Legal Organizational Behavioral	Source
1. Safety culture	-Central organization Structural Safety	O*	[4,5,6]
	-Mandatory failure reporting	L, O	[4,6]
	-Improve awareness/attention to safety related issues	O, B	[3,4,5,6]
	-Constructive attitude towards safety	B	[5]
	-Adequate response after warnings	O	-
	-Assessment system structural safety	O	[5]
2. Allocation of responsibilities	-Improved clearness and completeness contracts	L, O	[2,3,4]
	-Sufficient budget/tender on price and value/financial incentives	O	[3,4,5]
	-Mutual trust	B	[5]
	-Lead engineer (single point responsibility)	L, O	[2,3,4,5,6]
	-Mandatory certification of lead engineer	L	[6]
	-Shift accountability to advisors	L	[5]
	-Maximum number of subcontractors	O	[6]
	-Integrated contracts/ chain integration	O	[5,6]
3. & 4. Risk management and control	-Guidance on performing structural risk analysis	O*	-
	-Mandatory risk analysis for CC3, light version for CC2	L	[1,2,3,4,5,6]
	-Positive attitude towards control	B	[5]
	-Application of effective control	O	[1,2,3,4,5,6]
	-Independent checking design and execution CC3	L, O	[1,2,3,4,5,6]
	-Shift accountability	L	[5]
	-Standardization	O	[5,6]
	-Prefabrication	O	[5]
	-Real time structural monitoring	O	-
5. Communication and collaboration	-Design review by contractor	O	[4,5]
	-Site engineer for CC3	L, O	[5]
	-Chain integration/integrated contracts	O	[5,6]
	-BIM/clash detection	O	[4]
	-Shift accountability to advisors	L	[5]
	-Mutual trust and interest	B	[5]
6. Knowledge infrastructure	-More attention technical knowledge in higher education	O*	[5,6]
	-HR management	O	[1,4,5]
	-Knowledge management	O	[4,5,6]

In the following sections an explanation will be given of the various listed measures and the expected improvements.

9.3 Improving safety culture

9.3.1 Safety culture on macro level

If safety culture within the sector is improved, this will have an influence on safety of individual projects.

Safety culture within the Dutch building industry is not assumed to contribute positively to quality of building projects, with fragmentation, focus on lowest price and time, reactive nature and anti-authoritative behaviour. These are part of the main observed threats. Change of the sector, however, is not easy, because of for instance the fragmentation in the industry.

It is believed that improvement starts with *awareness* (interview P. van Boom, in: (CUR Bouw & Infra 2011, p. 101)). For instance awareness that safety assurance will initially cost money, but can also lead to a reduction of failure costs. It is believed that in recent years this awareness has improved on management level; many initiatives were started that increased the awareness (see chapter 6). Various parties in the building industry have pronounced that they are willing to improve structural safety to decrease failure costs, fatalities and injuries, to improve image and satisfaction and to take personal responsibility (CUR Bouw & Infra 2011, p. 113).
However, it seems that this awareness is not disseminated within the complete building industry and is limited to a safety concerned subgroup of especially structural engineers. Van Boom states that structural safety is "too much the party of structural engineers." (CUR Bouw & Infra 2011, p. 103). Valuable initiatives like the Compendium Structural Safety and ABC registration are not widely known (CUR Bouw & Infra 2011; Schipper 2012).

The building industry might be inspired by other industries, like offshore and process industry, where the safety approach is more developed and integrated in daily practice. In a comparison of building industry with process industry and aviation, it was concluded that in the latter two industries the role of control is higher than in the building industry, the importance of risk analysis and failure analysis is higher, there is much attention for system certification and attention for certification of individuals, the importance of protocols is large and there is much attention for organizational issues (Terwel and Zwaard 2012). The author personally observed an example of a higher safety awareness in chemical process industry when he was required to watch an instruction video and perform an entrance test on safety items before entering a plant.

To coordinate initiatives of structural safety within the building industry, a *central organization* is necessary. Currently, Platform Structural Safety would be the appropriate actor to act as central organization that stimulates this awareness and coordinates initiatives of improvement. Communication of this Platform and useful recommendations for the entire building industry needs to be improved, as was stated in the evaluation of ABC registration (Terwel, Nelisse et al. 2012). Papers like 'De tikkende tijdbom onder de bouw' (Vambersky and Sagel 1997) have impact and are useful when properly written by renown authorities. In addition, it might be relevant to publish best practices on building techniques, forms of collaboration, forms of tendering (on cost and value) and financial incentives (like penalties or bonuses) that might stimulate structural safety. In the interviews with participants from industry, the author observed various relevant ideas and best practices, like the use of wikis, that are not expected to be commonly known within building industry.

A valuable initiative of the Platform Structural Safety to increase awareness of safety was the voluntary, confidential reporting of building failures. However, involvement of the

building industry was limited to merely structural engineers and officers from local building control (Terwel, Nelisse et al. 2012). A *mandatory registration of building failures* of a certain magnitude (Boot 2011) might be necessary, to acquire more failure data and to improve awareness. For job related accidents with serious injuries registration is already mandatory (see chapter 4). Other industries, like aviation and health industry are already experienced in mandatory registration systems. For government and building industry it will be easier to monitor the state of structural safety. Adequate measures can be developed, based on the failure investigations, especially when underlying process factors are included in the registration.
To motivate building industry for this initiative it is indispensable to provide proper feedback (Reason 1997, p. 197), and to use the information from the failure registration as input for risk management (CUR Bouw & Infra 2011, p. 105).

9.3.2 Safety culture on meso level

Safety culture in companies and projects might be improved by *attention to safety related issues,* where support by management is indispensable. It should be stimulated that information from Platform Structural Safety and other relevant organizations is shared within companies, thus stimulating a reporting culture and a learning culture (Reason 1997, p. 196).

Management within organizations should stimulate a *constructive attitude* with regard to structural safety. It would be beneficial to arrange internal meetings where failed projects are discussed to learn from mistakes. This might be especially fruitful for younger engineers when they experience *openness in speaking* about failures without a focus on blaming and shaming. The author experienced a relevant example when he was joining a "wake up session" in an engineering company, where structural deficiencies of a past project were shared and the way the problems were solved, to learn from them in current or future projects.

An *open attitude* when facing problems, without immediately taking a legal, defensive position, might be fruitful (interview Te Selle/Kremer, appendix VIII). Reason (1997, p. 195) explains that a just culture is needed: "an atmosphere of trust in which people are encouraged, even rewarded, for providing essential safety-related information – but in which they are also clear about where the line must be drawn between acceptable and unacceptable behaviour." However, it will not be easy to achieve this transformation from the current situation, which seems to be more legally oriented, and seems to be moving towards a claim culture (see the example of the legal-driven response on the report of the Dutch Safety Board in subsection 7.4.2).

Furthermore, the notion that every single person *has the right to be controlled* should get wide acceptance (interview Galjaard, appendix VII). Control should be positioned as something positive to improve quality and satisfaction, instead of a device which can be used to blame you, when deviations in work are revealed.

Moreover, from failure investigations it was concluded that many structures warned (cracks, excessive deformations) before final failure occurred. An important aspect of safety culture is an *adequate response after warnings* of the structure, which might reduce the number of failures. In these critical situations it is necessary to arrange feedback from colleagues (interview van Gijn, appendix VIII).

Finally, to improve safety awareness within projects, it might be helpful to *assess* the level of the main influencing process factors (for an example, see section 10.4).

9.4 Improving allocation of responsibilities

Within fragmented building projects often an unclear allocation of responsibilities is observed, which is strongly related to the level of coordination that is needed.

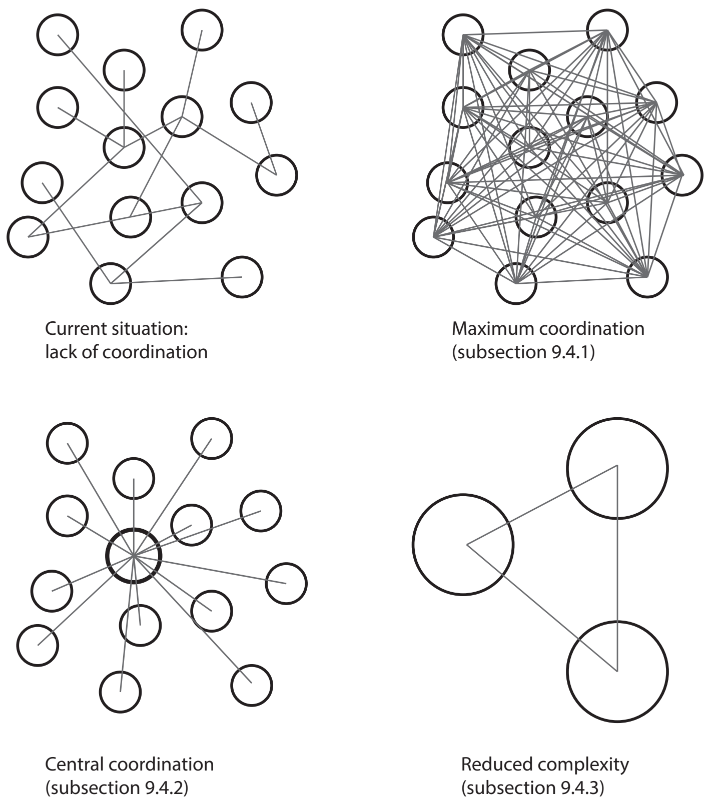


Figure 9.2 *Ways of dealing with fragmentation of the building process*

Figure 9.2 illustrates the current situation (upper left figure) with a lack of coordination. The situation is depicted statically, although reality shows dynamic behavior with often

changing of parties involved in a project.
Furthermore, figure 9.2 points out three ways to cope with an unclear or fragmented allocation of responsibilities: maximum coordination and improved clearness of roles, central coordination or reduced complexity. In the following sections these three strategies will be explained.

9.4.1 Maximum coordination and improved clearness of roles

In smaller projects, maximum coordination might be achievable, with intensive communication among the limited number of parties involved. *Improvement in the clearness and inclusiveness of contracts* is necessary for a better allocation of responsibilities. Software tools like VISO, where all contractual agreements are listed, might facilitate the allocation of responsibilities (Gulijk 2011). Various instruments are already available to make these allocations clear, like the Compendium Structural Safety, DNR 2011, STB (Standard Task Description) and Demarcation list for tasks prefab structures (KIWA 2012), see also subsection 6.8.2. Especially, tasks on the boundaries of responsibilities of various parties should be covered and coordination should be included. Transfer of knowledge between design and construction phase should be assured (see also subsection 9.8.2).

Although the sector supports clearness of contracts, clients are responsible themselves for the actual content and completeness of the contracts with their advisors (NEPROM 2008). It might be beneficial to give more transparency in the content of the contracts to the various parties, for easier detecting gaps in between the contracts.
However, completely covering tasks with contracts will usually be an illusion; it might be better to *provide sufficient budget and create a situation of mutual trust* ('giving and taking'), where problems of tasks that are not covered by the contract can easily be settled. This approach will not work in every situation; sometimes a stricter, legal approach is unavoidable (interview Te Selle/Kremer, see appendix VIII).

It is useful to search for alternative ways to deal with the problem of incomplete contracts, for instance by *financial incentives*. Alliance is a form of tendering where the risks are shared between client and contractors. For contractors there is a financial incentive to reduce extra costs, because part of these costs have to be paid by themselves.
In more traditional contracts it might be possible to reserve a certain amount of money for deviations from the contract. The client together with the other participants will discuss for every situation to which extent extra costs are reasonable. At the end of the project, the residual sum can be divided between the project participants as a bonus.

With regard to financial incentives, it should be commented that a limitless budget (and no planning restrictions) will not guarantee structural safety. It is questionable if a company will spend all the available time on the project, or that they just will increase their profits. For example, in a comparison research with smaller engineering companies and larger companies with higher fees it was found that the smaller companies, with limited budgets, tended to spend more time on control than the larger companies (Mendez Safont and Terwel 2012). This might indicate that larger budgets are not always spent on increased checking.

Although the listed recommendations might be useful for projects with a limited number of participants, when this number increases, maximum coordination will become almost impossible (see figure 9.1, position top right). It will be relevant to consider other approaches: central coordination with single point of responsibility or reduced complexity.

9.4.2 Central coordination

For the allocation of responsibilities many authors have *suggested a single point of responsibility* regarding structural safety. This party may be a structural engineer or someone from the contractor with profound structural knowledge. It should be discouraged that this responsibility is split between several parties, for instance during design and construction, because this will increase fragmentation and communication problems. This structural safety manager should be in close contact with the client, to include safety improving measures in the contracts and to be able to check and maintain these measures during the process.

It is necessary that a coordinating engineer is suited for the complexity of the project. A relevant measure might be a classification of engineering companies and contractors in the projects they are allowed to design or construct. The categories can be similar to the consequence classes of the Eurocode. In B1.1.2 Compendium Structural Safety lists some relevant questions with regard to the capability of engineering firms (Spekkink 2011):

- Does the engineering company have any experience with similar projects (similar in size and complexity)?
- What is the suggested approach of the engineering company for the project?
- Can the engineering company prove that its internal checking is sufficient?
- Does the engineering company have qualified personnel?
- Does the engineering company have the right facilities?
- Can the engineering company show positive references?
- Is the engineering company investing in knowledge development?
- Is the engineering company able to think out of the box?

In addition, requirements on the lead structural engineer might be stated. For certain projects (especially within CC3) *certification* of the responsible engineer of record might become mandatory, based on competence and experiences. This is already suggested in the Eurocode (see subsection 2.4.2).

When the advisor's responsibilities increase, his accountability should similarly increase. However, currently the level of accountability of advisors is regarded to be low (one of the main observed threats from chapter 6) and has to be reconsidered. Clients should not

agree with extreme limitations of liability in contracts of larger projects. When limitations of liability of advisors and contractors are reduced, this will result in a larger influence of insurance companies. When a company experiences a larger number of claims, this might result in termination of the insurance policy, an increase of insurance fees or an increase of the deductible (Boot, Terwel et al. 2012, p. 74).
A *higher level of accountability* might stimulate engineers to be more accurate and alert. It might result in a more proactive behaviour with for instance a refusal of incomplete or insufficient contracts by advisors. However, an accompanying increase in remuneration of the engineers will be necessary to cover increasing insurance costs.

In DNR 2011 (BNA and NLingenieurs 2011), the standard conditions for contractual agreements between advisors and clients, the restrictions in limited accountability are already loosened as compared to DNR 2005. The damage to be compensated by the consultant was limited to the consultancy costs with a maximum of € 1,000,000. In the new situation client and advisor can choose for this old limitation or extend it to a sum equal to three times the consultancy costs with a maximum of € 2,500,000 (see also section 6.8).

An increase of accountability is useful to a certain level, but will not be a guarantee for safety. In this regard Bea (1994, p. 230) cites Melchers: "There is evidence to suggest that sanctions may well be effective for premeditated crime but that in general the effect is likely to be most pronounced on those least likely to be involved. It is reasonable to suggest that few engineers premeditate to perpetrate errors, so that the most likely result of excessive threat of legal sanction is inefficiency, over-caution, and conservatism in the execution of work".

9.4.3 Reducing complexity of the process

Allocation of responsibilities will be easier when the complexity of the building process is reduced. Although this will not always be possible or desirable, it is worthwhile to consider it.

An approach that has been used in process industry is a *maximum number of project participants*, especially of subcontractors. With a smaller number of parties, allocation of responsibilities will be easier. Enforcement can be arranged in the contract with the main contractor, although it should be realized that for specialized work and for price competition the maximum number of subcontractors should not be chosen too low.

Another measure will be some form of *integrated contracts*. If you do not cut in the phases of the building process, you do not have to stitch the separated parts with coordination (interview Paul Smeets, Schipper 2012). If there is no strict separation between design and construction, it might be easier to implement construction knowledge into the design, resulting in easier construction and a lower probability of execution failures. In addition, design engineers are expected to be more closely involved during construction, which will improve construction according to the intentions of the design. For civil structures it is more usual that a site engineer is permanently on the job (interview Galjaard, appendix VIII); an initiative that deserves follow-up for residential and utility buildings. As a disadvantage of integrated contracts, the uncontrollable costs have been mentioned for complex structures, because a large financial compensation for uncertainties at the start of the project will be demanded. In addition, real independent control between structural engineer and contractor might be harder when working as a single party (Brouwer 2005). Furthermore, in integrated contracts coordination of various participants might still be an issue. Therefore, integrated contracts will not be the ultimate solution for every situation, although the influence of forms of collaboration and contracts on the allocation of responsibilities deserves future study.

Chain integration, when the same parties work together on subsequent projects, might result in an increased clearness of responsibilities. Although it is useful for standardized jobs like maintenance, it will be less relevant for unique jobs and might in these situations result in higher costs for the client, because project participants will translate the high risks into higher remunerations. For projects with a repetitive nature it is advisable to work with *set project teams,* because participants will get familiar with each other and it will be easier to work with standardized processes, thus, decreasing the probability of error.

It can be concluded that for improvement of the allocation of responsibilities a combination of the various ways to deal with fragmentation is needed: increased clearness of contracts, central coordination and reduced complexity where possible.

9.5 Improving structural risk management

It is believed that a risk management approach stimulates proactive behaviour, resulting in an improved ability to cope with risks that might occur during a project. Within Dutch building industry explicit structural risk analysis is not very common. Moreover, for buildings risk management often focuses on financial risks, not on risks regarding the structure itself.

However, in civil engineering there is much experience with risk management. In the Netherlands the RISMAN method is often used for (financial) risk management of civil structures. In this method risk management starts with a risk analysis (Van Well-Stam, Lindenaar et al. 2003). In this risk analysis the goal for the analysis is set, the possible risks are identified, the risks are prioritized and the possible measures are listed. This risk analysis may be qualitative or quantitative. For every project phase the risk analysis can be updated.
Risk management elaborates on risk analysis by selecting, executing and evaluating of measures. Strategies for measures are avoiding risks, reducing risks, accepting risks or transferring risks to other parties (Van Well-Stam, Lindenaar et al. 2003).

Within Eurocode for consequence class 3 a structural risk analysis is advised (EN 1991-1-7:2006, comment on art. 3.4), although there is little guidance as to what should be the content of this risk analysis (see subsection 2.4.4). In the Netherlands a generic risk analysis was performed resulting in a general approach to cope with structural hazards, like human error or terrorism (Adviesbureau ir. J. Hageman B.V. 2007; Terwel, Wijte et al. 2011). However, within this approach risks in the process and procedural measures are underexposed.

The Institution of Structural Engineers in Great Britain has issued a generic risk management approach that can be customized for every project (Cormie 2013). This approach is more specific than the approach as listed in EN 1991-1-7:2006 Annex B and the RISMAN method. Cormie explains that risk management should not be exclusively limited to class 3 structures, but for the following situations risk management should be considered:

- Buildings that do not fall in the standard Eurocode risk classification system (CC1-3)
- Buildings housing hazardous operations, like nuclear plants
- Structures featuring innovative, complex or unusual structural framing, stability arrangements, materials or construction techniques
- Structures with a high degree of modularisation and repetition where there is the potential for a systemic error
- Structures designed at the margins of the codes of practice
- Structures designed 'down to the bone' or optimised 'to within an inch of their lives', with very little redundancy
- Buildings exposed to abnormal, significant or extreme risks
- Structures having exposure or vulnerability in a temporary state
- Existing buildings undergoing extension, alteration or change of use, particularly where there are unknown structural characteristics and/or the potential of hidden defects
- Structures required to exhibit a high level of reliability or a greater level of performance than required solely for life safety

To this list the situation is added in which the project manager or project team is inexperienced with the kind of structure present. In addition, some kind of risk analysis (at least risk awareness) can be beneficial for every type of structure.

The risk assessment approach of IStructE consists of the following steps:

1. Identify the hazards (something with the potential to cause harm)
2. Eliminate the hazards where feasible to do so
3. Determine the level of tolerable risk
4. Evaluate the risks that remain (likelihood, consequence)
5. Identify risk reduction measures
6. Perform a cost-benefit assessment for each of the risk reduction measures
7. Implement risk reduction measures
8. Review the residual risk
9. Check the sensitivity of the risk assessment (cliff edge effects, low likelihood/high

consequences hazards, combined hazards)
10. Review the overall level of risk
11. Effectively communicate information about any risks that remain in the design

This method seems useful to apply for Class 3 structures (and other structures, possibly to a lesser extent), because adequate measures have to be developed for the major detected risks. However, quantifying the risks in exact probabilities will often not be easy, especially not for risks in the building process. It is believed that classification with for instance a 5-point scale from very low to very high will be preferable over completely leaving the risk analysis out.

It is recommended that in the National annex of the Eurocode *more guidance* will be given on the performance of a risk analysis in CC3. It would be helpful when examples would be provided of structural risk analyses of projects, like the example of Cormie (2013, pp. 63-73). In addition*, for CC2 a light qualitative version of a risk analysis* would be beneficial to improve proactive risk awareness. For this light version the main hazards in the process and in the product can be pointed out, for instance with a 5-point Likert scale, and measures which cover the main risks should be suggested and implemented.

9.6 Improving control

It is widely known and accepted that *control is relevant* to improve structural safety. However, it is often not adequately applied in less successful projects (chapter 8). Bea (1994) states in this regard (p. 236): "Checking…and verification of the structure design are more what we should do than what we actually do. This is satisfactory when the designs are evolutionary, the design processes well established and proven, the system is highly forgiving, and experienced engineers are at the helm of the design team." Often this is not the case.

In chapter 3 it was concluded that primary processes (like drawings and construction activities) are essential to make a structure, but that without control it is still possible to make a structure. In a situation with competing goals, for instance between time and budget and quality, it might seem easy to omit control. However, this will always be to the detriment of safety.

To avoid omittance of control, persons should be deeply convinced of the *relevance of control*. Often, on company level persons are conviced of the relevance of control. Some companies explicitly state that everyone has the right to be controlled (see 9.3.2). Top management should assure this principle, by providing adequate time, when competing goals present themselves. However, checking of other parties in a project should be facilitated by complete contracts of the client (see subsection 9.4.1).
Clients, however, are not always convinced of the relevance of adequate control, although the professional organizations for project developers NEPROM explicitly highlights the relevance of control in their Code of Conduct (NEPROM 2008, pp. IV-V).

Control can be effective when the right things are checked in the right way.
To check the right things, it is important to use the results of the risk analysis to point out the situations that need special attention.
IStructE (Cormie 2013) gives some examples of areas that need special attention of control:

- known to be particularly important to the robustness of the structure
- in which there is a high risk of mistakes or errors being made
- where supervision is known to be difficult during construction
- where a high degree of reliability is necessary because subsequent inspection and maintenance will be difficult.

To control in the right way, a distinction should be made in the type of structure and the type of errors that can be made.
For routine work of easy structures (consequence class 1) self control might be sufficient in many cases. However, for substandard situations, additional control by colleagues with overview checking will be necessary to avoid errors of omission (see section 3.3). The checking colleagues should be more experienced and have sufficient available time (interview Galjaard, appendix VIII and (Stewart and Melchers 1989)).

In CC3 situations a second opinion, or independent design review, should be applied, in conformity with Eurocode (see subsection 2.4.2). A TIS (Technical Inspection Service, see subsection 3.2.4) can be used for this purpose.

The main items that should be checked when performing an independent review are listed by APEG (2013):

- design code loadings and serviceability limits
- material specifications and geotechnical recommendations
- concept and integrity of the gravity load resisting system
- concept and integrity of the lateral load resisting system
- drawing completeness and continuity of load paths
- design check of representative structural elements
- review of representative structural details
- concerns discussed with the professional of record

A very important aspect of effective control is that deviations that are revealed by checking are adequately dealt with. It is possible to accept the deviation with motivation, or to apply measures to deal with the deviation (see chapter 3).

For quality assurance it might be relevant if someone (client, municipality, third party) checks if checking has taken place to achieve a system of double assurance (Vambersky and Terwel 2009).

Adequate application of control might be stimulated by *shifting accountability from client to advisors and contractors.* When likelihood of liability increases, the implementation of control is deemed more customary (see also subsection 9.4.2).

Initiatives where clients are better protected by *increasing the definition of hidden defects* (Chao-Duivis and Strang 2013, p. 112) might be helpful. In the current situation contractors are merely responsible for hidden defects, but often they can argue that a defect could already be known at delivering of a project. When every defect/deviation that was not written in a delivery report is considered as a hidden defect, the client might be better protected and the contractor is compelled to improve control.

An important difference with other industries is that every structure is a prototype, where in other industries extensive testing will be provided, before a product will be launched on the market (Terwel and Zwaard 2012). It is useful that within building industry forms of standardization are explored, which can improve the quality of the product, by making control more integrated in the process.

Standardization can be performed on element level (beam or connection), component level (floor, compartment) and system level (complete building/structure) with a combination of standardized products and standardized processes (protocols for working).
In the current building industry some standardization on element level is visible, with many available building products (for instance hollow core slabs or integrated beams) and by using standard protocols for tasks (for instance standard detailing in design tasks and check lists for standard construction tasks). Standardization on element level, by using specialized products that can be perfectly engineered and assembled by specialists might improve structural safety, although not necessarily (see comments on prefabrication).

In the past various initiatives with standardized buildings and components have been tried. However, usually these initiatives were not very successful, because too much supplier-driven without taking the demands of the clients into account. Currently, standardized buildings like the houses in a row of many new developed areas in the Netherlands are often not very well appreciated. However, standardization, without forgetting client's demands, is promising (see also section 9.10 on Legolisation).

Prefabrication can improve structural safety by a specialized approach with specialized engineers. In addition, for this approach the manufacturing will be done in the controlled environment of a factory with often a more thorough system of quality assurance, thus improving safety. With modern factories many options are possible to make interesting elements. However, a drawback of using prefabrication is that this often increases the number of parties involved, thus increasing fragmentation (Vambersky and Terwel 2009). Furthermore, the various elements/components should be assembled on the building site, which is a process that might become critical for the safety of prefabricated systems.

Monitoring
Real time structural monitoring of buildings is not common in the Netherlands. Exceptions are the use of sensors to measure dynamic performance of high rise buildings and stadiums.
For civil structures, like bridges, sensors are sometimes used to measure elongations, deformations and accelerations to predict for instance fatigue behaviour. The effect of monitoring on the failure probabilities can be estimated with Bayesian approaches (Vrouwenvelder 2014, p. 49).

With new technologies other ways of application are imaginable, which might help monitoring structural performance even during construction. Two examples are given.

First, Akinci, Boukamp et al. (2006) experimented with a system for active construction quality control. They used a 3D model and compared it with the images as derived by a laser scanner, which gave them the ability to check for misalignment of columns and deviations in sizes. When elaborating on this system with a 4D model (by including factor time) and real time laser images, this might result in a monitoring system of quality during construction. At this moment, the number of lasers, accuracy of data for various purposes (quality of welds demands higher accuracy than alignment of columns) and the amount of data are hurdles that have to be taken.

Second, with satellite radar interferometry it is possible to detect deviations in deformations from space. This technique is currently used for monitoring the quality of dykes (Tissink 2010). However, it is also possible to detect deformations of for instance balconies and settlements of buildings. It is claimed that the large settlements of the shopping mall 't Loon in Heerlen could have been observed with sattelite even before the situation developed into a dangerous situation (Chang and Hanssen 2014). Because of the limited number of available satellite images, only deviatons during longer periods can be monitored in the current situation.

9.7 Improving communication and collaboration

Collaboration and communication are closely related. When collaboration is perceived to be positive, usually communication is easier. Coordination is closely related to collaboration, communication, control and allocation of responsibilities. Communication is closely related to knowledge exchange (see section 9.8).

9.7.1 Communication

Especially communication between design and construction can be improved. It might be beneficial when *contractors are involved in design review* or when persons are involved with a profound construction knowledge. Similar to a design review by a contractor, for communication about the design during construction it is advised to arrange a *site engineer for buildings in CC3*. When this person resides at the same place as the responsible persons for construction, this might improve communication.

Integrated contracts, where contractors and structural engineers work together, might stimulate exchange of knowledge between design and construction related parties (see subsection 9.4.3).

BIM is often mentioned with regard to communication and coordination, because virtual prototyping, interface management and clash control can be performed. Because various project partners are working with the same model, communication and coordination will be improved. However, BIM might result in an overflow of information, for which it is essential that persons involved are skilled to notify the relevant partners of relevant changes. It is important that the files are adequately stored, to make as-built-drawings available for use and maintenance.

9.7.2 Collaboration

For successful collaboration various aspects are relevant, like understanding, communication, trust, humor, tolerance and respect (Broekhuizen et al. 2009). Laan and Sijpersma (2006) suggest that trust in someone's competencies and intentions is necessary for collaboration. Trust in someone's competencies means that one expects the other party to perform in conformity with expectations. Trust in someone's intentions means that one expects the other party is willing to perform well.

Trust within projects will be stimulated especially when parties can trust each other's competencies (interview Van Gijn, appendix VIII). In addition, a client can enhance the atmosphere within a project team by stimulating team building, for instance by celebrating mile stones in the project. A good atmosphere among the team members will result in easier dealing with unexpected situations.

In addition, it should be recognized that there are usually various cultures within a project: a management culture (project managers for clients and contractors, directors of engineering companies), an engineering culture (structural engineers) and an operator culture (craftsmen on the building site) (Schein 1996). These various groups have different values and ways of working. It is important that these parties *understand each other*, to collaborate successfully within projects. Therefore, *mutual interest* in the work and interests of the other parties is necessary (Interview Te Selle/Kremer, appendix VIII).

Chain integration (see subsection 9.4.3) might stimulate communication and collaboration, when parties work together on subsequent projects. Parties already know each other, which might facilitate collaboration.

9.8 Improving knowledge infrastructure on project level

For a high level knowledge infrastructure the level of knowledge should be well developed and extensive exchange of relevant knowledge should be possible. This will be elaborated in the following subsections.

9.8.1 Maintain high level of knowledge

The level of knowledge in the Netherlands in general can be regarded as high. This level should be maintained, in which education has an important position. Essential competencies for structural engineers are: design, drawing/modelling, detailing, calculating and reporting. In addition, knowledge of material behaviour, mathematics, structural mechanics, structural design and execution techniques is regarded to be essential (Terwel and Hermens 2012). With regard to improvement of education the main recommendations of Terwel and Hermens are restated: *more attention to technical knowledge* in higher education and lifelong education after the formal education has been finished.
This will deal with the main observed threat of the decrease in quality of higher education and will positively influence the available knowledge in future projects.
Within companies it is very important to *select new personnel* with sufficient knowledge or with the ability to acquire the necessary knowledge. Clients should select the right companies, that are suitable to do the jobs, proved with references of earlier projects. When selecting persons for projects, it is advisable to ensure that the leading persons are suitable for this kind of projects and clients (similar to demands on coordinating companies in subsection 9.4.2).

9.8.2 Exchange of knowledge

One of the main observed threats was the lack of use of available knowledge. This has been illustrated by various failure cases in chapter 7. It appeared that many failures were not caused by unique phenomena but that persons involved did not have the adequate knowledge available. Sometimes other persons within the projects would have had the relevant knowledge. An example is the case of the B-tower, where the assembling team was not aware of the necessity of bracings in two directions, that other project participants were acquainted with (see subsection 7.2.2).

Knowledge management is believed to tackle these problems. Knowledge management can be defined as: "the discipline that promotes an integrated approach to identifying, capturing, evaluating, retrieving, and sharing all of an enterprise's information assets. These assets may include databases, documents, policies, procedures, and previously un-captured expertise and experience in individual workers" (Duhon, as cited by Koenig (2006)).

On macro level, The Platform Structural Safety and industry associations on concrete and steel already play a role in the dissemination of knowledge.
On company level, computerized exchange systems of knowledge, with for instance project experiences and wikis are already in use and deserve wider implementation (interview Galjaard, appendix VIII). However, face to face contact between experienced and novice craftsmen cannot be completely substituted by digitalized systems.

Exchange of knowledge is closely related to communication. Other forms of exchange of (project specific) knowledge were described in the section on communication.

9.9 Attention for work-as-imagined or work-as-actually-done?

In subsection 3.2.4 the difference between work-as-imagined and work-as-actually-done was introduced. Work-as-imagined is the way a task is intended, as usually described in procedures or protocols, meeting the demands of regulations and law, whereas work-as-actually done is the actually performed activity. In this chapter measures are suggested to improve the critical factors. These measures can be regarded as work-as-imagined. From table 9.1 it can be concluded that at least 40% of the measures have already been mentioned in non-legal regulations (about 40% were listed in source 2-4, although there will be other publications where other measures were already listed).

When the difference between work-as-imagined and work-as-actually done is used to evaluate the critical factors, the following conclusions can be drawn.

1. Safety culture is an all-encompassing term, which includes many factors that are safety related. Some publications have explained what a healthy safety culture for the building industry should be (work-as-imagined). However, in the current building industry the actual safety culture is believed to be lacking. Other safety related industries like process industry and aviation can be examples for a more developed safety culture.

For projects the formal, intended safety culture is sometimes presented in a Safety Management System, which is a system that provides the administrative structures necessary to drive good safety practices (Reason 1997, p. 138). In the building industry the Safety Management System on project level will usually be equivalent to the quality management systems in conformity with ISO 9001 of the various project partners.
In subsection 2.4.4 it was explained that in the Dutch building industry a skeptical attitude towards quality management and procedures can be observed. It is commonly accepted that it will not be sufficient to perfectly design the procedures and to force compliance of the work-as-done to this image, because the current building industry is characterized by unique structures and unique forms of collaboration for which watertight procedures are an illusion. Some improvisation or deviation from procedures cannot be avoided. However, it would be beneficial to discuss the use of procedures within companies and the situations where deviations might be necessary.

Major improvements are usually not associated with more procedures and formal Safety Management Systems, but with implementation of procedures, knowing when deviation from procedures and working on a healthy safety culture is necessary.

2. Allocation of responsibilities is well covered by the Compendium Structural Safety (Spekkink 2011), which explains a way in which the responsibilities in projects can be allocated (work-as-imagined). Between project partners (client versus advisor or contractor, and contractor versus subcontractor or supplier) usually contracts are used with a broad description of intended tasks. However, allocation of responsibilities is sometimes limited to the sum of contracts and procedures of the individual companies, which might not cover all aspects in the relationship between companies.
It can be concluded that the work-as-imagined on a national level has been covered with the recommendations of the Compendium Structural Safety. Building industry is able to know a suitable allocation of responsibilities, although in practice especially tasks which are on the interfaces of various disciplines need implementation.

3. Structural risk management is not well documented in the current Dutch building industry. Is it is usually not covered within ISO 9001 procedures and in contracts. Companies have experience with implicit risk management, but explicit structural risk management as suggested by IStructE deserves succession. This factor lacks on work-as-imagined as well as on work-as-actually-done.

4. Control mechanisms are often described in ISO 9001 procedures and contracts (work-as-imagined), although the specifications are sometimes ill defined. Checking of the structural engineer on the building site for instance is often broadly described (phrases like: 'Sample checking on relevant moments'), with room for personal interpretation. The project manager has a responsibility for these lacunes, although he will primarily focus on delivering the project within time and budget and delegate responsibility for quality to the project participants. Sometimes, in traditional contracts, inspection is provided by the client, but usually it will not focus extensively on structural issues. Therefore, it is believed that some extra attention to the extent of control in contracts for specific projects will be beneficial. In addition, companies perform their own ways of control. This might be adequate, although guidance of adequate ways of control can be useful. Hence, control-as-imagined can be improved.
However, it is expected that the main problem with control is the effective application of it (see section 9.6). From failure investigations it was concluded that in many cases adequate checking could have avoided the failure. It can be concluded that the checking as actually done is often lacking or insufficient.

5. Communication and collaboration are not completely covered in the working procedures. This is due to the current way of working within the building industry, that can be characterized by improvisation and 'fixing' problems, because every project can be regarded as a prototype (Terwel and Zwaard 2012). It is believed that adequate implementation of BIM can lead to improvements, because several parties have to work together in one model, thus improving coordination and (clash) control.

6. Knowledge infrastructure is often covered in a Knowledge Management System, especially for larger companies (work-as-imagined). However, every company has its own way of working, and it is not known if companies are adopting adequate systems. Exchange of best practices on sector level is recommended, with examples of (large) companies who have adequately implemented knowledge management with for instance the type of training provided, type of meetings to exchange knowledge, standard calculations, check lists for setting up and controlling Finite Element Models, and the exchange of knowledge on risks of past projects. It can be questioned if the knowledge infrastructure as-actually-used will be adequate, if the systems-as-imagined are not well developed.

Conclusion
All in all it can be concluded that ISO 9001, contracts and Compendium Structural Safety among other initiatives provide guidance for a large number of critical factors on company level. However, for work on *project level, the work-as-imagined is not always clear or formalized.* Every company works with its own procedures, which might need coordination on project level. Certification of the processes between companies in large projects might be considered. At least a thorough risk management of process and product on project level should be considered, which might cover other critical factors too.

Furthermore, *relevant procedures and possible deviation from these needs discussion* within companies. It should be noted that for unique structures and unique forms of collaboration, water tight procedures might be an illusion. Improvising will be needed in these situations, although to avoid failures, the amount of improvising should be limited. Some authors even suggest to eliminate improvising (see section 9.10). It is recommended that the role of procedures and situations where improvisation is needed, will be discussed within companies.

Moreover, *actual implementation* of protocols and recommendations in projects needs improvement. It seems there is no problem with the listing of possible measures and availability of procedures, but selecting the effective ones and implementing them is the main challenge (interview Bol and De Backker in: CUR Bouw & Infra 2011). To support decision making, it is recommended to provide insight in the costs of measures to improve safety, and the achieved reduction of risk.

Van Staveren (2009) studied various aspects of the implementation of risk management within geo engineering, but his outcomes have a broader applicability. For implementation he states it is necessary that individuals are motivated and committed, which can be achieved by purposeful interventions. In addition, methodologies should fit with the targeted user groups; innovators, early adopters, early and late majority and laggards.

Hence, it is concluded that in the current situation work-as-actually-done needs most attention. The availability of procedures and measures is not the main issue, but implementing effective measures.

9.10 Transformation of the building sector

Some people argue that solutions on aspects of the building industry will not be sufficient. In their opinion, a total transformation is necessary, because problems in the building industry can be regarded as systemic and negative influences are deeply rooted in Dutch culture (section 8.5).

A promising concept is 'Legolisation', as suggested by De Ridder (2011; 2012). According to this concept suppliers should offer their specific solution space, for instance a catalogue with various options for a building, while clients should focus on establishing their wishes in a solution space, instead of the current fixed set of output specifications. By doing this, suppliers are able to use their creativity to meet the client's wishes. Competition should not be limited to price, but on the value-price ratio. Construction itself will focus on making the elements in the factories of the suppliers and assembling them on site. To make this possible, the relationships between the various disciplines should be set, thus avoiding complex integrated design.
De Ridder states that this method will offer more value at lower costs. By using the creativity of the supplier and not only focusing on price in the competition, value can be improved. By standardization of products, avoiding integrated design and introducing chain integration with better collaboration, (failure) costs can be reduced. It is plausible that this integral solution will overcome many of the problems regarding structural safety within the current building industry: allocation of responsibilities and communication and collaboration will be improved when working with the same parties during several projects (chain integration). In addition, risk management and control procedures are easier to apply in a more structured process of standardization and prefabrication. Thus, the need for external control will be lower, and system control can provide a satisfactory level of quality assurance.

Although this concept is promising for improving structural safety, even in this situation failures can occur. Errors of commission (see chapter 3) in for instance assembly of elements will be present and if an error in the system occurs, this can affect a series of structures.
It will take decades until resistance in the building industry will be overcome and the industry will be completely transformed to this new situation. Clients will be afraid to acquire standardized buildings without much appeal, will be afraid to lose control of the end product and they currently are not used to thinking in solution spaces.
Moreover, the focus on lowest price is deeply rooted in Dutch culture and it will take a lot of effort to convince clients to apply other selection criteria. In addition, it will take much investments until suppliers can provide sufficient alternatives for the solution spaces. The

suppliers have to provide excellent service to gain confidence in this new approach from clients. Some bad experiences will slow down or stop the transformation process towards legolisation.

Furthermore, there might be resistance by technical consultants, because they are afraid of losing interesting work, in combination with a comfortably low liability. Developers, who often are the land owners, might be reluctant because of losing profit opportunities.

And finally, this solution might be relevant and applicable to 80% of the buildings. However, there will be another 20% left with buildings like landmarks and multifunctional buildings for which this approach will not be suitable and integrated design will be necessary.

Therefore, a transformation of the building sector will take a long time. In the meantime it is recommended to improve structural safety within the traditional building process.

9.11 Conclusion

This chapter has provided a list of specific measures that are deemed necessary to improve the critical factors for structural safety within Dutch building processes. Section 11.3 will allocate the various measures to actors in the building industry.

The added value of this list of measures, above existing lists, is that they are based on a more extensive analysis of the problems within the Dutch building sector and its projects, which has led to a limited selection of measures.
It can be concluded that because lack of structural safety is caused by multiple factors, a combination of legal, organizational and behavioural measures is necessary to cover the various aspects. The suggested measures will be relevant for building industries similar to the Dutch situation.

A large number of the suggested improvements have been mentioned before by other authors. Therefore, it can be concluded that the main problems in the Dutch building industry are not in the first place related to the work-as-imagined, but to the work-as-actually-done. It is believed that implementation of the suggested measures deserves attention. For implementation of measures, a favourable cost-benefit ratio is necessary. However, this study did not include a cost-benefit analysis. Therefore, it is recommended to make a cost-benefit analysis for the various suggested measures.

In chapter 2 the current framework of the Eurocode was presented, with attention to its deficiencies. Chapter 10 will explore in which way this framework can be strengthened, with a focus on promising ways of combining underlying factors and human performance with structural performance.

10

Exploring improvements in the Eurocode approach

10.1 Introduction

Chapter 2 concluded that within Eurocode human and organizational factors were not adequately covered and that human behaviour was not adequately included in the reliability approach. Furthermore, it was criticized that the two ways of Eurocode (see chapter 2) are not developed to the same extent, with a detailed probabilistic approach for calculations and an often ill-defined quality management approach (see subsection 2.4.2).

This chapter will explore improvements for these two setbacks of the current Eurocode approach.
It will first discuss to what extent the critical factors derived in the current study are reflected by the Eurocode approach. Subsequently, two ways of combining human and organizational performance with structural performance will be explored.

- The first approach will combine Human Reliability Analysis with Structural Reliability Analysis.
- The second approach is an indicator method, which predicts the likelihood of a successful project, based on assessment of underlying factors.

These methods will be introduced and discussed.

This chapter does not intend to provide final solutions for combining human and organizational factors with structural performance, but aims at giving useful starting points for future research.

10.2 Improvements in the Eurocode approach

This section will explore to what extent the critical factors can be included in the Eurocode approach, to overcome the insufficient attention for human and organizational factors in the current code.

The critical factors for structural safety are reordered in the amount of attention Eurocode pays to these factors:

1. Control mechanisms
2. Risk management
3. Knowledge infrastructure

4. Allocation of responsibilities
5. Communication and collaboration
6. Safety culture

For *Control mechanisms* Eurocode specifies levels of supervision, which are useful. However, a more thorough description of the items that should be checked, the way they should be checked and by whom they should be checked (requirements on checkers) are lacking.

Risk management is prescribed for CC3. However, guidelines on the necessary elements of risk management are lacking (see section 9.5). For CC2 no risk management is prescribed. It is recommended to use similar categories for levels of risk management as there are for supervision levels for various consequence classes.

Regarding *knowledge infrastructure,* Eurocode only assumes a minimum level of skills and experience of personnel (EN 1990:2002 art. 1.3). Eurocode does not pay attention to knowledge infrastructure on project level.

In the Eurocode, *allocation of responsibilities, communication and collaboration and safety culture* does not receive explicit attention. Eurocode designates ISO 9001 as an acceptable basis for quality management measures. However, these three factors are not necessarily covered by ISO 9001 procedures.
Compendium Structural Safety shows that for allocation of responsibilities more procedural guidance can be given than currently provided by Eurocode. However, these recommendations might be different for various countries. Hence, if more requirements on the allocation of responsibilities would be included in the Eurocode, this has to be covered in national annexes.
For communication and collaboration and safety culture this will be difficult, because these factors are hard to operationalize. General requirements might be too broad and specific requirements might not be suitable for every project form. It is expected that Eurocode is not the appropriate way to improve communication, collaboration and safety culture.

In conclusion, the following recommendations are suggested for a better attention of human and organizational factors in Eurocode:
- Make risk analysis for CC3 mandatory, and advise a light version for CC2. Introduce levels of risk analysis.
- Provide more guidance on structural risk analysis in Eurocode
- Give a more detailed description of adequate control, like self checking and independent review

Because of differences in building industries on macro level (like the legal system) and differences in projects on meso level (like the form of collaboration) Eurocode will not be suited to cover all aspects of the critical factors. For knowledge infrastructure, allocation of responsibilities, communication and collaboration and safety culture, non-legal regulations might be a first start to improve these factors. Implementation of these factors deserves major attention.

The second main set-backs of the current Eurocode approach are the two separated ways to assure structural safety (see chapter 2). The following sections will describe two ways of combining underlying factors and human errors with structural performance (see figure 10.1). Section 10.3 will discuss a possible method within the context of this research, which combines human error probabilities with structural reliability analysis in conformity with Eurocode. The underlying factors are partially included as multipliers for the human error probabilities. Section 10.4 will discuss a risk indicator method which combines underlying factors directly with structural performance, thus avoiding the analysis of human performance in separate tasks.

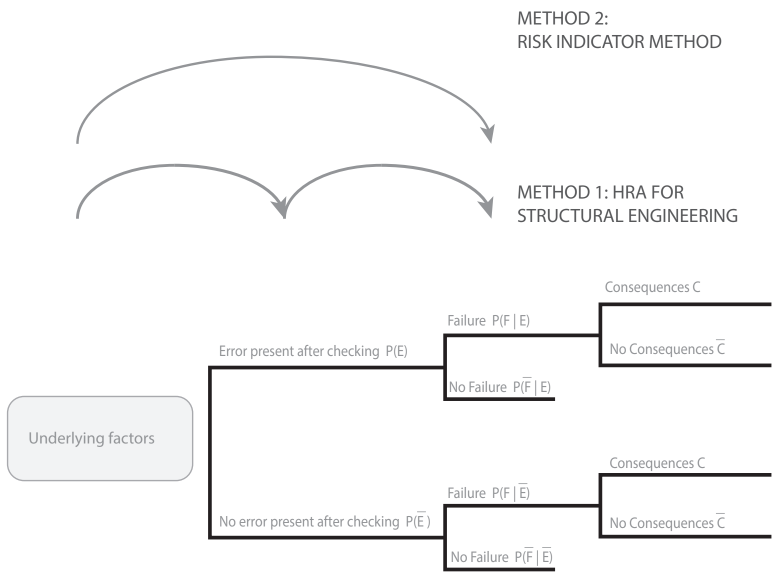


Figure 10.1 *Basic approaches of methods to combine human and organizational performance and structural performance*

10.3 Human Reliability Assessment (HRA) for structural engineering

10.3.1 Explanation method

Based on HRA models from other industries and on earlier attempts by Stewart (1993), De Haan (2012) developed a HRA model for structural engineering. It aims at enhancing the possibilities for a company to evaluate present and future vulnerabilities to catastrophic events, by incorporating the effects of human error in structural engineering.
The model consists of four steps. Process and boundary conditions are identified in the first step. The effect of human error on a single task is defined in the second step. The separate effects are combined in an overall effect in the third step. The effect of some underlying factors is included with multipliers for the Common Performance Conditions. The structural failure probability is estimated by combining the strength and loading conditions with a Monte Carlo simulation. Figure 10.1 schematically illustrates the relationship between human errors (and its multipliers: the underlying factors) and structural performance in this method.

The use of the model is demonstrated for the (structural) design process of a beam element in an office building. In the case study scenarios are explored with various forms of design control and levels of professional knowledge. A more elaborate description of this method is given in De Haan et al. (2013).

10.3.2 Limitations of the method

There are some limitations on de Haan's approach. His model only covers a small part of the design and construction process: the design of a single concrete beam or a simple framework. In addition, underlying factors are included by using a simple multiplier in the error probabilities, but it is questionable if the assumed linear relationship between context and task is correct (see section 10.5). Furthermore, the reliability of values for the human error probabilities and the multipliers for the underlying factors can be questioned. Moreover, there are underlying factors that were not included in the model. The interactions between various parties, for instance, are almost neglected, because the case was rather simple with the design of a beam. Hence, the critical factors from the current study are not reflected by De Haan's initial approach.
Inclusion of the various lacking aspects, is expected to result in a model with a very high level of complexity with large confidence intervals.

10.3.3 Opportunities of the method

Although the modelling has its limitations and needs further development, it can be used to quantitatively compare the influences of various measures, like various types of control, in the building process on the expected performance of the structure. Extension of the model with tasks in the construction phase is an opportunity.
Critical factors derived in this study can be included as follows:

- Safety culture: include as multiplier for all human error probabilities

- Communication and collaboration: include as multiplier for human error probabilities related to communication
- Risk management: develop scenarios with adequate control for error prone tasks (when assumed that proper risk management will improve effectiveness of control)
- Control: ditto
- Allocation of responsibilities: develop scenarios in which certain tasks are omitted
- Knowledge infrastructure: include as multiplier for knowledge related tasks

Other underlying factors might also influence the human error probabilities. It is for instance possible that the use of protocols and sufficient time and budget reduces the human error probability, although these factors were not assigned as critical.

Changes in the process will impede modelling. Therefore, modelling will be easier in standardized approaches, like prefabrication.

10.4 Risk indicator method

In literature various lists of characteristics of the building process or the structure itself are given that might indicate the proneness to errors (e.g. Pugsley 1966). However, usually these are not quantified.

10.4.1 Explanation of quick risk assessment tool

Terwel and Jansen propose a quick assessment tool based on risk indicators to give building participants an idea of the quality of their process regarding structural safety (Terwel 2013; Terwel and Janssen 2014 submitted for publication). Risk indicators are "any observable or measurable characteristic of the system or its constituents containing information about the risk" (Faber et al 2008). In this model a direct relationship is assumed between the underlying factors (indicators) and successfulness (related to the absence of risk, see chapter 8 for definition of a successful project related to structural safety).

The quick assessment tool uses data of the national survey on structural safety regarding the presence of factors in successful and less successful projects regarding structural safety (see Chapter 8). Hazards might be interpreted as lacking communication, control, etc. From these data it is possible to derive a function that predicts the probability of an outcome. The dependent variable consisted of two categories: successful of not successful. Therefore, logistic regression was used to derive a function from these data that predicts the probability of a successful outcome, based on just a small number of predictors. It should be noted that a regression model does not prove causal relationships between variables, but highlights relationships between variables that can work in two directions.

The regression function for the dataset from chapter 8 can be written as (for an explanation see appendix IX):

$$p(y)=\frac{1}{1+e^{-(-2.679+0.422\cdot X_{1n}+1.275\cdot X_{1p}+0.662\cdot X_{2n}+1.18\cdot X_{2p}+0.295\cdot X_{3n}+1.892\cdot X_{3p})}}$$

With:
p(y)= probability of a successful project regarding structural safety
X1n= neutral assessment of the factor risk analysis
X1p= positive assessment of the factor risk analysis
X2n= neutral assessment of the factor control
X2p= positive assessment of the factor control
X3n= neutral assessment of the factor collaboration
X3p= positive assessment of the factor collaboration
X1 to X3 are dummy variables. The reference is a negative assessment of the particular indicator. They have a dichotom value 0 (not given) or 1 (given)

A project participant has to assess the quality of risk analysis, control and collaboration. Imagine the situation that a project participant agrees that risk analysis and control can be regarded as good, whereas collaboration is assessed as neutral. This can be translated in: X1p=1, X2p=1, X3n=1 where the other predictors are 0. Using these values within the function leads to p(y)=52%, which indicates that the estimated percentage that the project will be successful regarding structural safety is 52%.

A project that scores negatively on the three factors has an estimated probability of less than 20% of being a successful project, whereas a project that scores positively on all three factors has an estimated probability of success of over 80%. The influence of collaboration appears to be the most determining for the outcome.

This model, with only the factors collaboration, risk analysis and control, can predict a successful project correctly in 85% of cases and a less successful project correctly in 74% of cases in the sample that was used. This means that, based on the assessment of three variables of a case, the function correctly predicts if a project assessed in the national survey had been regarded as a successful or less successful project.

Not all critical factors are included in this function, because the limited dataset will not allow for too many variables to be reliably included (see appendix IX). It is possible that from strongly correlated predictors, just one has been included in the logistic regression function.

The method gives a quick indication of the degree to which problems regarding structural safety are to be expected. It is easy to use the derived formula; application in an app is possible. However, this method has also some limitations.

10.4.2 Limitations of the method

First, not all variance is explained by the formula. Nagelkerke's r^2, which is a pseudo measure for the amount of explained variance, is 0.464 for the derived model, while it might be 1.0 in an ideal situation. This means that about half of the variance that distinguishes a less successful project from a successful project is not explained by the model.
In addition, due to a lack of data in some categories, the positively valued factors with a value '4' or '5' were combined in one factor; and a similar combination was made for the values '1' and '2'. This reduces refinement of the predictions.
Furthermore, every variable in the function has a confidence interval, which means that the predicted values have no absolute values.
Moreover, this formula does not include project characteristics, which might influence the relevance of various factors.
Finally, the predictors in the function (presence of control, quality of collaboration) are broadly defined and interpretation will depend on subjective perception.

10.4.3 Opportunities of the method

However, this tool has the potential to develop into a useful risk management tool. Projects can be assessed on the variables in the function, and an indication of the probability of success can be provided. In future studies, data on project characteristics can be included and more cases can be collected. By constantly updating the logistic regression function with new data, the model will get learning capacity and the value of the coefficients can be updated.
In addition, it is recommended to refine the assessment of the predictors. For instance it is possible for the predictor control, to make a distinction in the percentage of invested time for self checking, checking by a colleague or third party checking.

A second opportunity is to develop a certification system for structural safety, like BREEAM for sustainability, where clients can get an impression of the quality of the product. This might give added value to a project, just as is the case with projects with high BREEAM scores for sustainable performance. To develop a certification system, data sources of failure databases, surveys and additional expert judgement are necessary to evaluate the various factors. The acquired data might also be useful for the suggested HRA model in subsection 10.3.1. Further details of this method are presented in appendix IX.

10.5 Opportunities of CATS and resilience engineering

De Haan's method assumes linear relationships between underlying factors (CPCs) and human error probabilities. However, the deterministic relationship between underlying factors and human error probabilities may be questioned, because this relationship is expected to be more complicated. Within safety science the CATS (Causal model for Air Transport Safety model) includes underlying factors in a more sophisticated way. This model has been developed for the Dutch Ministry of Transport and Waterworks with the aim to quantify the risk of air traffic and to support the development of measures and methods to reduce these risks. This method first developed a model with Event Sequence Diagrams (ESDs are typical ways an accident can or cannot happen), Fault Trees (FT represent technical failures and human errors) and Bayesian Belief Nets (BBNs represent human response models which are influenced by management models) (Ale, Bellamy et al. 2009). BBN is a graphical, probabilistic representation with nodes and arcs. The nodes represent variables and the arcs represent relationships between the variables. Probability tables are provided which represent the probability of a state of a variable. With these BBNs it is possible to combine underlying factors and their dependencies and use distributions rather than point estimates. However, data of these distributions are usually not easy to collect, although methods are available which improve the reliability of the estimates, like paired comparison. For more information on the quantification of management influences within aviation, see Lin (2011).
Linear causal relationships in event chain models, as assumed in chapter 4 between human error and failure and in De Haan's model between underlying factors and human error probabilities, are currently heavily questioned by persons who promote resilience engineering. Leveson (2009, p. 16) lists four main areas of criticism on these models: 'the requirement of direct causality, subjectivity in selecting the events to include, subjectivity in identifying chaining conditions, and exclusion of systemic factors'.

Resilience engineering tries to find an appropriate answer to the mentioned draw-backs of current approaches by taking the complexity of real life into account. The essence of resilience is nicely formulated by Wildavsky: 'The mode of resilience is based on the assumption that unexpected trouble is ubiquitous and unpredictable; and thus accurate advance information on how to get out of it is in short supply. To learn from error (as opposed to avoiding error altogether) and to implement that learning through fast negative feedback, which dampens oscillations, are at the forefront of operating resiliently' (cited by Weick and Sutcliffe 2007 (2001), p. 69).

The criticism of resilient engineering on traditional approaches, like De Haan's model, often makes sense, but it currently does not deliver a practical approach for including human factors in structural analysis. However, attempts are made with for instance Functional Resonance Analysis Method - FRAM (Hollnagel 2012). This method assumes variability in the outcomes of human activities. This variability might lead to positive or negative outcomes. When various activities together have a negative variability, this might lead to resonance and might lead to failure. Although this basic idea is interesting, resilience engineering currently has not produced instruments to quantify this method for the building process.

10.6 Conclusion

The current Eurocode framework is generally resulting in safe structures, with regard to the number of fatalities. However, human and organizational factors are not adequately included. Furthermore, the two-way approach with structural reliability calculations and quality management are almost independent of each other.

It is recommended to provide more guidance on risk analysis and control within current Eurocode. Attention to the other critical factors can be included in non-legal regulations, because they are sometimes hard to operationalize or the differences in building practices of various countries are too large to include them in Eurocode.

Two methods to combine human and organizational performance with structural performance were discussed in this chapter. These methods proved to be promising and useful, although currently they are still immature.

The quantification of management influences in building industries is beyond the scope of this thesis. However, for future research, development of the suggested methods deserves attention. Furthermore, it would be useful to explore the opportunities of FRAM and BBNs for including management influences within structural engineering.

11

Conclusions and recommendations

11.1 Introduction

The main research question of this thesis was: 'What factors in the design and construction process need improvement with regard to structural safety in the Netherlands?' This chapter will highlight the main outcomes of the three parts of this thesis and will provide an answer to the main research question.

The setup of this chapter is as follows. In section 11.2 the main conclusions from part I and II will be presented. In section 11.3 the main recommendations for building industry as suggested in part III of this study will be highlighted. Subsequently, an evaluation of the validity of the outcomes will be presented and recommendations for future research will be listed.

11.2 Conclusions

From the analysis of 741 structural incidents in the Netherlands it was concluded that the current Eurocode approach results in an acceptable level of structural safety, with regard to the number of fatalities among residents. However, the amount of failure costs, which is estimated at about 10% of the yearly turnover is regarded as unacceptable (chapter 4).

In addition, from the analysis of incidents it was concluded that about 80-85% of the structural failures were caused by human errors within design or construction process and about 5% by human errors during use (chapter 4). The approximately 10% of structural failures not related to human errors can predominantly be attributed to material deficits and force majeure.

The occurrence of human errors in design and construction process can be induced by underlying factors. Underlying factors can manifest themselves on macro level (building sector), meso level (company or project) or micro level (individual persons, chapter 5).

The answer to the main research question has been provided on macro level, with main observed threats (chapter 6), and on meso and micro levels, with the derivation of critical factors (chapter 8). Critical factors are those few key areas of activity, in which favourable results are absolutely necessary for a particular manager to assure structural safety.

Main observed threats
From literature it appeared that especially cultural factors within the Dutch building industry are expected to negatively influence structural safety. The main observed threats are a focus on lowest price, fragmentation, reactive and anti-authoritative culture.
In addition, although the level of technical knowledge within the Netherlands is well developed, the knowledge infrastructure within the Netherlands is fragmented. Therefore, it is not always easy to retrieve relevant knowledge for specific projects from the total available amount of knowledge. Furthermore, it was concluded that in the current situation the legal position of clients can be improved (chapter 6).

Critical factors for structural safety
From a national survey it was concluded that in the current situation the following factors on project level are critical for structural safety:
- safety culture
- allocation of responsibilities
- risk management
- control
- communication and collaboration
- knowledge infrastructure

These factors, that are especially relevant for larger projects, might be influenced by the main observed threats (chapter 8).

11.3 Recommendations: measures for improvement
Some specific measures are suggested which are deemed necessary to improve the critical factors for structural safety within Dutch building industry. The relationships with the critical factors are explained in chapter 9.

Various recommendations for the building industry were listed in table 9.1. These recommendations can be allocated to the following actors.

For Dutch government, together with the sector, the following recommendations follow from the study:
- Pay more attention to technical knowledge in higher education
- Support a central organization for structural safety
- Make failure reporting mandatory
- Shift accountability from client to advisors and contractors
- Impose an extensive risk analysis for CC3 structures, and a light version for CC2 structures
- Provide more guidance on risk analysis in codes
- Enforce independent checking of design and execution for CC3

For clients and project management the following recommendations have been made:

- Pay attention to suitable contracts. Do not accept too low liabilities. Make a clear and full allocation of responsibilities in the contract. Provide insight in the content of the tasks according to the contracts, to the various members of the project team. Limit the number of subcontractors. Appoint a certified engineer of record
- Provide sufficient budget and tender on price and value
- Consider integrated contracts or chain integration
- Consider standardization and/or prefabrication
- Invest in the design and construction team to create mutual trust and improve collaboration. Select an adequate group of team members suitable for the type of project
- Find ways to perform adequate risk management for process as well as product
- Make knowledge available within an organization. Stimulate BIM and clash detection to improve coordination
- Arrange a design review by a contractor and a site engineer during construction for CC3 structures

To management of companies the next recommendations will apply:

- Select the right persons to do the project work
- Stimulate a positive safety attitude. Consider an assessment system for assuring structural safety within the process
- Respond adequately on warnings
- Apply suitable control: everyone has the right to be controlled
- Make knowledge available within the organization and facilitate lifelong learning

For the Eurocode the following recommendations are made, based on subsections:

- Maintain the current 2-way approach with reliability calculations in combination with quality management
- A full probabilistic approach which includes robustness and human error with reliable results is currently not available and might be far away. However, future research on this topic is recommended (see 11.5)
- Make risk analysis for CC3 mandatory, advise a light qualitative version for CC2
- Provide more guidance on risk analysis in codes, introduce levels of risk analysis
- Provide a more detailed description of adequate control, like the content of self checking and independent review

In general, it was concluded that procedures and measures for improvement are available, but actual implementation within the projects deserves attention.

11.4 Discussion

In the following subsections the reliability and validity of the research will be discussed. In addition, limitations of the study will be listed and contributions to science and building industry will be highlighted.

11.4.1 Reliability and validity of the research

For scientific research it is necessary to aim at reliability and validity of the research results. Reliability means that if the study would be replicated under the same conditions, the same results should be obtained. Validity includes that the research adequately measured what was intended (see: Yin (2009)).

Reliability

For the analysis of failure cases in Cobouw and Storybuilder this topic was of major concern (chapter 4, appendix II and III). Reliability issues were addressed in these failure investigations. First, by using well defined search terms for finding relevant cases. Second, by analysis in conformity with a procedure with defined aspects with limited choice options. Third, by storing the data digitally, thus making a repetition of the analysis possible. And finally, by comparing the analysis with the results from other studies and by checking the method and results by other persons.

However, from failure investigations it is known that several experts might come to various explanations for causes of an accident, even if the accident is well reported. This means that these analyses are subjective by definition. The reliability of the analysis of Cobouw data was expected to be lower compared to the analysis of ABC registration and Dutch case law, because of poor data in some cases and limited checking of the analysis (see chapter 4).

For the national survey it is expected that a replication of the study in a similar response group would yield the same outcomes, because the survey had been tested beforehand and was found to be clear and coherent, and because a relatively large number of respondents was obtained (over 200).

Validity

For validity three types are distinguished: construct validity, internal validity and external validity (Yin 2009, p. 40).

Construct validity is assured if the operational variable actually measures the investigated construct. In this thesis construct validity is an issue of concern, especially for the national survey. The dependent variable structural safety is difficult to operationalize, because if a structure does not show damage, this does not mean it is safe. On the other hand, even if a structure collapses, it is theoretically possible that it should have been regarded as safe, when the risk was found to be within acceptable limits.

For the survey, structural safety had to be operationalized and it was defined as: the confidence of respondents that no structural damage had occurred and that there were no (hidden) design and construction errors. It is unavoidable that subjective interpretations of this variable were made. However, the subjectivity was limited by providing respondents with a formal definition of structural safety (structurally safe is when a structure is adequately able to deal with all forces affecting it during its reference period). The influence of subjectiveness was reduced by focusing on the difference between a successful and less successful project. For the assessment of structural safety, the difference in safety of both projects was essential. If a person tended to be negative in the assessment of structural safety, this would appear for both situations.

The independent variables of the survey had a similar problem regarding construct validity. Every respondent might have his own interpretation of the variables 'communication' or 'control procedures'. For some variables, which were perceived as less clear - like safety culture - brief definitions ('the tendency of an organization to pay profound attention to structural safety') or explanations were provided. It was expected that giving a long list of definitions would have annoyed the respondents and had made them quit the questionnaire or, at the least, skip the definition part. Control questions, where similar assessment was asked with other wording, have not been provided, because the questionnaire was already quite long.

Internal validity questions whether the study results allow further interpretation. Usually, this concern focuses on the perceived causal relations: are presumed causal relationships that have been found in the study actually caused by the intended factors? Because structural safety is a multifaceted concept, there are various process factors that actually influence structural safety of the product. By collecting a reasonable number of responses in the survey, statistically significant relationships of various variables could be determined. However, statistics offer the possibility to investigate relationships, although these relationships are not necessarily causal. Because the outcomes of the survey were recognized by experts from building industry, a causal relationship was supposed, to be able to suggest possible measures in chapter 9.

External validity has to do with the possibility of generalization of the results of a study. This study was using a theoretical framework, based on literature from safety science and project management, which was tested by literature study, failure case studies and by a survey. By performing a survey with 226 completed responses, statistically significant conclusions could be drawn. Limited generalization therefore is possible.
The respondents, who were involved in the survey, primarily worked for larger companies, which are usually involved in larger projects. It is believed that the outcomes of the critical factors are especially applicable for larger building projects with at least five parties involved. In chapter 8 it was stated that project characteristics might influence the relative importance of the main influencing factors, although the main critical factors are expected to stay similar.
The critical factors are specifically derived for the Dutch building industry, although it appeared that other countries' building industries have to deal with similar issues (see section 8.5).

Triangulation
In this study *triangulation* (Yin 2009, p. 116) has been used to enhance validity. Triangulation means that several different methods have been used and the results obtained with the different methods have been compared for similarity.
First, *data triangulation* was used by including various data sources. For the failure studies (chapter 4) data from Cobouw, Dutch case law and ABC registration was used and compared with data from Storybuilder. For the theoretical framework (chapter 5), literature was used from safety science and management. For the survey (chapter 8), data was collected from 226 respondents, resulting in information on more than 400 building projects. In addition, in the survey analysis, data was used from delivered projects (delta approach) and compared with the opinion of experts (direct judgement). Finally, the results of the survey were discussed with an expert panel from building industry. The outcomes pointed in the same direction.

Second, *investigator triangulation* was used. For instance in the analysis of the Cobouw cases, many cases were checked by a second person and the results were compared with an analysis from TNO (Netherlands Organisation for Applied Scientific Research) on comparable cases. In the survey, the analysis was checked by a second person and the overall results were discussed with an experienced group of building professionals and in four interviews.

Third, *methodological triangulation* has been used by using qualitative methods (theoretical framework and the calibration of it for the Dutch situation in the building industry by literature study and case studies) and quantitative methods (survey with statistical analysis). In addition, for the statistical analysis, two methods were used: the delta approach and the direct judgement approach, which lead to similar results.

It can be concluded that, although the study has some limitations, reliability and validity issues have been addressed.

11.4.2 Limitations of the current research
The research has some limitations, which are partly a result of the selected aim.
First, a primary focus on non-structural factors was chosen, while structural measures, like alternative load paths, undoubtedly deserve attention.

Second, the primary focus was on the situation in the Netherlands and it was concluded that the derived critical factors were especially suitable for projects with several project partners.

Third, macro level factors which might threaten structural safety have been observed. However, it was not the focus of this study to validate these observations. This could have been done by a thorough investigation of macro level factors, from literature, observa-

tions, interviews or surveys, but was beyond the scope of this research.
Fourth, in the analyses of Cobouw and other failure databases causal linear relationships have been assumed between human actions and structural performance. In part II of this study a relationship between underlying factors and structural performance is assumed, although this relationship is not necessarily linear. These linear relationships are currently heavily questioned (see section 10.5).

11.4.3 Scientific and practical contribution
This study is an applied research, which is based on theories from safety science and project management. It aims at contributing to scientific knowledge as well as to practical applicability.

First, by the thorough comparison of three failure databases and the additional research on the Storybuilder database, figures for the order of magnitude for individual risk could be derived, and it could be proved that currently the number of fatalities due to structural failures is within (questionable) limits, especially among residential users.

Furthermore, this research showed that there are various reasons to pay attention to structural safety and to improve the current situation with a high level of failure costs, ranging from personal attitude to shareholders value (see section 9.3). These reasons can be used as incentives to motivate other people in the building industry to pay attention to structural safety.

Third, this study delivers a theoretical framework for underlying factors, which can be used for failure investigations and comparison of failure investigations. Especially, for underlying factors, current investigations used incomparable lists (see chapter 4.)
In addition, the theoretical framework can be used for a risk analysis of the building process of a specific project. The questions as used in the questionnaire (see appendix VII) can be used to compare the evaluation of a project with the existing evaluations.

One of the major contributions of this study is the derivation of the critical factors in the current building industry. Several of them have been mentioned before, but no earlier studies have been based on the experiences of over 400 projects. Although the factors are still broadly defined, these outcomes have been accepted with enthusiasm. VNConstructeurs (in English: Association for Dutch structural engineers), Bouwend Nederland (in English: Dutch association for contractors) and Platform Structural Safety stated on their websites and in newspapers that they were glad with the results of the research, resulting in the derivation of critical factors.

Furthermore, implementation of the suggested measures in chapter 9 is expected to contribute to actual improvement of the current building practice regarding structural safety.

Moreover, at the end of this study some ways of including human and organizational factors in reliability analysis are suggested, which can be starting points for relevant future research.

Finally, attention to the topic of structural safety in general will improve awareness. This PhD study, together with presentations, contributions to committees, scientific publications and media attention has resulted in a considerable amount of attention to structural safety, thus, increasing awareness.

11.5 Future research

This PhD-thesis covers various aspects influencing structural safety to a limited extent. Further research is advised on the following topics:

- Best practices related to safety management from other safety related industries which are applicable within the building industry
- Best practices related to safety management from other building industries which are applicable within Dutch building industry
- The influence of various forms of collaboration and contracts on structural safety
- A typology of warnings of the structure and within the process and ways to adequately address them
- The effectiveness of ISO 9001 certification for structural safety. It is hypothesized that this is effective, because the main problems are not on company level (for which the certification is applicable) but on project level, although the general attitude towards certification is sceptical.
- Opportunities for certification similar to ISO 9001 on project level.
- A combination of structural risk analysis of the process and of the product. Risk analysis of the process can make use of the theoretical framework of this study. Risk analysis of the product can make use of outcomes of failure databases.
- The effectiveness of various types of control for error reduction in structural engineering (self control, overview control, independent review)
- Measurable aspects of the critical factors which can be used for a risk assessment tool of the process (see chapter 10)
- Cost benefit analysis of measures, where the costs of measures to improve structural safety are related to the accompanying reduction of risk
- Development of ways to combine human and organizational factors with structural performance. State of the art ways of modeling like CATS and FRAM could be explored for the building industry
- Development of tools to include underlying factors in failure investigations

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Appendices

Appendix I: List of definitions

Allocation of responsibilities: the amount or share of responsibility that is given to a person or organization. A good allocation of responsibilities includes a project organization suited to size, complexity and urgency of a project with a clear and suitable assignment of responsibilities (5.3.4).

Attitude: someone's opinions or feelings about something. In this study a positive attitude is regarded as a constructive position and commitment towards safety by the various participants of the project (5.3.5).

Collaboration: the way various project partners cooperate with each other (5.3.4).

Communication: exchange of information within a company or between the various project partners (5.3.4).

Complexity of the building process: the extent to which the design and construction process is regarded to have a complicated nature (5.3.3).

Complexity of the project: the extent to which the design and final appearance of the building or structure is regarded to have a complicated nature (5.3.3).

Construction phase: phase in which the elements of the structure are produced and the structure itself is assembled (related to 3.2.4).

Control mechanisms: ways to keep something at the right level/limit. In this study the focus will be on the way checking is performed (5.3.4).

Critical factors for structural safety: those few key areas of activity, in which favourable results are absolutely necessary for a particular manager to assure structural safety. Operationalized by: a process factor that showed the largest difference in presence in successful and less successful projects and that was regarded by respondents as most important to assure structural safety (1.2.1 and 1.3).

Culture: the collective mental programming that distinguishes between the members of a group or category and other members (5.3.2).

Design phase: phase in which the structure is designed and calculated. The result is a technical design with specifications (tender documents, 3.2.3).

Detailed engineering phase: phase between design and construction, in which the structural design is elaborated to suit the needs for construction (3.2.3).

Economic factors: factors related to the current state of the economy (recession or boom), inflation, interest rate variations, exchange rate fluctuations, current state of the market (available supply of labour, materials, equipment and level of competition) and tax level (5.3.2).

Error of commission: incorrect performance of a task (3.3.2).

Error of omission: failure to perform a task (3.3.2).

General factors: project characteristics, soil conditions and extra requirements by government (after 8.3.4).

Hazard: an unusual and severe event or something with the potential to harm (2.2.1).

Human error: a departure from acceptable or desired practice on part of an individual that can result in unacceptable or undesired results. Human errors can be made on operational level or on management level (3.3.1).

Insufficient functionality: manifestation of structural failure, which might take the form of insufficient water tightness, too large deformations, unacceptable aesthetical cracks or deprivation (3.4).

Instruments: the provided tools (software or equipment) that are necessary to perform the tasks properly (5.3.4).

Knowledge infrastructure: presence and availability of technical as well as process knowledge of relevant solutions (5.3.4).

Latent failure: the situation where a structure cannot fulfil the specified requirements, but no damage has occurred yet (3.4).

Legal factors: the entirety of laws and rules issued by the government to assure structural safety (5.3.2).

Less successful project: according to persons involved structural safety was assured to a lesser extent and during the building process or after delivery a relatively large number of hazards was observed. Damage was present, or could have easily arisen (8.2.1).

Macro level factors: factors on sector or country level (5.3.1). Alternative name: external factors.

Management skills: the skills to lead oneself and others (5.3.5).

Material deterioration: manifestation of structural failure. Degradation of the material, which leads to reduced performance over time and could lead to structural damage and/or reduced lifetime if no measures would be taken (3.4).

Mental resilience: the way in which an individual can cope with stress (5.3.5).

Meso level factors: factors on project or company level. Project characteristics are included in this level (5.3.1).

Micro level factors: human factors (5.3.1).

Mistakes: deficiencies or failures in the judgmental and/or inferential processes involved in the selection of an objective or in the specification of the means to achieve it, irrespective of whether or not the actions directed by the decision-scheme run according to plan (3.3.2).

Near miss: the situation where a latent failure has been detected and corrected or where a design error has been detected and corrected before a structure was constructed (3.4).

Phase within the building process: a limited period between the initiation of the project and the delivery of the structure (5.3.3).

Physical factors: the natural circumstances of a location, such as the ground conditions, groundwater level (fluctuations), climate (temperature, humidity, wind, rain), existence of earthquakes and organic situation (deterioration by insects or micro-organisms) (5.3.2).

Physical resilience: the way in which an individual can cope with long term and heavy physical loading (5.3.5).

Planning and budget: the amount of available hours and budget to deliver a product (5.3.4).

Project: a unique process, consisting of a set of coordinated and controlled activities with start and finish dates, undertaken to achieve an objective conforming to specific requirements, including the constraints of time, cost and resources (3.2.1).

Protocols: the rules describing the way tasks should be performed (5.3.4).

Quality assurance: part of quality management that is focused on providing confidence that quality requirements will be fulfilled (2.4.1).

Quality control: the operational techniques and activities that are used to fulfil requirements for quality (2.4.1).

Quality management: the coordinated activities to direct and control an organization with regard to quality (2.4.1).

Quality: the degree to which a set of inherent characteristics fulfils requirements (2.4.1).

Reliability: the ability of a structure or a structural member to fulfil the specified requirements, including the design working life, for which it has been designed (2.3.1).

Risk: the function of the probability and the consequences (2.2.1) or: the likelihood that a hazard will be realized and the consequence should it do so (2.2.1).

Risk analysis and allocation: the identification and assignment of risks, associated with structural safety of the building product and the building process (5.3.4).

Robustness: the ability of a structure to withstand events like fire, explosions, impact or the consequences of human error, without being damaged to an extent disproportionate to the original cause (2.3.2).

Safety: a state in which te risk of harm (to persons) or damage is limited to an acceptable level. It is usually associated with the freedom from personal harm (2.2.3)

Safety culture: the total of practices, conventions and habits that affect the way the organization is dealing with risks (5.3.4).

Safety goals: objectives with regard to structural safety (5.3.4).

Slips/lapses: errors which result from failure in the execution and/or storage stage of an action sequence, regardless of whether or not the plan which guided them was adequate to achieve its objective (3.3.2).

Social-communicative skills: the abilities with regard to interpersonal communication (5.3.5).

Socio-political factors: factors related to political or religious movements, political conditions and public opinion (5.3.2).

Structural accident: structural failure with fatalities and/or injuries (Appendix V).

Structural damage: category of structural failure. Visible deprivations of the structure, like cracks or insufficient integrity, which could lead to collapse if no adequate measures would be taken (3.4).

Structural collapse: category of structural failure. (Sudden) breakdown of a structure due to insufficient strength or stability (3.4).

Structural failure: the inability of a structure or a structural member to fulfil the specified requirements. It is associated with exceedance of the resistance of (part of) a structure by the effect of the loads and it might take the form of a (partial) collapse, structural damage, material deterioration, insufficient functionality or no damage (2.3.1 and 3.4).

Structural incident: a near miss or a failure (4.1).

Structural safety: the absence of unacceptable risk associated with failure of (part of) a structure (2.2.3).

Successful project: according to persons involved, structural safety is well assured and during the building process a relatively small amount of structural hazards was existent. In a successful project no damage has been observed or incidents for which measures were necessary to avoid damage (8.2.1).

Tasks on knowledge based level: tasks in which different options are considered mentally and finally a sequence of actions is chosen in an unfamiliar situation (3.2.5).

Tasks on rule based level: tasks which can be performed in familiar situations based on known rules which previously proved to be successful (3.2.5).

Tasks on skill based level: tasks that can be carried out on routine by sub-conscious behaviour (3.2.5).

Technical competencies: demonstrated abilities to apply knowledge and skills for the design and construction of a structure (5.3.5).

Technical factors: the current state of technology within a country, like available structural systems, building technologies, quality of materials, level of education and transfer of knowledge (5.3.2).

Underlying factors: aspects that might influence assurance of structural safety, which can take the form of resources or conditions, attributes or activities (3.3.4).

Work-as-actually done: the way an activity is actually performed (9.9).

Work-as-imagined: the way a task is intended, as usually described in procedures and protocols (9.9).

Working conditions: factors related to the influence of the environment on the performance of work (5.3.4).

Appendix II: Set up database Cobouw

In this appendix the starting points of the Cobouw database will be explained. This is a summary of chapter 2 in the Dutch report: "Verslag uitkomsten database constructieve incidenten in Cobouw 171212" K.C. Terwel, Delft University of Technology, Delft, 2012.

Searching and analysing process

Selection criteria
It was decided to select cases from the digital archive of Cobouw in the period 1993-2009. Those cases were selected in which the likelihood of failure or the actual failure of a structural element of a built structure (except dikes and roads) or a temporary structure that is used for the construction of a structure, potentially endangers people. Fire is not included. Monuments older than 50 years that are deteriorated are excluded.

Searching process
For the searching process 'key words' were used to select relevant cases in an iterative way. The searching process started with 11 initial key words, which were used to select cases. For the period June 2003-December 2003 an integral search was performed by reading all article-titles in the Cobouw and selecting the relevant ones. For a number of cases the initial key words were not adequate; 11 key words were added. This process was repeated. Finally, the results were compared with a similar database from TNO. Two key words were added. A final set of 25 key words was used to search the entire period from 1993-2009. The key words used are: "constructieve veiligheid, veiligheid, risico, ingestort, instorten, instorting, ongeval, bouwschade, schade, onveilig, gevel, betonrot, scheuren, verzakking, stutten, constructiefout, instortingsgevaar, incident, gestut, gevelplaten, scheurvorming, funderingspalen, instortte, oorzaak" and "voorzorg".

At the end the final results (395 cases) were compared with the results from the TNO database (230 cases). It appeared that 6 cases from TNO could not be selected with the key words. These cases were added to the final selection, resulting in 401 cases.

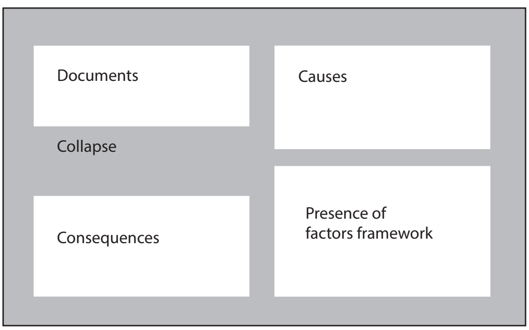
Reliability of the searching process and analysis
The results of the key words were compared with the results of integral searching of limited periods. In addition, the results were compared with the results of TNO's database. It appeared that this searching process has resulted in a higher number of cases than TNO's searching routine.

The analyses of the Cobouw database have been done by K.C. Terwel and H. Hendrikse. All cases that were analysed by H. Hendrikse (over 50%) have been checked by K.C. Terwel. A selection of the results of the analysis of the TU database have been compared with the analysis of the same cases in the TNO database. An inter-rater agreement was calculated, which indicates the extent of consensus between various judgements. The inter-rater agreement of 0.5-0.8 for the origin phase of the main cause represents some consensus, although it appeared that there were differences in analysis, which can possibly be explained by the assessment based on a relatively small amount of information. Finally, a selection of the outcomes of the Cobouw database was compared with the database of ABC registration and Dutch case law and the differences were explained (see chapter 4).

Technical set up of the database
Microsoft Access 2010 was used to set up the database. This software is convenient to link various modules and provides various opportunities for analysis with queries.

Input has been done with forms. The main form is "collapse", to which various subforms are added (documents, causes, consequences en validation). The main form has the function of a "dashboard" on which all relevant input for a case is compiled on a single screen (see fig. II.1)

The input fields of the forms are saved in tables with the same names.



Figuur II.1 *Schematic presentation of the dashboard "Collapse"*

The analysis was performed with queries. In these queries data from various input variables can be combined, resulting in numeric or graphic output. Some analyses have been done in Microsoft Excel 2010.

Bow-tie approach
For the modelling of occupational accidents often the concept of the bow-tie is used, for example in the Storybuilder-approach ((Aneziris 2008). Figure II.2 shows a generic bow-tie model for a structural failure, which can be used as a basis for the analysis of structural failures. Within this model the basic elements of the relationship between human errors and structural failure (as depicted in figure 3.5) are included.

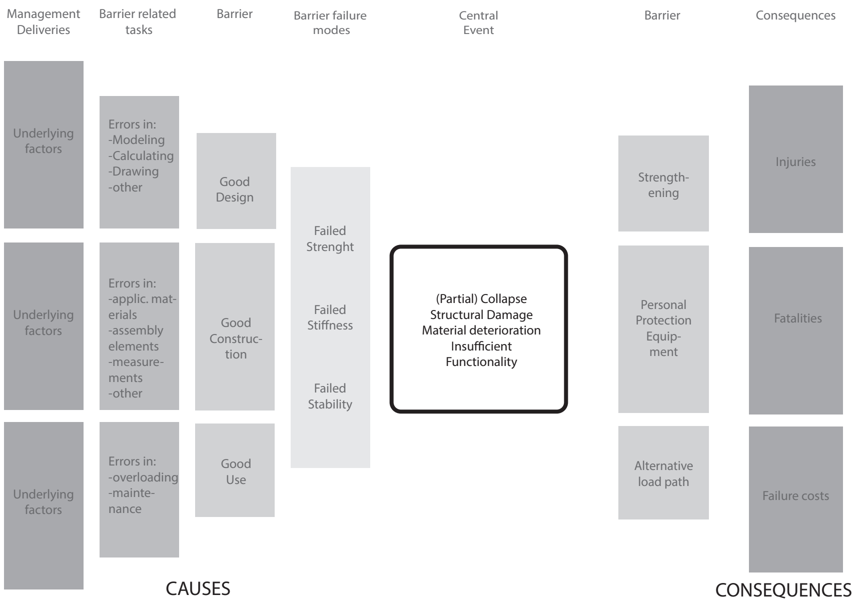


Fig. II.2 *Generic simplified bow-tie model for structural failures*

In a bow-tie model the central event is the incident, in this research a structural failure, with usually physical damage.
The failure might take the form of a (partial) collapse, structural damage, material deterioration or insufficient functionality (see section 3.4). In this figure structural failures without damage are not depicted.

On the left side of the bow-tie the causes leading to the failure are presented. On the right side the consequences are depicted. The bow-tie model makes uses of the hazard-barrier-target concept. A hazard is regarded as anything with the potential to cause harm (see subsection 2.2.1). The causing of harm might be prevented by barriers, which can be regarded as a physical entity (object, state, or condition) that acts as an obstacle in an accident path (Aneziris 2008). In process industry these barriers are often physical, like valves, warning lights, etc. However, when studying the building process, these barriers are usually immaterial, with a broader definition. The barriers in the building process can be regarded as good design, good construction and good use/maintenance (Priemus and Ale 2010).

When design, construction or use errors take place, these barriers might fail. Barrier failure modes might be insufficient strength, stiffness or stability. Barrier related tasks are the tasks that are necessary to place the barriers and keep them in good condition. Usually,

a distinction is made in Provide (specify and design technology or human tasks and procedures), Use (technology should function or humans should carry out defined actions), Monitor (check functioning of technology or people) and Maintain (restore function to the designed level) (Priemus and Ale 2010).
The focus in the current analysis will be on the Use tasks on operational level (like modelling, drawing, assembling), because the available failure cases will often not provide information on the other Barrier related tasks.

Underlying factors that might influence the performance of tasks can be included. Within the bow-tie approach these are called management deliveries, which are "the resources and commitments delivered by the management systems in place, through the tasks towards the technical system to enforce the barriers that prevent accidents and/or reduce their consequences" (Aneziris 2008). These management deliveries can be regarded as part of the underlying factors, although they are limited by Aneziris et al. to only eight factors:

1. plans & procedures
2. availability
3. competence
4. communication/collaboration
5. motivation/commitment
6. conflict resolution
7. ergonomics
8. equipment.

These factors are incomplete for the situation of structural safety, because they have been primarily derived for the process industry, focusing on occupational safety. Furthermore, they are neglecting contextual factors, like the legal situation or culture of a sector. In the theoretical framework of chapter 5 these factors will be included (see Ref 13 in chapter 5 which focuses on ARAMIS), but in the current Cobouw analysis these underlying factors will not be extensively studied, because of a lack of available information.

On the right side of the central event the consequences are depicted, which usually are presented as injuries, fatalities or failure costs (see section 3.5).

Data input fields
As a starting point for the database in 2009, the structure of an earlier database of TNO has been used (Dieteren and Waarts 2009; Terwel and Waarts 2010).
The categories were compared with the work of Schneider and Matousek (1976), Eldukair and Ayyub (1991), Wardhana and Hadipriono (2003), Fruehwald et al. (2007) ABCregistration from TNO (Nelisse and Dieteren 2009) and the database on Dutch case law from Wouter Boot (2010). Based on this comparison, a final categorization was selected (see appendix 1 of Terwel (2012).

Input fields Collapse
In this input field general information on the project and the type of damage are depicted. The following options are provided:

-Collapse ID: unique number in the database. This makes linking between the fields possible.

-Fldsource: source the description is based on. In addition to Cobouw newspaper articles, info was used from publicly available reports and other media.

-Reliability source: an indication of the reliability of the description is given based on the type of source and the number of articles. Classes of reliability:
- only newspaper articles with personal opinion: very low
- news paper article with opinion of expert: low
- various newspaper articles with opinions of experts: medium
- independent investigation report: high
- various independent investigation reports: very high

-Town: location where the incident happened

-Storeys: number of floors (1, 1-5, 5-10, >10)

-Involved parts: the parts that were damaged during the incident. This is not necessarily restricted to the element that collapsed or was the origin of collapse. The following options are given:

Foundation:
1. Piles
2. Foundation beam
3. Pile cap
4. Wall of building pit (sheet pile, auger pile wall, etc.)
5. Floor of building pit
6. Connections
7. Other

Main load bearing structure above foundation:
- Wall of basement
- Floor of basement
- Wall and floor of basement
- Columns
- Beams
- Floor elements

- Structural façades / walls
- Stability braces or core
- Columns, beams and floor elements
- Columns and beams
- Beams and floor elements
- Columns and floor elements
- Floor elements and walls
- Stability structure and walls
- Stability structure and floor elements
- Structural façades and floor elements
- Connections
- Other

For the comparison with the other databases a reduction of categories has been made.

-Project: concise description of the title of the project.

-Building type: description of the building type. A number of categories has been listed, based on the Dutch Building Decree. The main categories are:

1 Buildings
1.1 Residential
1.2 Meeting
1.3 Prison-like structures
1.4 Health
1.5 Industry
1.6 Office
1.7 Lodging
1.8 Education
1.9 Sports
1.10 Commercial
1.11 Other
1.12 Multifunctional

2 Structures not being buildings
2.1 Traffic (bridges, viaducts etc.)
2.2 Transport
2.3 Storage
2.4 Marketing
2.5 Industry
2.6 Partition (e.g. fences)
2.7 Utility (energy installations, water filtration, etc.)

3 Soil, hydraulic and road works
3.1 Road
3.2 Dikes
3.3 Hydraulic
3.4 Railroads
3.5 Airstrip

4 Other
4.1 Secondary structure (like scaffolding)
4.2 Temporary accommodation
4.3 Building pit

In chapter 4 it was decided to make a main categorization in buildings, civil structures and other structures. Bridges, viaducts and tunnels were included in civil structures, together with soil, hydraulic and road works.

-Owner: owner of the structure. Newspapers often do not provide this information.

-Flduser: User, sometimes the same party as the owner.

-People: other relevant actors mentioned in the sources.

-Materials: the materials that were involved in the incident, with a special focus on the materials of the damaged elements. The options are:
1. Concrete
2. Reinforcement in concrete
3. Steel/metal
4. Steel-concrete structure
5. Timber
6. Glass
7. Masonry
8. Lime sandstone
9. Other

-Description: description according to the sources used.

-Research: investigators of the incident

-Status: the current status of the structure. This partially overlaps with "consequences".

-FaseDiscovery: Phase in which the damage/incident was discovered. Options:

1. Design (Preliminary and Detailed, 'VO+DO' in Dutch)
2. Detailed Engineering (Technical design and Construction-ready design)
3. Construction
4. Use (and asset management, maintenance and renovation)
5. Extensions
6. Demolition
0. Unknown

In the classification of the main thesis (see chapter 3) it was decided to include technical design in the design phase. However, this does not lead to problems, because in the analysis of chapter 4 design and detailed design were combined.

-Fldyear: year of the incident

-Flddate: date of the incident

-Engineering: party responsible for the engineering

-RestParts: other relevant parties

-Damage: type of actually occurred damage (In Storybuilder terminology: Central event). Options:

1. (Partial) collapse
2. Structural damage: cracks in structure or incoherent structure, etc. that might lead to collapse without measures
3. Insufficient functionality (no watertightness, too large deflections, inacceptable aesthetical cracks or damage, settlements)
4. Material deterioration. Without repairs a decreased life span is expected
5. No consequences
6. Other

In the cases of insufficient functionality there should be an indication of unsafety to include the cases in the database.

-Load case: load case at the moment of the occurence of damage. Options:

- Permanent loads (dead load)
- Combination with live load of persons
- Combination with snow
- Combination with rain
- Combination with wind
- Accidental load: collision, explosion, fire

- Temperature load
- Time dependent load (shrinkage, creep)

-FldYearBuild: year in which the structure was delivered

-Project characteristics: the option is given to rate if the design was unusual, if many parties were involved (>10) and if there were many changes in the building process. These are indicators for project or process complexity.

-Warnings: the option is given to point out if warnings in the process (by persons, or earlier cases) or in the product (cracks, small deformations before final damage) were observed.

Input fields of Documents:
The next input fields are possible:

-Collapseid: unique code that links various forms
-Paper: name of the source, always a Cobouw news article is included
-Issuedate: Issue date of the paper/article/report
-Issuetitle: Title of the publication
-Bestand: Name of the file. Starts with year of the case. Continues with unique number per case. Every publication that was used for the case receives a subnumber. For example: 2002/C045-01.pdf
-Link: in this field a hyperlink is added, by which the original source can be accessed directly.

Input fields of Causes:
The following input fields are provided:

-Collapseid: unique code that links various forms

-Technical cause (or likelihood of…) (In Storybuilder terminology: Barrier Failure Mode):
1. Failed element of the load bearing structure
2. Failed connection of the load bearing structure
3. Instability of the load bearing structure
4. Failed element of the secondary structure
5. Failed connection of the secondary structure
6. Instability of the secondary structure

-Faseorigin: Phase the origin of the case is ascribed to (In Storybuilder terminology: Failed Barrier). This might be a combination of phases. The following options are possible:
1. Design (Preliminary and Detailed, "VO+DO" in Dutch
2. Detailed Engineering (Technical design and Construction-ready design

3. Construction
4. Use (and asset management, maintenance and renovation)
5. Extensions
6. Demolition
0. Unknown
12. Design and detailed engineering
13. Design and construction
14. Design and use
23. Detailed engineering and construction
24. Detailed engineering and use
123. Design, detailed engineering and construction
124. Design, detailed engineering and use

Other combinations might be possible, but the current classification was adequate for analysis of the cases.

-Fasenotes: a brief summary of the causes can be given.

-Maincause: the most important direct cause of the damage. Often this is a type of human error. The following options are given:

1. Design error (including material failures when the wrong material was prescribed)
2. Construction error (including material failure when inferior quality was applied. If construction without a design, this is categorized as a construction error.
3. Use error
4. Combination
5. Other (new materials, force majeure)
6. Unknown

The focus is on failures in the primary process and not on underlying factors

-Secondcause: in addition to the direct cause sometimes further refinement is possible with a more specific cause. The options are explained in chapter 3 (In Storybuilder terminology: Barrier related tasks):

For design errors:
1.1 Incorrect modeling or calculation error
1.2 Incorrect dimensioning on drawings
1.3 Conflicting drawing and calculation
1.4 Absence of drawing and/or calculation
1.5 Other

For construction errors:
2.1 Incorrect quality of materials applied
2.2 Incorrect assembling of elements on the building site
2.3 Insufficient amount of material used
2.4 Erroneous measurements on the building site
2.5 Other

For use errors:
3.1 Higher load than in calculation
3.2 Insufficient inspection
3.3 Insufficient maintenance
3.4 Other

Input fields of Consequences
The following input fiels are provided:

-Collapseid: unique code that links various forms

-Deaths: number of fatalities due to the incident

-Injuries: number of injuries due to the incident

-Damage costs: direct damage in euro, caused by the incident

-Situation after damage: description of the situation after potential measures have been considered:

1. rebuild in conformity with original design
2. rebuild in conformity with changed/improved/renewed design
3. building closed
4. elements strengthened or improved
5. other

-Consequences for other parties: a description is given of law suits and bankruptcies after the incident

Finally, it was analysed to what extent underlying factors from the theoretical framework were present in the cases (in Storybuilder terminology: management deliveries). However, this did not lead to reliable results for the majority of cases, due to lack of information. This analysis is therefore not included in chapter 4. However, in chapter 7 this analysis has been performed for three well documented failure cases, not necessarily included in the Cobouw database.

Appendix III: Selection of scenarios from Storybuilder database

Search criteria:
All job related accidents caused by the failure of a (part of a) structure are selected. Permanent and final structures are selected. Secondary structures like fixed and mobile scaffolds, struts and fall through protections are included. Not included are ladders, moving parts of building lifts and finishing structures (like non-structural panels).

Selection of scenarios (bow-ties):

1.1.1 Fall from height: ladders & steps
Only those situations are included where the floor or supporting structure underneath the ladder fails (LCE243).

1.1.2 Fall from height: scaffolds
The following situations are included: losing of stability (LCE 177) and losing strength (LCE 350) of (parts of) the scaffold. Some specific modes are added to this selection: failing of floor or supporting structure (BFM 117), insufficient anchorage or fixation of scaffolding (BFM 147, failing structure at given load (BFM 320), insufficient strength of floor panels (6_IF284), failing fall protection (7_IF 317 and 7_IF 319).

1.1.3 Fall from height-roof/floor/platform
The situations where strength of the structure (LCE 135) fails due to a failing condition (2_BFM 134). In addition, failing of fall protection (3_BFM170) is included by breaking (3_IF203) or external load related to fall protection (3_IF 206).

1.1.4 Fall from height – hole in the ground
The situation where the strength of the protection/cover of a hole in the ground fails (LCE 132) is regarded.

1.1.5.3 Fall from height – other
The situation where someone falls from a height like a wall or mast is considered when strength of stability fails for:
-structures and buildings (ET1 21) or other structures/surfaces (ET1 40) and
-loss of strength (LCE 298) or
-stability support fails (LCE 363).

1.3 Fall down stairs or ramp
The next situations are considered: staircase loses connection, slides or collapses (LCE 55) and part of stairs lacks/fails (LCE 117, without the situation of lacking steps 2_IF 119).

3.2 Contact with falling objects – not cranes

The situations where the fallen objects are buildings, structures, surfaces or building materials (ET 206, 597, 620 or 796) are considered. Falls, with the falling objects falling from machines, vehicles, transport systems and other materials are not considered (ET1b 389, 414, 474, 537, 543, 545, 594). The initial state should be static (ET2a 332).
The following type of failures are considered: failing connections (BFM 908), failing strength (BFM 947, without situation of failing lift mechanism 978), insufficient strength supporting surface (5_IF 1093) and failing internal stability of a part of a structure (ET2a 327) due to removal of essential parts (3_IF 1016), collapse of lowest part (3_IF 1017) and insufficient strength underground (3_IF 1018). Not included are fall in wrong direction (BFM 1095) and incorrect timing of fall (BFM 1126).

4. Contact with flying/ejected objects

In this situation (parts of) buildings or large building materials (ET1 8, 51 or ESAW 204) are considered where the strength of the object failed (1_IF 342) or where the connection failed (2_BFM 343).

10. Buried in bulk mass

The situation with an insufficient supporting structure of failing stability of the underground is regarded (1_IF 200 or 4_IF 311).

Not included in the selection of bow-ties are:
1.1.5.1 Fall from height – moveable platform
1.1.5.2 Fall from height –non-moving vehicle
1.2 Fall on same level
2 Struck by moving vehicle
3 Contact with falling objects – cranes
5 Hit by rolling/sliding object or person
6 Contact with object used/carried
7 Contact with handheld tools operated by self
8.1 Contact with moving parts of machine
8.2 Contact with hanging/swinging objects
8.3 Trapped between
9 Moving into object
11 In or on moving vehicle with loss of control
12 Contact with electricity
13 Contact with hot or cold surfaces or open flame
14.1 LOC Open containments
14.2 Contact with hazardous substance without LOC
15 Loss of containment from normally closed containment
17 Fire
20.1 Human aggression

20.2 Animal behaviour
22.1 Hazardous atmosphere in confined space
22.2 Hazardous atmosphere through breathing apparatus
23 Impact by immersion of liquid
25 Extreme muscular exertion
26 Too rapid (de)compression
27 Explosion

Results:

Table III.1 *Fatalities due to structural failure of (part of) a structure 1998-2009*

	Number of cases building sector [all sectors]	Number of fatalities building sector [all sectors]
1.1.1 Fall from height-ladders & steps	34 [59]	1 [2]
1.1.2 Fall from heigt - scaffolds	265 [394]	8 [15]
1.1.3 Fall from height - roof/floor/ platform	194 [309]	8 [11]
1.1.4 Fall from height - hole in ground	8 [21]	0 [0]
1.1.5.3 Fall from height - other	21 [39]	0 [0]
1.3 Fall down stairs or ramp	6 [24]	0 [1]
3.2 Contact with falling objects - not cranes	186 [321]	27 [35]
4. Contact with flying/ejected objects	2 [9]	0 [0]
10. Buried by bulk mass	2 [3]	0 [0]
Total 1998-2009	*718 [1179]*	*44 [64]*
Average number per year	*60 [98]*	*3.7 [5.3]*

Appendix IV: Description of key publications regarding Critical Success Factors

Selection of following references was made by Favie (2010).

Ref. 2 (Ashley, Lurie et al. 1987) attempted to explain projects with better than expected results on cost, schedule, quality, safety and participant satisfaction. First, 2000 possible factors were reduced to 46 possible influencing factors in the categories: 1. Management, organization and communication, 2. Scope and planning, 3. Controls, 4. Environmental, Economic, Political and Social, 5. Technical. Eight companies were asked to rate an average and an outstanding project on these 46 factors. The results were statistically analyzed.

Ref. 3 (Belassi and Tukel 1996) developed a framework with factors related to the project, the project manager and project team members, the organization and the external environment. A survey was conducted in the US to check if these factors were critical for the successful completion of a project with regard to cost, time, quality and client satisfaction. A response of 57 was achieved from project managers from various industries. The results were statistically analyzed.

Ref. 4 (Chan, Ho et al. 2001) derived 31 factors contributing to the success of D&B projects from a review of empirical studies and opinions of D&B practitioners. A survey with questionnaires was performed on public D&B projects in Hong Kong, resulting in a response of 53. Respondents were requested to rate the project success factors on a 5-point Likert scale. The results were statistically analyzed.

Ref. 5 (Chua, Kog et al. 1999) abstracted possible factors from previous studies and arranged them in the categories: project characteristics, contractual arrangements, project participation and interactive processes. The success objectives were divided in budget performance, schedule performance and quality performance. A questionnaire was set up and 20 experienced practitioners in Singapore were willing to participate. The data were statistically analyzed.

Ref. 6 (Jaselskis and Ashley 1991) developed a database with 34 average and 41 outstanding projects regarding overall project success, better-than expected schedule performance and better-than expected budget performance. The study highlights the results of the influence of the project team, project planning effort and project control effort. Based on the same data, a budget performance model of building projects was built with neural networks by Chua, Loh et al. (1997).

Ref. 7 (Lam, Chan et al. 2008) held a survey among D&B participants in Hong Kong, with a result of 92 valid responses. Project success was regarded a function of time, cost, quality and functionality. The probable independent variables were categorized in 12 groups:

Competency of client, competency of construction team leader, effectiveness of project management action, competency of contractor's design consultants, working relationships among project team members, client's input in the project, project nature, client's emphasis on time and cost, application of innovative management approaches, client's emphasis on risk transfer, physical and social environments, economic environment. The participants were asked to evaluate factors affecting the performance of their projects and furthermore to rate their level of satisfaction. The results were statistically analyzed.

Ref. 8 (Ling 2004) operationalizes success into cost, time, quality and owner's satisfaction. Thirty two responses were collected on 42 projects in Singapore. Sixty explanatory variables were suggested in three categories: project characteristics, owner & project manager characteristics and contractor characteristics. Correlations between the explanatory variables and the success criteria were investigated.

Ref. 9 (Sanvido, Grobler et al. 1992) assume that success is meeting the expectations of the various project participants. These expectations may be different for every participant. Ten categories of success factors were developed: facility team, contracts/changes/obligations, facility experience, resources, products, product information, external, optimization information, performance information and external constraints. Eight pairs of successful and less successful projects were investigated on these factors. The results were statistically analyzed.

Ref. 10 (Songer and Molenaar 1997) developed six success criteria: on budget, on schedule, meets specification, in conformity with user's expectations, high quality of workmanship and minimizes construction aggravation. Fifteen possible influencing success factors (project characteristics) were suggested. A survey among public-sector representatives focusing on Design-Build projects was performed with a response of 88. Structured interviews were conducted to provide additional insight into the ordering of project characteristics. A weighed pairwise comparison was performed on the results of the interviews.

Ref. 11 (Favie 2010) investigated quality-audit outcomes in Dutch infrastructural Design-Build projects. Based on Ref. 2-10 he developed a framework were success was defined as compliance with the requirements. His initial framework consisted of supplier-related factors (company size, type and experience, tendering process), client-related factors (client's experience, understanding project scope, project management skills), project-related factors (complexity, size, time span and pressure, project type and phase, flexibility of scope, room for supplier's input, procurement related factors, new or common responsibility), external factors (technical environment, economic environment, traffic density during execution, problems with authorities) and state variables (capabilities regarding quality management, communication, technology, planning, finances, safety, coordination, risk management). Favie's data consisted of 5659 audit questions on civil engineering works. These were statistically analyzed on the correlation between input and state variables and output variables.

Appendix V: Selection of literature regarding structural safety in the Netherlands

The following sources regarding structural safety in the Netherlands have been consulted.

Dutch professional journals
For Dutch professional journal papers two series of articles are included. In 1997 magazine 'Cement' published the series 'De tikkende tijdbom onder bouw' (in English: 'A ticking time bomb underneath the building industry') (Vambersky and Sagel 1997a; Vambersky and Sagel 1997b; Vambersky and Sagel 1997c). In these often cited series it was argued that the Dutch building industry is suffering from structural flaws, such as a lack of coordination.
The second series of articles that are covered in the literature review is 'De 'juridische constructeur" (in English: 'Legal structural engineer) (Boot, Terwel et al. 2011; Boot, Terwel et al. 2012a; Boot, Terwel et al. 2012b). This often read series in magazine 'Cement' cover legal aspects within structural engineering and describe the role of legislation and insurance when a structural incident occurs.

Reports by Dutch government
VROM-inspectie (in English: Inspectorate of Housing, spatial planning and environment) is responsible for monitoring and assuring the quality of the environment. They published several research reports on for instance the collapse of flat roofs due to rain (Kool, Kolner et al. 2003) and snow (Kool and Schmidt 2006).
The general outcomes of these studies, together with the general vision on structural safety at that moment, were included in 'Castle or House of cards' (VROM-inspectie 2007). This report is the English translation of a problem analysis of the Dutch situation 'Kasteel of Kaartenhuis?' (in English: 'Castle or house of cards?') (VROM-inspectie 2007) and an accompanying action plan 'Weg met de zwakke schakels!'(in English: 'Eliminate the weak chains!') (VROM-inspectie 2008b).
Another study of VROM-inspectie was the investigation of 15 building projects on the assurance of structural safety (KplusV 2007; VROM-inspectie 2008a; Mans et al 2009). This study performed an assessment of the structural design and the actually built structure and combined it with an organizational assessment of the building process.
Furthermore, VROM-inspectie was involved in pilot projects for new forms of building regulations, but these are beyond the scope of this thesis.

Reports by Dutch professional organizations
Professional organizations in the Dutch building industry play an important role in determining a shared vision on structural safety. For structural engineers several organizations are existent: NLingenieurs (in English: Association for all engineers in the Netherlands, formerly known as ONRI) and Constructeursplatform (in English: Platform for Structural Engineers) which was transformed into VNConstructeurs (in English: Association for

Dutch Structural Engineers) in 2010. Specialized associations exist on e.g. steel (Bouwen met Staal (in English: Building in steel)) and concrete (Betonvereniging (in English: Concrete association)). Many contractors and suppliers are organized within Bouwend Nederland (in English: Dutch Association of Building Companies). Employees of building control have their own association in 'Vereniging Bouw- en Woningtoezicht Nederland' (in English: Dutch Association for Building Control). Project developers are allied in the NEPROM (in English: Association for Dutch Project Developers).

Together with the government, professional organizations launched a major initiative with the development of the Compendium aanpak constructieve veiligheid (in English: 'Compendium Strategy for Structural Safety') and its predecessor 'Plan van Aanpak Constructieve Veiligheid' (in English: 'Approach towards Structural Safety') (VROM-inspectie et al. 2006; Spekkink 2011). In this Compendium the responsibilities are listed for every building participant: the project developer or owner, the architect, the structural engineer, building control and the contractor. For every phase in the building process, project definition, conceptual design, definitive design, technical design, execution and use, the possible process risks and necessary tasks are presented.

NEPROM, the association for project developers, was not part of this initiative. They issued their own code of conduct for structural safety (NEPROM 2008). This code gives an overview of responsibilities of project developers with regard to structural safety and provides recommendations to assure structural safety.

Reports by Platform Structural Safety

The Committee Leren van instortingen (in English: Learning from collapses) was established in 2004 by CUR Bouw & Infra. In this committee representatives of a variety of building participants were involved. The goal of the committee was to support the structural safety of buildings in the Netherlands by:

-research on near misses and failures and their technical and non-technical causes
-open communication about causes and necessary measures.

The ultimate goal was a limitation of repetition of failures in a cost-effective way. In 2008 the Committee was transformed in the Platform on Structural Safety which aims at making structural safety common practice in the Netherlands. The Platform has issued some publications on structural safety.

First of all, the report 'Falende constructies' (in English: 'Failed structures') (CUR Bouw & Infra 2010a) was published in 2010. In this report 15 cases with structural failures are investigated on technical and non-technical causes. A similar report on geotechnical failures, 'Leren van geotechnisch falen' (in English: 'Learning from geotechnical failures') was published in 2010 by a committee of geotechnical experts (CUR Bouw & Infra 2010b).

In addition, the Platform initiated the confidential reporting system ABC registration on building mistakes, after some major incidents (see chapter 4). After this project had been running for about 3 years it was evaluated, resulting in an extensive report (CUR Bouw & Infra 2011; Terwel, Nelisse et al. 2012). The value of a reporting system was recognized, although practical implementation of derived knowledge was hard to achieve.

Furthermore, the Platform contributed to the book 'Leren van instortingen' (in English: 'Learning from collapses') (Van Herwijnen 2009). In this book contributing factors of structural safety are explained, 26 cases are investigated with a focus on technical causes and initiatives to improve structural safety in the Netherlands are listed.

Reports by Dutch Safety Board

The Onderzoeksraad voor Veiligheid (in English: Dutch Safety Board) was established in 2005 to investigate the (probable) causes of incidents and accidents (incidents with injuries and/ or fatalities) in all sectors of society. The objective of these investigations is to prevent repetition of similar incidents. The first report related to the building industry was on the safety of façade elements (Onderzoeksraad voor Veiligheid 2006). The report concluded that the safety of these elements is not satisfactory in the Netherlands, due to lack of coordination, control and inspection.

In 2008 the board presented a report on the collapse of a tower crane in Rotterdam, resulting in a fatality (Onderzoeksraad voor Veiligheid 2008). This report concluded that the safety of (temporary) cranes is not sufficiently assured within Dutch building industry.

In 2010 two reports were presented: one on the collapse of a floor during erection in Rotterdam (Onderzoeksraad voor Veiligheid 2012b) and one on the collapse of the roof of the stadium for FC Twente in Enschede during erection (Onderzoeksraad voor Veiligheid 2012a). Similar conclusions as in the report of façades were restated; the Dutch building industry suffered from fragmentation and a lack of coordination. Chapter 7 discusses the FC Twente and B-tower cases in more detail.

Peer reviewed papers

Swuste et al. (2012) performed an extensive literature review in the international repository of Delft University of Technology library on the causes and prevention of accidents in the building industry. Apart from a paper of the Dutch safety board on a crane incident (see reports Dutch Safety Board) only two of the reviewed papers appear to be relevant for the study of underlying factors of structural safety in the Netherlands. Most of the papers in the mentioned literature review are not focusing on the Netherlands and not on structural safety. Often the papers deal with construction safety, with a focus on the safety of labourers.

One of the selected papers is an analysis of a failure case with insufficient detailing of a concrete deck in Amsterdam and is included in this review (Priemus and Ale 2010). The other paper is about the project Storybuilder, a method with underlying factors to analyze construction incidents in the Netherlands (see chapter 4). A report on Storybuilder is included in the current review (Beek and Dijkshoorn 2011).

In addition to the study of Swuste et al., a leading Dutch journal on Building law (in Dutch: TBR) has been searched using the search term 'constructieve veiligheid' (in English: 'structural safety'). This led to a selection of four relevant papers. In 'Constructieve veiligheid in juridisch perspectief' (in English: Legal perspective on structural safety') (Gambon 2008) several legal aspects on structural safety are listed. 'Constructieve veiligheid van bouwwerken en het rapport commissie Dekker' (in English: 'Structural safety and the report of the Dekker committee') (Vambersky and Terwel 2009) warned for the threats of the promoted liberal philosophy that every activity that could do without involvement of the government, should be done by private parties. 'Constructieve schade – een analyse van oorzaken aan de hand van jurisprudentie' (in English: 'Structural damage – an analysis of causes based on jurisprudence') (Boot 2011b) presented outcomes of the analysis of 151 damage cases collected by Dutch case law. In addition, it elaborated on legal issues like the obligation to warn, which might influence structural safety.
The fourth paper from the Dutch journal on Building law focuses on the way in which communication within the building process can be improved, possibly with legal measures (Gulijk 2011).

Furthermore, some peer reviewed conference papers were included in the list.

The list is as follows:

- 'Trends in the Dutch building industry: potential threats for structural safety' (Terwel and Mans 2011) lists several observed threats for structural safety like inferior quality of education and increasing complexity of building projects and building processes.
- 'Learning from safety in other industries' (Terwel and Zwaard 2012) compares aviation, process industry and building industry on safety related issues. It concludes that the risks within the building industry are usual lower than in the other industries. However, the safety culture of the building industry is less developed than in the other industries.
- 'Comparison of structural performance of Dutch and Spanish Building industry' (Mendez Safont and Terwel 2012) compares the performance of Dutch and Spanish engineering companies. From a survey it appeared that smaller companies declared to spend more time on control, although their fees were usually lower.
- 'An initial survey of forensic engineering practices in some European countries and the USA' (Terwel et al. 2012) explains the way in which several countries deal with failure investigations and in which way failures are used as a learning lesson to improve the sector

Appendix VI: Presence of meso and micro level factors in selected literature

To investigate if the outcomes of the presence of meso and micro level factors in the three failure cases in chapter 7 have a broader applicability, the selection of literature from chapter 6 (see table 6.1) has been reviewed for the presence of these factors. The results are depicted in table VI.1.

Table VI.1 *Presence of meso and micro level factors in selected literature*

	Project characteristics			MESO												MICRO					
	Complexity of the project (19)	*Complexity of the building process (19)*	*Phase within the building process (12)*	*Safety goals (11)*	*Safety culture (11)*	*Allocation of responsibilities (21)*	*Risk management (15)*	*Control mechanisms (23)*	*Protocols (17)*	*Communication (24)*	*Collaboration (22)*	*Reasonable planning and budget (19)*	*Knowledge infrastructure (10)*	*Working conditions (5)*	*Instruments (12)*	*Technical Competencies (22)*	*Management skills (6)*	*Social-communicative skills (1)*	*Attitude (16)*	*Mental resilience (2)*	*Physical resilience (0)*
1		•				•		•		•	•	•				•			•	•	
2*						•		•		•	•				•	•					
3	•	•	•	•		•	•	•	•	•	•	•	•		•	•	•	•	•		
4	•	•		•	•	•	•	•	•	•	•	•	•		•	•			•	•	
5	•	•	•	•	•	•	•	•	•	•	•	•	•			•			•		
6	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•		•		
7	•	•	•	•		•	•	•	•	•	•	•				•					
8						•		•	•	•	•										
9*	•	•		•		•		•		•	•	•		•		•			•		
10		•	•			•		•	•	•	•		•		•	•					
11**	•	•	•			•	•	•	•	•	•	•	•			•			•		
12*	•	•				•		•		•	•	•		•	•	•			•		
13*	•	•	•		•	•	•	•	•	•	•				•	•					
14*	•				•			•	•	•	•	•									
15*																					
16	•	•				•	•	•		•	•	•				•					
17	•	•	•	•	•	•	•	•	•	•	•	•	•			•			•		
18*	•	•	•		•	•	•	•		•	•	•	•		•	•	•				
19	•		•	•		•	•	•	•	•	•					•	•		•		
20	•	•		•	•	•	•	•	•	•		•	•		•	•	•		•		
21**	•	•		•	•	•	•	•	•	•	•	•	•	•	•	•	•		•		
22**	•	•	•		•	•	•	•	•	•	•	•		•		•			•		
23	•	•		•	•	•	•	•	•	•	•	•			•	•			•		
24									•	•	•	•		•	•	•			•		
25*	•	•	•					•		•		•				•			•		

**=publication in which author of this thesis was involved*
***=case Bos & Lommer, B-tower or FC Twente. There might be slight differences with table 7.1 because general observations, not specifically aimed on the cases, are also included in table VI.1.*

The selected sources provided a variety of information on the underlying factors, ranging from experts with the opinion that a specific factor is of utmost importance to plausible reasoning that a certain factor was one of the causes of an incident. Some sources primarily focused on factors influencing failures, and some paid attention to factors that might assure structural safety. Therefore, comparison of the selected publications is not easy and the sources will not in the first place be used to explain the way structural safety might be influenced by the various factors, but to verify if the various factors are relevant for Dutch building industry.

The amount of attention to a specific underlying factor in literature can be an indication of the relevance of this factor for structural safety in the Dutch building industry.
All factors, except for physical resilience, are mentioned in the selection of literature. Complexity of projects, of the building process, allocation of responsibilities, control mechanisms, protocols, communication, collaboration, reasonable planning and budget, technical skills and attitude are mentioned more than average.

Therefore, it is expected that the suggested underlying factors on meso and micro levels can influence structural safety in the Dutch building industry.

Appendix VII: Condensed version list of questions in national survey [translated from Dutch]

Survey structural safety

What is the motivation for this survey?
The Platform Structural Safety aims at making structural safety within the building industry common practice. With this study it tries to answer the question: "What organizational and human factors in the building process are of influence on structural safety and what is the strength of these influences?"

What is the definition of structural safety in this survey?
For this survey it is expected that a structure is safe when it can adequately withstand all actions that are imposed on the structure during its reference period (for instance: 50 years from construction until demolition). Structural safety is not the same as occupational safety and health. In situations where for instance a formwork collapses, structural unsafety directly influences labour safety.

How will a structure be safely constructed?
To fulfil the structural demands, a structure needs to be well designed and calculated by a (lead) engineer. Subsequently, detailed engineering should be performed in the right way, based on correct and complete information provided by the main contractor. Adequate checking should be performed. Finally, during production and construction the quality of the building products should be good. The assembly should be carried out correctly and in the right sequence. Every step in this process is of importance, from design until delivery to the client.

What is the added value of joining this survey?
The experience of persons working in the building industry gives adequate insight into the factors that are influencing safety. Furthermore, cooperating in this study will increase awareness of safety risks for the participants.

Why are you asked to fill in the questionnaire?
You are working in the building industry. Without your opinion, experience and ideas it will not be possible to improve assurance of structural safety.

Is the survey anonymous?
Yes, it is anonymous. However, you will be asked to answer some personal questions to be able to check if age or years of experience are influencing the results.

Will I receive a response on the results of the questionnaire and the analysis?
A public report will be published with the outcomes of this study around June 2013 on the website: www.platformconstructieveveiligheid.nl.

What kind of questions will be asked?
The questionnaire consists of two parts:
1) A comparison of two projects: a successful and a less successful project regarding structural safety.
2) Selecting a top 3 for possible causes of structural unsafety in the building process.

How much time will it take to fill in the questionnaire?
It will take around 15 minutes. The number of open questions is very limited.

What should I do when I have additional questions?
The questionnaire is facilitated by Karel Terwel and Sylvia Jansen. You can contact Karel Terwel by mail.

Part 1: Comparison successful and less successful project
For this part of the research you will be asked to think of two building projects which were executed by your company; a successful and a less successful project. You will be asked to answer a number of questions for both projects.

A. Successful project: project with adequate assurance of structural safety
Please think of a finished project (maximum 10 years ago) in which, in your opinion, structural safety was adequately assured and in which just a relatively low number of hazards was faced during the building process. For structural hazards you can think of: mistakes in calculations or drawings, miscommunication, failure of temporary structures that were necessary for assembly, etc. In a successful project no structural damage occurred nor incidents happened that necessitated measures to avoid damage.

To which category did the (largest part of the) structure belong?
- Residential building
- Utility building
- Civil works (tunnels, viaducts, etc.)
- Other, ….

Which grade would you give for the structural safety of this successful project?
You can grade it with a mark from 1-10. A "1" is equal to "structurally very unsafe" and a "10" is equal to "structurally very safe." The higher the grade, the more sure you are that no structural damage occurred and that there were no hidden design or construction errors.

General propositions for the successful project

Please assess the following propositions, with the successful project in mind (response options: 1=fully disagree, 2=partially disagree, 3=neutral, 4=partially agree, 5=fully agree, 6= no opinion):

- It was a complex project (little repetition, innovative, unusual, complicated)
- It was a complex building process (many design or construction parties, unusual forms of collaboration)
- Adequate soil information was available
- The demands of the codes were clear (for instance NEN-codes)
- The demands of local building control and fire brigade were clear.

Organizational factors

The following propositions are related to the collaboration between the parties (like client, architect, MEP advisor, structural engineer, contractor, subcontractors, suppliers, project management) within the successful project.

Please, assess the following propositions, with the successful project in mind:

- Explicitly stated safety goals were available on project level (explicit, formal attention to structural safety)
- A healthy safety culture was present between the participants (tendency of the organization to thoroughly pay attention to structural safety)
- The allocation of responsibilities regarding structures was clear between the parties
- Structural risks were identified on project level (for instance: highlighting of design parts that were prone to mistakes during construction)
- For the identified structural risks adequate measures were taken on project level and a responsible party was appointed
- Adequate checking of information related to structures (calculations, drawings, constructed facilities) was performed by other participants
- (Change) protocols were used
- There was open communication between the participants
- Collaboration between the participants was regarded as good
- Planning was realistic
- Sufficient budget was made available
- A developed knowledge infrastructure was existent (experience and knowledge were shared, learning from mistakes)
- Working conditions on project level were adequate (not too hot/cold, adequate chairs, clothing, etc.)
- Instruments on project level were adequate (materials and tools of good quality, good hardware and software, etc.)

The same propositions for project level had to be assessed for company level (related to collaboration within the own company) of the successful project.

Human factors
The following propositions are related to human factors of all participants involved in the successful project.

Please assess the following propositions, with the successful project in mind:
- Technical competencies of employees involved were adequate to perform their own tasks successfully
- Management skills of the executives involved were adequate to guide the project in the right way
- Social-communicative skills of the employees involved were adequate to run the project successfully
- Attitude of the involved employees was adequate to run the project successfully
- Mental resilience of employees was adequate to perform their own tasks successfully
- Physical resilience of employees was adequate to perform their own tasks successfully

Do you have any other items that might have influenced the successful assurance of structural safety in this project?

B. Less successful project: project with suboptimal assurance of structural safety
The same propositions as for the successful project had to be assessed. In addition, some extra information on the less successful projects had to be provided.

In which phase of the building process did you observe the highest number of hazards for structural safety in this project?
- Design
- Detailed engineering
- Construction
- Combination of design, detailed engineering and construction
- Transition between phases
- I don't know

Optional questions:

What was the largest hazard for structural safety in the design phase?
- Incorrect modelling or calculation error
- Incorrect dimensioning on drawings
- Conflicting drawing and calculation
- Absence of drawing and/or calculation
- Other …

Same question for detailed engineering.

What was the largest hazard for structural safety in the construction phase?
- Incorrect quality of materials applied
- Incorrect assembling of elements on the building site

- Insufficient amount of material used
- Erroneous measurements on the building site
- Other …

Which damage has occurred or could easily have occurred?

- (Partial) collapse of the structure
- Structural damage, like cracks which could lead to failure if no measures were taken
- Material deterioration, which would lead to reduced life time if no repair was done
- Too large deformations or vibrations
- The probability that damage would occur was almost zero
- Other …

Part 2: Direct judgement

The following question is related to your opinion on organizational causes of threats for structural safety within the building process.

In the following list please point the three major factors for structural safety. Which three statements are in your opinion of major importance for assurance of structural safety within the building process (from design until delivery)?

Statements:

- Specific attention for structural safety is necessary (stating safety goals)
- A healthy safety culture should be existent
- Clear arrangements on the allocation of responsibilities should be made for all parties involved
- Structural risks of the project should be identified and communicated
- Checking by another person or organization should always be performed
- Work should be executed in conformity with protocols (checklist: Do I have all necessities to perform my task? Did I do the right thing to perform my task? Did I use a step by step approach?)
- Good communication and feedback is existent between employees and partners of the project
- Good collaboration between all project partners is existent (making agreements and keeping them)
- Sufficient time to perform my task/the project is available
- Sufficient budget to perform my task/the project is available
- A well-developed knowledge infrastructure within the organization is existent (exchange of knowledge and experiences with colleagues, learning from mistakes, learning from other companies)
- Adequate working conditions are existent (not too hot/cold, good chairs/clothing, etc.)
- Adequate instruments are available (materials and tools of good quality, good hardware and software, etc.)
- Other, …

General

Finally, we will ask you some personal questions.

What was your role in the projects?

- Client/project director/project manager
- Site manager/Supervisor
- Structural engineer (design)
- Structural engineer (detailed engineering)
- Main contractor (preparation)
- Main contractor (construction)
- Supplier
- Other, …

What was the size of your company?
(1-5, 6-50, 51-250, >250)

In which phase did you primarily perform your tasks?

- Design phase
- Detailed engineering
- Construction phase
- In all three phases about equal involvement
- Other, …

What is your age?
How many years of experience do you have in the building industry?
How many years are you working for your current employer?

This is the end of this questionnaire. We would like to thank you for your appreciated cooperation. The results will be made available in April 2013 on www.platformconstructieveveiligheid.nl

Appendix VIII: Headlines interviews after national survey

Project developer

Company: MAB Development Nederland B.V.
Interviewees: Henk te Selle (HS) and Auke Kremer (AK)

HS recognizes the main outcomes of the survey. He deems risk management the most important. Often structural risks are underexposed. You have to reserve some time to discover them.

In the second place, collaboration and communication are very important. It is essential to listen carefully and to be serious about the other's ideas. Be vulnerable. When you are facing problems, it might be beneficial to take a humble and open attitude, without immediately taking a legal, defensive position. Although there are situations when a legal approach is unavoidable.

Control comes in on the third place; it is more reactive than risk management. For large projects MAB currently always demands a second opinion.

Allocation of responsibilities is important, but you do not have to be too strict; it is also a matter of giving and taking; contracts are never 100% watertight.

Structural Engineer

Company: Van Rossum Raadgevende Ingenieurs Rotterdam B.V.
Interviewee: Fokke van Gijn (FG):

FG recognizes the main outcomes of the survey.

For FG safety culture is the most important factor. For a structural engineer it is of utmost importance that his work is of good quality, otherwise he loses trust from his clients. Control, therefore, is indispensable. FG does not use strict protocols for control. Awareness of the importance of control is very important. In a second opinion you have to develop your own opinion of the structure, instead of redoing all calculations exactly. It is easier to detect a calculation error than a conceptual error. Control on execution depends on the project.

In addition, technical knowledge is indispensable. Especially with 3D FEM calculations you should be aware that currently just a few structural engineers are really skilled to use this kind of modeling. For difficult bottlenecks in engineering it is important to arrange feedback from colleagues.

Collaboration and communication are also part of FG's top 3. Especially coordination is essential. For collaboration it is less important that you like each other (although it helps) than that there is trust in each other's competencies.

Integrated contracts have the advantage that construction knowledge is included in the design, provided that the appropriate persons from the contractor are involved. Furthermore, it is important for the success of this kind of contracts that the client of the structural engineer (often the contractor) appreciates the efforts of the engineer for optimization. A disadvantage of integrated contracts is that often design changes are made until the very end.

If there is discussion who is responsible for a certain part of the engineering tasks, van Rossum sometimes decides to perform these tasks himself. FG explains that they are used to continuing their standard way of working with good control, even when the budget is depleted, because the relationship with the client is essential.

A structured working environment and good tools are important for structural safety. Self esteem/confidence of the structural engineer is important, but it should be backed up by profound argumentation.
FG's experience with other industries (offshore) is that within these projects often quality is better assured, although these projects also tend to be more expensive.

Engineering contractor
Company: Volker Infradesign
Interviewee: Hans Galjaard (HG):
HG recognizes the main outcomes of the survey. Safety culture is the most important factor. Safety culture is equivalent to control. Everyone has the right to be controlled. There are three types of control: checking on headlines, detailed integral checking where every number is checked and independent recalculation (like a second opinion). For starting structural engineers step by step checking is necessary for several stages of the modelling and calculation. It is harder to detect what is lacking in a calculation than what is incorrect in a calculation. Experience is important for checkers.
For large projects Volker Infradesign always provides a site engineer at the building site. The right attitude of employees is essential. People should be aware of the limitations in their knowledge and skills.
A structural engineer should provide clarification in what is structurally possible and what is not. Too flexible, or too much 'servicing' the architect is not beneficial. In addition, an engineer should not be arrogant by claiming that certain failures will not occur due to his activities. He should develop a critical attitude, in which checking by hand is standard for computer calculations. A structural engineer should 'take his role' and should never stop thinking himself. For HG the starting point for structural safety is that you can explain to your client or other parties of interest that it is safe.
In the third place technical knowledge is key. Volker Infradesign maintains a knowledge infrastructure, with a web based knowledge portal (with wiki, best practices, critical indicators), lectures and courses. Furthermore, they stimulate engineers to become a certified structural engineer or structural designer (RC or RO in Dutch).
Other aspects are also of importance, but less urgent. With integrated contracts there is an increased amount of common interest, which is an incentive to deliver work of better quality. For utility buildings integrated contracts are not common. By including

construction knowledge into the design, an easier construction will be possible and a smaller likelihood of failure.
A financial incentive (for instance a bonus when delivered within a limited period of time) might not always work, because the bonus might be calculated as part of the budget, thus resulting in extra pressure of time.

Preparation contractor
Company: Ballast Nedam
Interviewee: Dick Lassche (DL)
DL immediately recognizes the six critical factors.
For DL allocation of responsibilities is key. Everyone has to know for which part he is responsible. His role as a planner is that he does not perform all tasks himself, but that he organizes the process (including checking). In addition, he should organize the right knowledge and skills at the right moment.
Furthermore, risk management is essential. Checking can be based on risk analysis. An example can be a start meeting between the planner and the project leader of assembly in which the risks are discussed. These might be standard or special risks. DL introduced a special meeting on the quality of the main load bearing structure before the start of the assembly of the structural skeleton. In this meeting the starting points of the engineering team were transferred to the assembly team.

DL observes various safety cultures in the building industry. Supervisors tend to be more theoretical and emphasize safety issues. Executors on the other hand focus on progress of the project. Mutual understanding and respect is needed. A cooperating lead engineer is useful, although when he is too cooperative (e.g. making promises he cannot live up to) this might lead to trouble.

Communication is also important. Often it is more useful to first call and confirm it by email, otherwise there is too much digital spam when every small issue is communicated by email. By splitting up the process with the introduction of a large number of sub-suppliers, more coordination is needed. There should be a willingness to avoid choosing the easiest path and to communicate with other parties.

A good atmosphere may be beneficial, but trust in each other's competencies is even more important for collaboration. If a party can be trusted, less checking is needed.

General pattern from the interviews:

The general pattern is very similar. A healthy safety culture and attitude are the starting points. It is beneficial when various parties work with common objectives and interests; this is stimulated by integrated contracts. Good quality of work should be standard and everyone has the right to be controlled.

To deliver good quality of work, technical knowledge is indispensable. If you do not have this knowledge yourself (e.g. because of a high level of specialization), you should mention this and organize to incorporate the essential knowledge in the project.

Because projects are often done by multiple parties and, as a result, are fragmented, it is essential to pay attention to communication and coordination. Collaboration will be improved when one can trust each other's expertise. It is useful when construction knowledge is included in the design. A too strict allocation of responsibilities is not always helpful; sometimes it is beneficial to work with an open, vulnerable attitude of giving and taking. Awarding (in Dutch: 'gunnen') is key.

Making an error is always possible. Risk management is therefore needed. From the performed risk analysis it can be decided which parts need extra control. One can control samples, perform integral control or an independent recalculation or second opinion. A second opinion is usually the best way to eliminate conceptual errors.

Appendix IX: Indicator Method[1]

Basic requirements of regression
Statistical analysis provides an opportunity to estimate the probability of successfulness of a project, regarding structural safety. Based on the outcomes of the assessed projects of the national survey a regression function can be developed. In this regression function the influencing factors (called: predictors) are included that have had a significant influence on the project results (called: dependent variables). Multiplication factors were added for every predictor. The model predicts the probability of a successful project, with regard to structural safety (see list of definitions).

For this situation statistics offer logistic regression in which the predictors might be continuous or categorical (with the use of dummy variables).
The dependent variables should be dichotomous with only two options (0 or 1). In the current situation this is a successful project or a less successful project with regard to structural safety.

A logistic regression-function in general can be presented as:

$$p(y) = \frac{1}{1 + e^{-(b_0 + b_1 \cdot X_1 + b_2 \cdot X_2 + \ldots + b_n \cdot X_n)}}$$

(Field 2005)

Met:
$p(y)$=probability of the outcome of a variable
b_0= constant variable
b_1= coefficient for predictor 1
b_n= coefficient for predictor n
X_1 = value for predictor 1
X_n= value for predictor n

For logistic regression one of the requirements is that cases are independent. However, in the current survey every respondent was asked to assess a successful and less successful project on 39 aspects. The advantage of assessing a successful and less successful project is that personal differences between respondents are expected to be eliminated. The role of subjectiveness is reduced by including a successful and a less successful project for every respondent.

[1] *The indicator method has been developed in collaboration with Sylvia Jansen, OTB. The description in this appendix is based on the report 'Verschilmakers voor constructieve veiligheid' (Terwel, K.C.(2013)) and a conference paper 'Quick assessment tool for assurance of structural safety in the building process' which was submitted for publication for the IABSE symposium in Madrid (Terwel, K.C. and S.J.T. Jansen (2014)).*

However, the basic assumption of independence might lead to a bias in the standard error, which can influence statistical significance (the p-value for the predictors). A correction can be applied by performing a multi-level analysis. A separate level of the respondent is distinguished in the data. In this way, a correction is made for the situation that the majority of respondents has delivered two cases and that there might be correlation between these assessments.
With the software program Stata for the final model of the logistic regression with risk analysis, control mechanisms and collaboration is checked if a multi level model would have a better fit on the data than a common logistic regression model. This appeared not to be the case and it was concluded that the situation in which the majority of respondents had delivered two cases did not influence the results. Therefore, the data can be analysed by logistic regression.

The five Likert categories were reduced to three categories (agree, neutral, do not agree). This simplifies interpretation of the outcomes. Furthermore, some categories on the 5-point Likert scale hardly contain any responses, for which it is hard to perform a reliable statistical analysis.

For every statement this results in three categories. Every statement is a predictor. The statements are included as categorical predictors. It was decided to compare the categories 'neutral' and 'agree' with 'disagree'. Thus, 'disagree' is the base category and 'neutral' and 'agree' are compared against this base category.

Logistic regression and its outcomes
Three methods of logistic regression have been used: 'backward stepwise', 'forward stepwise' and 'backward elimination by hand' method.

Backward elimination is a built-in algorithm of SPSS19. Briefly described, this algorithm starts with all variables and eliminates the variables with the lowest p-value, until all variables meet the demands of the minimum p-value ($p<0.05$).
Forward selection is also a built-in algorithm of SPSS 19. This algorithm starts with an empty model, except for a constant. Variables with the lowest p-value are included until a cut-off value is met (in this situation $p<0.05$).
Backward elimination by hand is similar to automated backward elimination, with the difference that in automated backward elimination variables can be added again when the p-values of a certain variable in a new model might have been improved.
The use of stepwise models is usually regarded with suspicion, because unreliable results might be found due to a coincidental (ideosyncratic) combination of predictors in the specific sample. The use of these algorithms is therefore usually limited to exploratory use. However, when using three different types of stepwise regression with similar outcomes, the reliability of the derived function will be improved.

Nagelkerke's r^2
In logistic regression, the fit of the model can be represented by Nagelkerke's r^2, which is a pseudo measure for the amount of variance that is explained by the factors in the model. Nagelkerke's r^2 is measured on a scale from 0 to 1, with a higher value indicating a better fit.

Confidence interval (CI)
Using categorical variables may result in an unreliable coefficient, because the variable is sometimes estimated with a low number of cases in the relevant category. It was decided to check the 95% confidence interval around the odds ratio (OR). The OR represents the odds that a successful outcome will occur given a particular exposure, compared to the odds of the outcome occuring in the absence of that exposure. In this situation it is the probability of a successful project divided by the probability of a less successful project. When this ratio increases, there is a larger probability of a successful project.
When the highest value in the 95% confidence interval was 20 times as high as the lowest value, it was decided to eliminate the variable from the analysis.
For instance, if the odds ratio of a certain predictor is 14.9 with a 95% confidence interval between 1.4 and 153.9, this means that when one would draw 100 samples of the same size as the original population and doing the same analysis, this would result in an odds ratio which would be between 1.4 and 153.9 in 95 of these cases. This would be an unreliable result, because of the large range of the odds ratio.

Outliers and cases with a large influence
To assure reliability it is important to check if there are outliers that largely influence the data. For the proposed models there are no outliers larger than three times standard deviation, which is acceptable. In addition, the values for the Cook's distance are far below 1. This indicates that there are no single cases in the model that largely influence the outcomes of the model (Field 2005).

Multicollinearity
In chapter 8 it was concluded that some variables were highly correlated. It is to be expected that some variables that showed a high delta score will have no significant influence in the regression function due to multicollinearity. Multicollinearity means that two or more variables are strongly correlated to each other and, while there is a relationship, with the dependent variable. Only one will be included in the final regression function, because these variables explain more or less the same variation of the dependent variable. An indication of multicolinearity is VIF (Variance Inflation Factor) with a value of close to or over 10. In the final function this was not the case.

Four models derived with logistic regression
From the various methods of logistic regression, finally two groups of significant factors remain that give a reliable explanation of the outcomes. On the one hand these are risk

analysis, collaboration and control and on the other hand: risk analysis, collaboration, knowledge infrastructure and technical competencies.
Apart from technical competencies these are all factors on project level.

From these two groups of variables, four different models with a combination of statistically significant variables are composed. These models are called parsimoneous because they only include statistically significant predictors.

- Model 1: Collaboration
- Model 2: Risk analysis and collaboration
- Model 3: Risk analysis, collaboration and control
- Model 4: Risk analysis, collaboration, knowledge infrastructure and technical competencies

Table IX.1 (see following page) presents the results of the logistic regression. The table clearly shows that with the inclusion of additional predictors, the individual influence of a particular predictor decreases (weight per predictor). However, the total explained variance of the model increases (Nagelkerke's r^2).

Table IX.1 shows that for some predictors where the neutral assessment is compared against the negative assessment the significance $p>0.05$. This includes that there is not a large difference in the assessment for the categories neutral and negative. However, the overall predictor has a significance $p<0.05$ and therefore these predictors are included. It is plausible that the influence of the category positive againgst negative is larger than the category neutral against negative.

The final rows of table IX.1 show the percentage of correct predictions according to the regression models. The reference for these models is the initial situation. In our study, a slightly higher number of successful projects (n=244; 51.4%) than less successful projects (n=231; 48.6%) were included (numbers presented for model 3, the others are similar). This means that if all projects would have been termed successful, this would have been correct in 51% of the cases. Next, the probability of being a successful project is calculated on the basis of the predictors in the model and each case is classified into the category of a successful project or a less successful project, according to this probability. Finally, the predicted classification is compared to the observed classification (successful or not successful) in order to examine the value of the model with the predictors.

Table IX.1 *Results for various models*

	Model 1 Weight	OR (95% CI)	Model 2 Weight	OR (95% CI)	Model 3 Weight	OR (95% CI)	Model 4 Weight	OR (95% CI)
Constant	-1.90		-2.31		-2.68		-3.26	
Collaboration								
disagree	-		-		-		-	
neutral	0.9	2.47 (1.23-4.96)	0.45 *	1.57 (0.75-3.31)	0.30 *	1.34 (0.62-2.91)	0.08 *	1.09 (0.46-2.54)
agree	3.04	20.91 (11.37-38.47)	2.30	9.96 (5.18-19.16)	1.89	6.63 (3.32-13.24)	1.70	5.48 (2.46-12.21)
Risk analysis								
disagree			-		-		-	
neutral			0.48 *	1.62 (0.82-3.18)	0.42 *	1.52 (0.76-3.07)	0.55 *	1.73 (0.80-3.74)
agree			1.59	4.88 (2.73-8.74)	1.28	3.58 (1.94-6.59)	1.40	4.04 (2.07-7.9)
Control								
disagree					-			
neutral					0.66 *	1.94 (0.92-4.10)		
agree					1.18	3.25 (1.68-6.29)		
Knowledge infrastructure								
disagree							-	
neutral							0.93	2.53 (1.16-5.54)
agree.							1.13	3.11 (1.45-6.65)
Technical competencies								
disagree							-	
neutral							-0.02 *	0.98 (0.34-2.83)
agree							0.78	2.18 (0.92-5.19)
Nagelkerke's r^2	0.39		0.44		0.46		0.50	
Correct prediction of successfull projects (%)	83.1%		77.3%		85.2%		85.3%	
Correct prediction of less successfull projects (%)	72.4%		78.9%		74.0%		75.3%	

* predictors with $p>0.05$; for all other predictors $p<0.05$

From four models to one

For the risk indicator method one model has to be selected. It was chosen to select the model with an optimum in the number of predictors and the correct prediction of the outcome.

To get a quick impression of the likelihood of a successful project, model 1 has a high predicting value, by only using the variable collaboration. The regression model gives a strong relationships between the predictor collaboration and the outcome of a project. However, just as with all regression models: the model does not prove a causal relationship between collaboration and success. It just observes a strong relation. For example, it is possible that when a project faces problems with structural safety (less successful), the atmosphere among the parties might be poor, thus resulting in a poor collaboration. The factor collaboration therefore is an indicator of the successfullness of a project.

To improve the predictive power, it is possible to include extra predictors in the model. Model 2 includes the variable risk analysis. The predictive value for less successful projects improves to the detriment of the predictive value for successful projects.

Model 3 also includes the factor control. The likelihood of a correct estimation of a successful and a less successful model is increased compared to model 1, and so is Nagelkerke's r^2.

For model 4 the increase in the successful prediction is very limited, when the factor control is substituted by knowledge infrastructure and technical competencies. When a model with risk analysis, collaboration, control, knowledge infrastructure and technical competencies is composed, technical competencies and control are not significant anymore.

It can be concluded that model 3 gives a good prediction with a relatively low number of variables.

Estimation of the successfullness of a project

In the data of the survey the ratio of successful and less successful projects is 48,6%:51,4%. In reality this ratio might be different.

The estimated probability of a successful project can be calculated by logistic regression with:

$$p(y)= \frac{1}{1 + e^{-(b_0+b_1 \cdot X_1+b_2 \cdot X_2+...+b_n \cdot X_n)}}$$

The constant b_0 and the coefficients b_1 to b_n are derived with regression analysis (see table IX.1)

The regression-function from model 3 can be presented as:

p(y)=

$$\frac{1}{1 + e^{-(-2.679+0.422 \cdot X_{1n}+1.275 \cdot X_{1p}+0.662 \cdot X_{2n}+1.18 \cdot X_{2p}+0.295 \cdot X_{3n}+1.892 \cdot X_{3p})}}$$

With:
p(y)= probability of a successful project with regard to structural safety
X1n= neutral assessment of the factor risk analysis
X1p= positive assessment of the factor risk analysis
X2n= neutral assessment of the factor control
X2p= positive assessment of the factor control
X3n= neutral assessment of the factor collaboration
X3p= positive assessment of the factor collaboration
X1 to X3 have a dichotomous value 0 (not given) or 1 (given)

The neutral and positive assessments are always compared with the negative assessment (the reference). It can be noticed that the weighing factor for the positive assessment of the factor collaboration is the highest. Collaboration therefore is of major influence within the function.

Based on the regression-function, figure IX.1 presents the estimated probability of a successful project with regard to structural safety for various assessment options (disagree, neutral, agree) for the three determining factors.

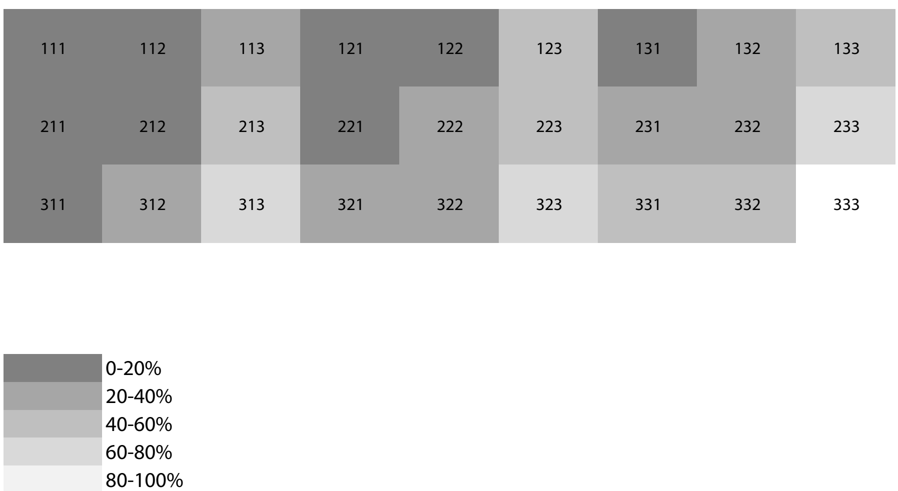


Figure IX.1 *Estimated probability of successful project*

Every cell of the figure is a combination of the assessment of the three predictors. The first number is for risk analysis, the second number for control and the third number for collaboration. A '1' reflects a negative assessment of the predictor, a '2' reflects a neutral assessment and a '3' a positive assessment. A combination '123' for instance reflects a negative assessment of risk analysis, a neutral assessment of control and a positive assessment of collaboration. The colour depicts the estimated probability of a successful project:

From figure IX.1 it can be concluded again, that the factor collaboration is determining for the outcomes. If there is no good collaboration (the third number is lower than 3), the estimated probability of a successful project is under 40%. If the collaboration is regarded as good, the estimated probability of a successful project will be over 60%, regardless the assessment of the other factors.

Nawoord

Na 7 jaar in het bedrijfsleven werkzaam te zijn geweest, was het combineren van onderwijs en onderzoek een geheel nieuwe ervaring. Soms was het lastig om alle activiteiten te combineren, maar over het algemeen zorgde de combinatie voor afwisseling. De contacten met studenten gaven vrolijkheid tijdens de intensieve onderzoekswerkzaamheden.
Van tevoren had ik besloten dat ik een onderwerp wilde doen dat maatschappelijk relevant was. Met het onderwerp constructieve veiligheid bleek ik daarmee een goede keuze te hebben gemaakt. De relevantie bleek uit diverse persoptredens, zowel na schadegevallen bij B-tower en het FC Twente stadion als na het gereedkomen van eigen deelonderzoeken. Ook werd er diverse keren een beroep op mij gedaan om een bijdrage te leveren met betrekking tot constructieve veiligheid bij symposia, lezingen en onderzoeksprojecten. Daarnaast bleek het een onderwerp dat waarde kreeg in de samenwerking met andere mensen. Binnen het Platform Constructieve Veiligheid heb ik gedurende mijn onderzoek veel geleerd en heb ik een bijdrage kunnen leveren. Bij de Vereniging Nederlandse Constructeurs werd ik lid van commissie Vakmanschap; een inspirerende commissie voor zowel mijn onderwijs- als mijn onderzoekstaak. Internationaal heb ik kunnen leren van de ervaringen van de leden van de commissie Forensic Engineering vanuit IABSE.

De samenwerking en contacten met diverse andere mensen maakten mijn promotieonderzoek tot een mooie tocht; delen liep ik alleen, maar geregeld kwam er iemand naast mij lopen.

Ik wil beginnen met mijn promotoren. Prof. Jan Vamberský was er het hele traject, vanaf het begin in 2008, bij. Vanuit zijn directe betrokkenheid en passie voor het onderwerp constructieve veiligheid was hij altijd stimulerend en ondersteunend en introduceerde mij in zijn netwerk. Hartelijk dank daarvoor. Prof. Ton Vrouwenvelder raakte vanaf 2010 betrokken. Zijn grote kennis op het gebied van schadegevallen, Eurocode en probabilistiek en opbouwende kritiek heeft de kwaliteit van mijn proefschrift naar mijn mening sterk verbeterd; waardering daarvoor.
Dik-Gert Mans was in zijn rol als voorzitter van het Platform Constructieve Veiligheid nauw bij de totstandkoming van het onderzoek betrokken. Bij diverse deelonderzoeken zijn wij samen opgetrokken; ik heb geleerd van zijn overzicht en het talent om projecten tot een succesvol eind te brengen.
Daarnaast waren er allerlei mensen met wie ik artikelen schreef en/of die gelegenheid hadden om met mij over het onderwerp te discussiëren of stukken te becommentariëren: Jeroen van der Heijden, John Stoop, Sylvia Jansen, Mirjam Nelisse, Paul Waarts, Shahid Suddle, Adri Frijters, Frank Guldenmund, Martijn Mud, Walter Zwaard, Simon Wijte en Jan van der Windt. Dank voor het meedenken! Dat geldt ook voor de andere mensen die ik geconsulteerd heb, maar hier niet bij name worden genoemd.

Het was mooi om studenten bij mijn onderzoek te betrekken. Diverse bachelor en master projecten, gerelateerd aan constructieve veiligheid, werden uitgevoerd. Met een aantal masterstudenten leidde dit ook tot publicaties: Marta Mendez Safont, Wouter Boot, Geert Dijkshoorn en Johan de Haan; het was een genoegen!

Met diverse collega's heb ik uren koffie gedronken en vaak gediscussieerd, onder meer tijdens het promotieoverleg: Marjo, Roel, Sander, Dick, Henk, Casper, Jeroen en Anke; ik heb het gewaardeerd. Jan Rots en Rob Nijsse, dank voor de support in het beschermen van mijn tijd voor de afronding van het proefschrift.

Een speciaal woord van dank ook voor Hayo Hendrikse. De samenwerking in zomer 2010 aan de Cobouw database was een waar genoegen. Erg leuk dat we nog steeds geregeld contact hebben.

Veel dank ben ik ook verschuldigd aan Simon Kiefte en Wouter Boot. Zij namen de gelegenheid om mijn concept proefschrift integraal door te nemen en van relevante opmerkingen te voorzien. Het gaf mij weer extra licht aan het eind van de tunnel! Ook wil ik Corrie van der Wouden noemen die het proefschrift nauwgezet op taalkundige missers heeft doorgenomen en Jos Almekinders die mij adviseerde bij het maken van de layout.

Vrienden en familie heb ik afgelopen jaren niet altijd de aandacht kunnen geven die ze verdienden. Vele avonden en halve zaterdagen werken, hadden invloed op mijn sociale leven. Ik hoop dat daar weer meer balans in komt! Pa en ma, dank voor jullie support en liefde. Ik heb veel aan jullie te danken.

Rachel: "You are my sunshine!". Wat heb ik toch met jou geboft! Jij was er altijd; zowel bij de vrolijke als bij de taaie momenten. Je hebt me geweldig ondersteund, zeker ook door mij telkens weer in de gewone wereld te trekken in de spaarzame momenten dat ik vrij was.

Tot slot wil ik God danken voor energie en levenslust. Wat is het leven rijk geschapen! U zij de glorie!

Curriculum Vitae

Karel Coenraedt Terwel (1975) studied Civil Engineering at Delft University of Technology (DUT) and graduated in 2001 (specialization: Building Engineering). From 2001 until 2007 he has been working as a structural designer/project leader at Zonneveld Engineers (Rotterdam) on complex structural designs, like two office towers (height: 146m) for the government in The Hague (awarded Dutch concrete prize 2013 in categories 'Structural Design' and 'Utility building') and the Palace for Music (in Dutch: 'Muziekpaleis') in Utrecht. Since 2007 he has been a lecturer on structural design at DUT. In addition, he has been working on a PhD-study on structural safety in the Netherlands from 2008-2014.
Terwel is a member of the Platform Structural Safety, an interdisciplinary board which aims at making structural safety common practice in the Dutch building industry. He serves in the committee 'Professional Skills' of the Dutch Association for Structural Engineers. Furthermore, he is a member of WG8 'Forensic Engineering' of the International Association for Bridge and Structural Engineering (IABSE). From January 2014 he is a member of the editorial advisory board of the International Journal 'Forensic Engineering' of the Institution of Civil Engineers (ICE).
In December 2013 Terwel founded Coenraedt B.V. He is committed to providing consultancy in investigations of structural failures, second opinions and structural risk management.