Seismic retrofit

an architectural approach for the situation in Groningen

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This is my research paper for my graduation at the Architectural Engineering studio of the TU Delft faculty of Architecture and the Built Environment. The research paper proposes a strategy for the seismic retrofit of an unreinforced masonry building in the area of the Groningen gas field. The paper is intended to function as a preparation and preliminary research to facilitate my graduation design. I would like to thank my design mentor Job Schroën for his adequate guidance and my research mentor, Joop Paul, for steering the research.

A word of thanks goes to experts out of several disciplines: Mauricio Morales de Beltran, Andy van der Dobbelsteen, Helen ter Laan, Masa Daycen, David van Raaij and Arno Scheepens, Jurry Bonnema and Jacolien Massink, for taking the time to discuss their view on the subject with me.

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Contents

Abstract

Keywords: Seismic retrofit, unreinforced masonry, performance-based, multi-criteria approach

The production of gas induces seismic events in the area above the Groningen gas field. A predominant part of the building stock is built with unreinforced masonry, which performs poorly during earthquakes. Around 250.000 buildings are assessed (Arup, 2013) for potential strengthening. This paper aims to prepare the architect for a seismic retrofit of one building in Groningen, by decomposing the process and researching which factors play a part in the design. The process starts with the project definition and task distribution. Firstly the seismic hazard is analysed. The next step is to analyse the existing and define performance objectives. These objectives are based on factors related to the existing building, its context and its stakeholders. Subsequent criteria directly influence the suitability of seismic engineering solutions.

An overview is given of the criteria which should be taken into account, and an engineering toolbox with design principles, retrofit principles and retrofit techniques is provided. The challenge in the process is found to be the matching process between the implications generated by the existing and the impact of the retrofit technique. At the end of the retrofit process, a balancing assessment must be done, weighing the criteria and making a choice for the final seismic strategy. A starter is made in the final chapters of this paper, by stating examples of implications which the stated criteria can have on the chosen engineering solutions and introducing a case study, on which the research shall be tested.

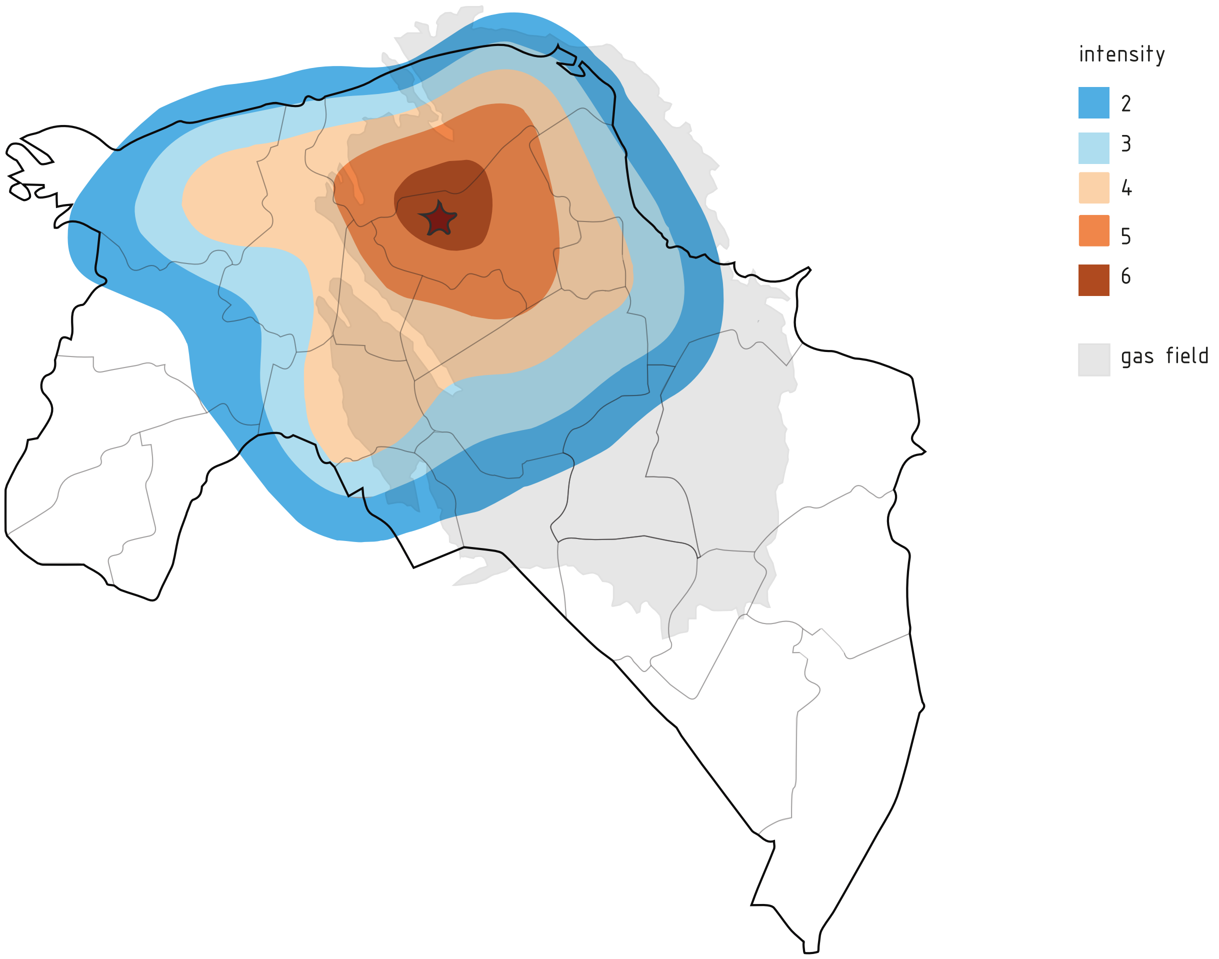


Figure.1: Macroseismic intensity map of Huizinge earthquake 2012 | Source: adapted from KNMI (2014)

1. Introduction

In 2012, an earthquake occurred near Huizinge with a magnitude of 3.6 M. Although there had already been minor seismic events in the area, this quake was felt more strongly by the population than previous tremors. Above 2000 damage reports were submitted to the NAM[1] (Drost & Kraaijpoel, 2013). The earthquake near Huizinge functioned as a turning point in the Dutch policy with respect to gas drilling in the Netherlands and the start of a thorough study trajectory and structural upgrading plan for the building environment in Groningen. Earthquakes of significantly larger magnitudes take place all over the world. In countries such as Japan and Chili earthquakes are experienced of the

1 Dutch company responsible for gas production

magnitude 6.0 M on Richterscale[2] and higher. So what is all the fuss about in Groningen, where 'minor' earthquakes are experienced up to 3.6 M?

First of all, the earthquakes in Groningen are induced. This means that they are provoked by humans, in this case by drilling gas out of the soil. Consequently, the hypocentres lie at a depth of only 3 km, causing the quakes to have a larger impact on a smaller scale. Furthermore, since the quakes are man-made, governmental policy can influence the occurrence. However, there is still a lot to research on the precise causal relationship between the gas production and the seismic .

Secondly, the building stock of Groningen is not engineered for seismic resistance, since earthquakes were no serious threat before. Consequently, there is little experience and knowledge on seismic design and retrofit in the Netherlands. On top of that, the dominant part of the building stock (up to 80%) is built with one of the worst possible materials to cope with the seismic forces: unreinforced masonry, due to its brittle behaviour and lack of ductility. Since there is a lot of experience on seismic design all over the world, it is relatively clear how to build new structures for earthquakes[3]. The greatest challenge at the moment in Groningen is strengthening of the existing building stock: the seismic area in Groningen contains 250.000 buildings which potentially need strengthening.

How to deal with such a seismic retrofit? The fitting strategy for seismic retrofit will vary per building and depends on a lot of factors which cannot be assessed independently of one another. A lot of stakeholders are involved in the situation, having different interests. Users of buildings feel that the earthquake hazard and damage has decreased the liveability and value of many buildings. Politicians have therefore suggested that a retrofit should add value to compensate for the experienced discomforts. In order to do so, it is essential to comprehend the process of structural upgrading and the constraints and possibilities imposed by the specific situation. Thorough understanding of the existing situation is essential to set up an integrated approach which respects the integrity and character of a building, as opposed to intrusive additions or posted-on interventions.

The research focusses on proposing a strategy for seismic retrofit of an unreinfroced masonry building in Groningen and providing the architect with the necessary tools and background knowledge.

After this introduction, in **chapter 2** the problem statement will be addressed, starting with the seismic hazard in Groningen, the problems of the building stock and socio-economic situation. In **chapter 3** the research methodology of the paper will be discussed. The results of the research start at **chapter 4**, containing the definition and set-up of a retrofit strategy. **Chapter 5** comprehends the seismic hazard of Groningen and characteristics of the earthquakes and **chapter 6** describes the assessment of seismic resistance. **Chapter 7 and 8** contain an engineering toolbox for dealing with seismic design and retrofit. Afterwards, in **chapter 9** a value assessment and criteria overview is listed with respect to conditions which define the performance objective. In **chapter 10** it is described how all the information should be combined to a seismic strategy and how the aforementioned criteria are linked to the engineering toolbox illustrated by some examples and a case study: the Municipality building of Loppersum.

2 The Richter scale is logarithmic; a higher level contains 31 times the seismic energy.

3 Nevertheless there is also a lot of new research done on innovative measures such as damper systems and Fiber Reinforced Polymers.

2. Problem statement

2.1 Earthquakes in the Netherlands

In 1959, one of the largest gas fields in the world was found in Groningen, providing a production volume of 2800 billion m^3 of gas (Namplatform, 2014). The winnings of gas are and have been very beneficial for the Dutch economy. 98% of the households run their gas stoves and boilers on the gas from the Groningen gas field. The downside is that the production of natural gas is acknowledged to cause subsidence and earthquakes (Namplatform, 2014), deteriorating the positive reputation of natural gas as one of the 'cleanest' of fossil fuels.

In 1986 the first earthquake was measured. Since then, 1024 seismic events have found place within the range of 0.2 to 3.6 M. Research of Arup (2013) shows that a tremor can be expected of a magnitude of 4.1 M, with a PGA of 0.12g. Chances on an earthquake with a higher magnitude are estimated on 10% (NAMplatform, 2014). The company Arup is employed by the NAM to investigate a database of approximately 250.000 buildings in the affected area above the Groningen gas field. The calculations indicate that buildings are susceptible to damage or collapse, with potential casualties as a result (Leemput, 2013).

2.2 Situation built environment

The 250.000 buildings in the study area are not seismically designed by engineers, and therefore they potentially need structural upgrading. The buildings are characterized by non-structural elements such as parapets and chimneys, which create falling hazards. Floor- and roof diaphragms are generally not stiff enough and in many cases an adequate connection to the walls is lacking. The brittle unreinforced masonry walls are heavy and weak in withstanding lateral loads. The masonry is easily damaged during seismic events and there are many notions of tears in walls. In some cases there is even danger of collapse. A complicating factor is that the cause of the damage can be hard to establish. The earthquakes have a fair share, but also a large amount of the tears can be related to bad construction, maintenance, sagging, etcetera.

Since the phenomenon of earthquakes-, and designing for earthquakes is relatively new for the Netherlands, new building codes are made. Existing measures, referenced from other countries, cannot be implemented directly since the situation in the Netherlands is unique due to the combination of the specific building stock and the weak subsoil in Groningen (NAMplatform, 2013).

The whole situation has become very sensitive, in which there is many frustration and discomfort for the inhabitants and there are difficult decisions to take for policy makers. In order to provide compensation for the experienced discomforts, politicians suggest restoring the decrease of value and living comfort. An option for increasing value is improving energy efficiency, which can enhance the quality of the indoor comfort.

2.3 Socio-economic problems

Next to earthquakes, the area deals with other structural problems such as a decline of the population, aging, low levels of education and income and high unemployment (Meijer & et al, 2013). Population decline influences the quality of daily life and facilities such as living, working, schooling and healthcare (Woon- en leefbaarheidsplan Eemsdelta, 2012). The Earthquakes deteriorate this problem. Suggestions are made that the inhabitants could migrate; however, many people living in the area really appreciate their homes, cultural heritage and the green and peaceful neighborhoods.

2.4 Objective

Each building demands a specific approach. Setting up a seismic retrofit strategy is a complex task, in which many many disciplines, factors and stakeholders come together.
The objective for this paper is to prepare an architect for a seismic retrofit of one building in Groningen, by decomposing the process and researching which factors play a part in the design. To set up a strategy, the research focusus on how the characteristics and criteria of the existing situation and stakeholders have implications on the performance objectives and engineering solutions which are chosen.

2.5 Scope and relevance

A very acute and current societal problem is addressed, affecting up to 500.000 people directly. Up to 250.000 buildings potentially need structural upgrading, of which 80% is unreinforced masonry. Focusing on this building method, this paper addresses the potential seismic retrofit of approximately 200.000 buildings in the Groningen Gas Field area.

The first priority is to prevent immediate risk and damage repair. Although the task of structural upgrading seems in the first place to be a structural engineering challenge, for the quality of the built- and living environment it is important to research an approach which aims to take also non-technical conditions into account. Challenges are addressed such as preservation of emotional or historical assets, integrating interventions in the character of a building, involving users and increasing value and comfort. This assessment is important to make, since these factors have implications on the engineering solutions which are chosen.

Due to the experienced discomforts adequate handling of the retrofit is of great importance for the well-being and state of mind of the inhabitants of the area and the livability of the neighborhood.

2.6 Research questions

The main research question is:

"How to set up a strategy for a specific retrofit situation,taking the stakeholders, characteristics and qualities of the existing building and context into account?

The research is split up into three parts: technical research, social and cultural research and implementation research.

1. Technical research

1.1 Seismic retrofit

- What is the nature and magnitude of the seismic hazard?
- What are the structural properties of unreinforced masonry and what are the effects of earthquake loads?
- Which methods are there to assess the seismic resistance of a building
- What are the principles for seismic design and retrofit?
- Which structural upgrade measures or techniques are feasible for unreinforced masonry structures?

2.2 Climate performance

- What is the current energy demand of dwellings in Groningen?
- Towards which standard should one aim to go?
- Which measures are there to reduce energy demand?

2. Social / cultural research

2.1. Stakeholders

- Who are the relevant stakeholders?
- What are their stakes, problems and opportunities?

3.1 Value and criteria

How to assess the value, characteristics and criteria posed by the:

- the context and neighborhood?
- the building type and building use?
- the emotional value of the building?
- the historical and cultural value of the building?
- the architectural qualities?

3. Implementation research[1]

3.1 Which constraints are imposed by:

- the costs?
- the speed of implementation
- the standardization of techniques

3.2 Combinations

- Is it possible or feasible to combine seismic retrofit measures with other kinds of renovation measures?

1 This subject was added later on in the research so it less extensively elaborated.

3. Methodology

3.1 Methods

Literature review

A literature review is executed in order to gain understanding of the performance of existing buildings in the Groningen gas field area, seismic, and energy efficiency retrofit. With respect to seismic retrofit of unreinforced masonry structures the following topics where researched: the seismic hazard, structural properties, earthquake damage, seismic design principles and -retrofit techniques.

Socio-economic analysis

Through literature and demographic statistics of the area, research is done on the composition of the population; topics with respect to dejuvenation, aging, unemployment.

Site visit

During the research two visits of the site were done. The first visit was executed as an orientation on the subject and circumstances. The visit included viewing of the building stock and short interviews with inhabitants. The second visit was focused on damage observation and in depth-conversation with inhabitants and representatives of the municipality of Loppersum.

Figure.2: Site visit: renewal of farm wall, Loppersum | Own image

Figure.3: Site visit: tear above a window arch, Loppersum | Own image

Interviews

For the project two kinds of interviews were held. Several expert interviews were done, in order to approach the multi-faceted problem. Researchers and experts from several fields were consulted including: seismic engineering, structural properties of unreinforced masonry, climate interventions, energy efficiency, user-involvement and eco-cost with respect to created value. The second type of interviews consisted of user- and stakeholder interviews including the interviews with inhabitants and the representatives of the municipality of Loppersum.

Courses and conferences

A 3-day course on earthquake engineering was visited, provided by the NEN, addressing building codes, the earthquake hazard, dynamics of structures, building with masonry, concrete, steel, timber and foundations. For energetic upgrade the conference 'Human in the Loop – Designing for Sustainable Technologies in Homes' was visited.

Stakeholder analysis

A stakeholder analysis is made, structured by the scale of the group or organization. Literature research and the input of interviews were used to accomplish this analysis.

Reference study

Relevant reference studies for seismic retrofits where hard to find, due to the uniqueness of the problem. Mostly individual interventions or techniques were found, as opposed to holistic concepts. The retrofit techniques which were found are included in the engineering toolbox.

Research by design

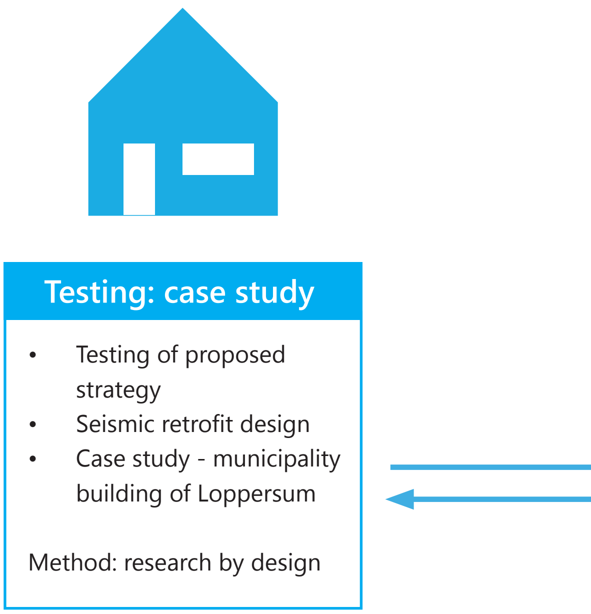
The proposed strategy will be tested by applying it on the renovation of a Case study: the Municipality of Loppersum.

3.2 Methodology

Seismic research functions as the input for an engineering toolbox. This information is combined with social, cultural, technical and implementation research into a framework which helps to set up (objectives for) a seismic retrofit strategy.

The research is set up (and tested by) a retrofit design for the city hall of the municipality of Loppersum. For more information, refer to chapter 12.

The structure of the research is illustrated in the scheme on the next page. >>



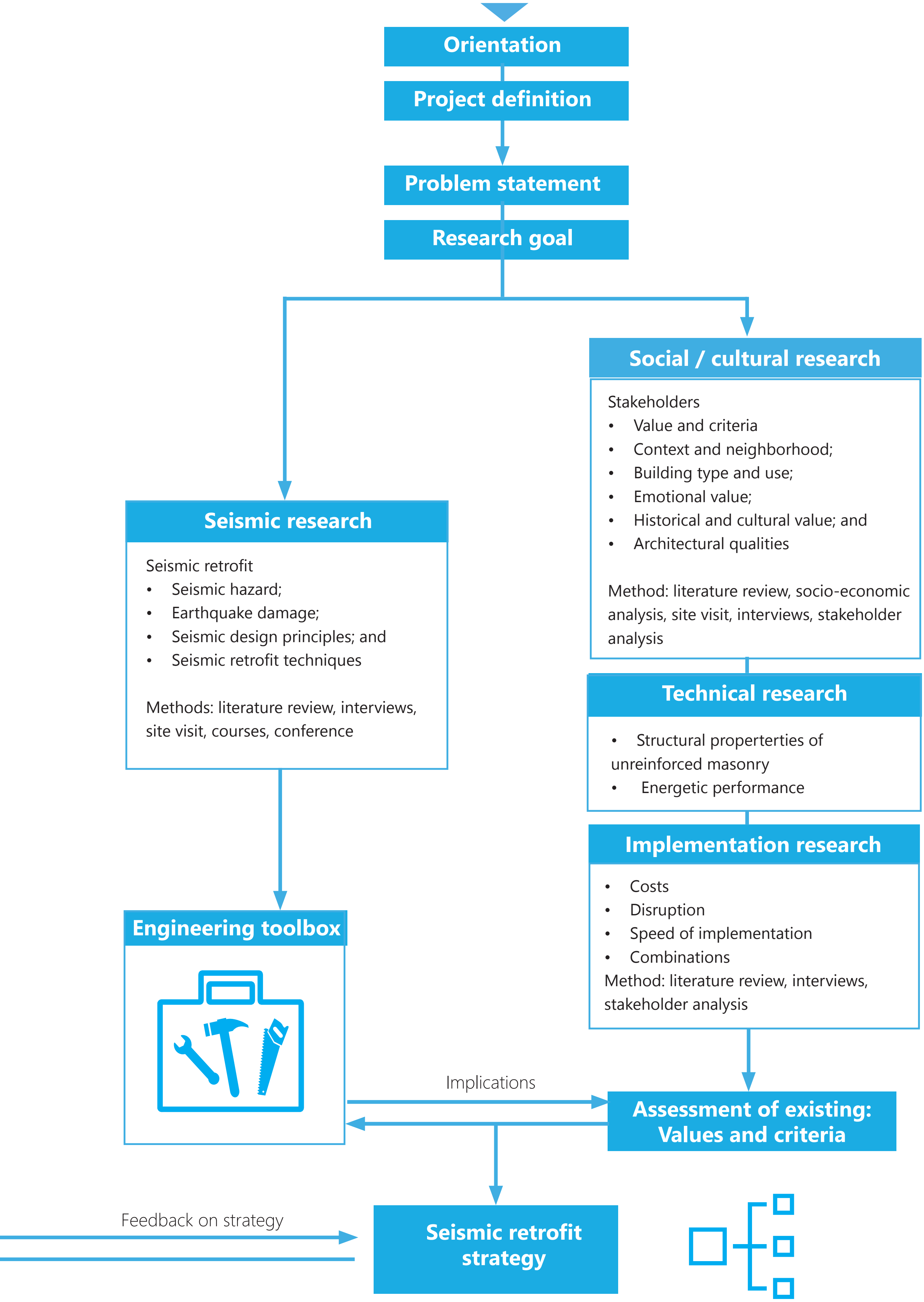


Figure.4: Research topics and methodology | Own image

4. Retrofit

4.1 Definitions

The term seismic retrofit is the general term for activities which aim to increase the resistance of buildings to seismic activity. It is the generic term used for repair, rehabilitation, strengthening and upgrading. The terms are defined by R. K. Goel (2004) as follows:

In case of damage:

- Repair; the restoration of the original condition without an increase of the performance.
- Rehabilitation; the restoration of original geometry and performance but also increasing strength or resistance

No damage:

- Strengthening; improving the seismic performance since the building does not satisfy the existing requirements at time of design/ construction
- Upgrading the structure; improving the seismic performance since the building does not meet new requirements (such as new code provisions)

In Groningen there are damaged buildings which need rehabilitation and undamaged buildings which need pre-emptive structural upgrading. The buildings do not meet the new building codes, which are changed since the acknowledgement of the seismic hazard in Groningen.

4.2 Retrofit scheme

A scheme is made in which a sequence is proposed for a seismic retrofit. The research starts with an assessment of the seismic hazard. This is followed by an by an assessment of the existing structure; the seismic performance and deficiencies. To set up a seismic strategy, an engineering toolbox with design principles, retrofit principles and seismic retrofit techniques is analysed.

In order to set performance objectives an assessment must be made of the building and context. This assessment should be done by research and in consultation with the users/ inhabitants and other stakeholders. On the basis of the engineering toolbox and the analyses of the existing, a seismic strategy is proposed. This strategy will attempt to fulfill the performance objectives to the weighting of their importance.

4.3 Task division

At the start of a seismic retrofit case it is necessary to set up a team of specialists, according to Khan (2013) existing of:

- An architect
- A structural engineer
- A building code specialist
- A geotechnical engineer
- An environmental engineer
- A building contractor

Architect

In consultation with the stakeholders, the architect performs a value and criteria assessment with respect to the existing building. In the choice of strategy, his responsibility is to take care for symmetry of planning, avoidance of soft-story effects and dangerous conditions.

Structural engineer

In consultation with the environmental engineer and code specialist, the structural engineer defines the loads on the structure and performs a detailed analysis and design. In the choice of strategy, his responsibility is to propose materials and construction alternatives and techniques.

Code specialist

The code specialist provides advise with respect to the methods used and checks if code provisions are followed adequately.

Geotechnical engineer

The geotechnical engineer investigates soil conditions – since the soil can amplify vibrations-, and the foundation capacity. His task is to assess the risk on seismic site hazards such as liquefaction, landslide and surface fault rupture.

Environmental engineer

In consultation with the structural engineer, the environmental engineer defines the loads on the structure by assessing the seismic hazard, ground accelerations and prognosis of seismic events.

Building contractor

The building contractor has an overview of the implication produced by costs, standardization possibilities, speed of implementation and building planning.

4.3 Performance requirements

Together with the stakeholders, performance objectives and requirements are set up. Since not all criteria can be met for 100%, some kind of ranking needs to be defined stating which criteria are more important.

For seismic retrofit, the main priority lies on reducing risk. By approaching this definition in the broadest sense, demolition of inadequate structures is also reduction of risk. If the building or use of the building is assessed as being too valuable to demolish, an acceptable level of risk is defined in order to design a retrofit strategy.

This seismic performance requirement is in first place defined by the Government in the building codes. According to Arup (2013): ‘for new construction, the objective of seismic design principles and codes of practice is not to experience significant damage under frequent, smaller, earthquakes – which is called damage limitation, and to have sufficient confidence that occupants will not be severely injured or killed under a rare larger earthquake, called life safety’.

The objective of life safety and collapse prevention comes before the objective to protect the building from damage (Goodwin, Tonks, & Ingham, 2011). Furthermore, it is not economical to take on the objective for buildings to remain undamaged after a large earthquake. Large earthquakes are seen as ‘rare’, with the confidence the occurrence will not ‘exceed over the life of the structure’ (Arup, 2013) Therefore, safe exit is the design goal during large seismic events. Further objectives should be established on the basis of an assessment of the specific situation, which will be elaborated on in chapters 6 and 9.

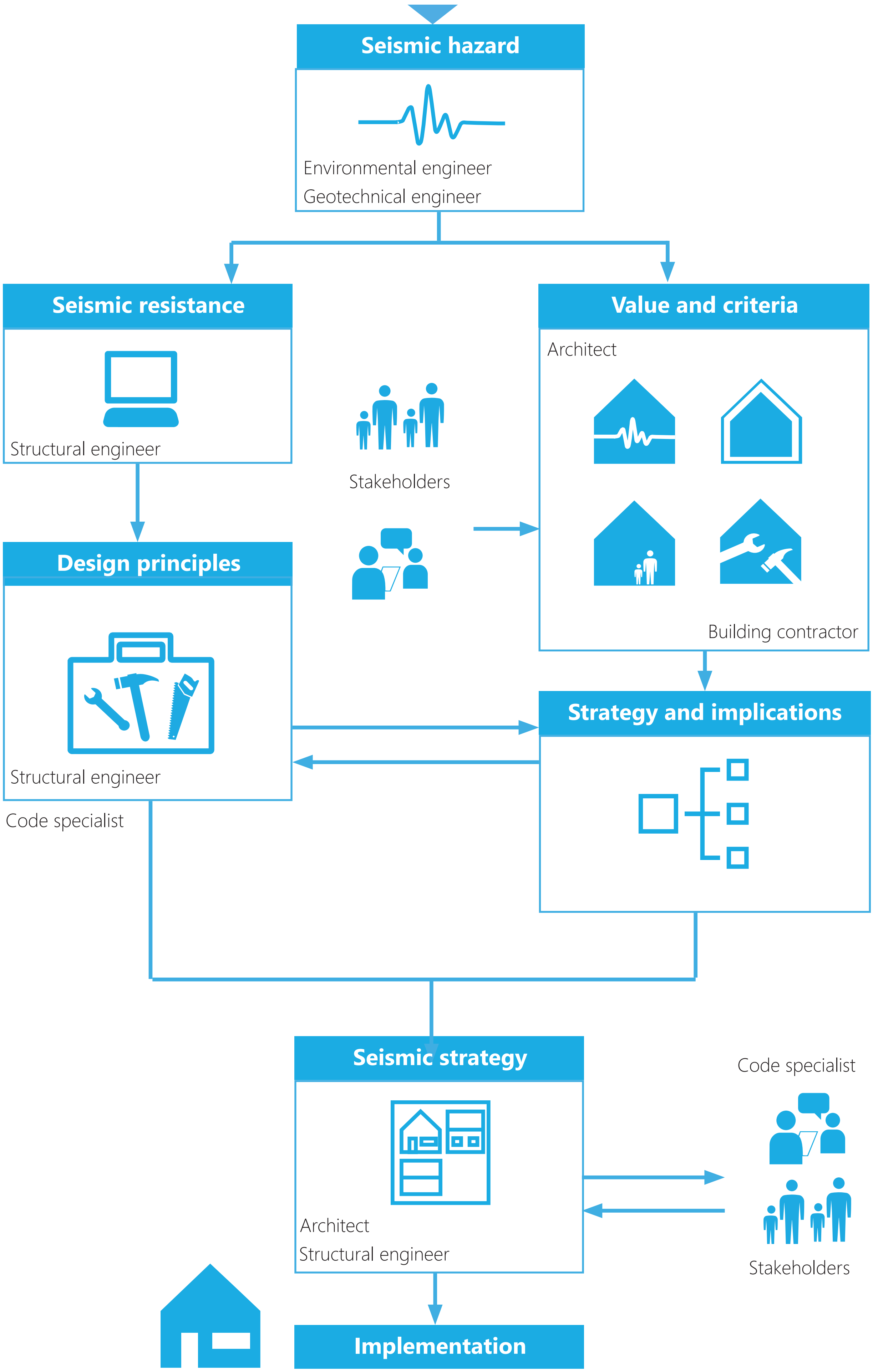


Figure.5: Proposal for a seismic retrofit scheme and sequence | Own image

5. Seismic hazard

5.1 The Groningen gas field

The Groningen gas field was discovered in 1959. The field turned out to be one of the largest of the world, measuring a total production volume of 2800 billion m3. The production of the gas started in 1963, and proved to be very important for the Netherlands. Gas production from Groningen covers 75% of the total production in the Netherlands (NAMplatform, 2014). Approximately 98% of the Dutch households receive gas from the field to provide for their gas stoves and boilers, consuming around 1600 m^3 of gas per year. These devices are accustomed to the specific type of low-calorific gas, coming from the Groningen field. Also the light industry and greenhouse horticulture profit from the gas. The earnings up till now for the Dutch government have been €250 billion (NAMplatform, 2013).

5.2 Earthquakes in Groningen

The removal of natural gas from the pores of the Sandstone causes an enormous drop of the high pressure in the layer. The drop in pressure leads to compaction, and when earth layers are compressed near natural fault lines, stress can arise which causes the layers to shift. These movements are called earthquakes .

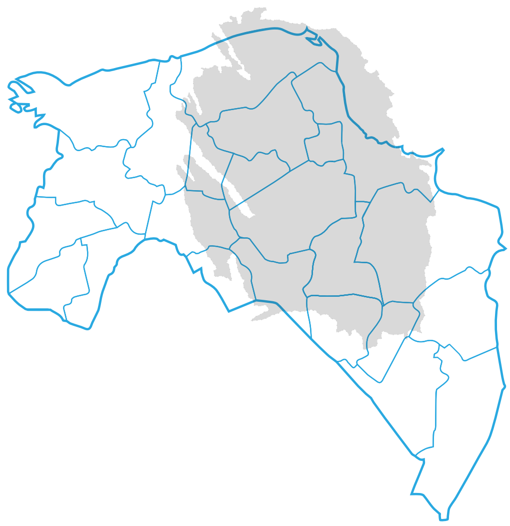


Figure.6: Location of Groningen gas field | adapted from Arup

In 1986 the first induced earthquake was measured. In 2000 the production rate was increased after a period of moderate production. At this change, the seismic rate also demonstrated increase. In 2012, a seismic event of M 3.6 struck at Huizinge, causing considerable damage. The quake was felt more intense and had a longer duration than experienced before. Until 2014, 1024 seismic events have taken place within the range of 0.2 to 3.6 M. (Kamp, 2014).

The seismic event at Huizinge was the motive to completely change the production plan for the field, and called for a re-assessment of the seismic risk. Currently around 60% of the gas has been won. The leftover volume can provide gas until approximately

2080. However, from 2020 and on, the production rate will strongly decline (NAMplatform, 2013). A reliable prognosis of the maximum seismic event which can be expected is difficult to make (Eck, 2014). On the basis of measurements, estimations can be made for the coming 3 to 5 years. Research shows that a tremor can be expected of a magnitude of 4,1 M, with a PGA of 0.12g. Chances on an earthquake with a higher magnitude are estimated on 10% (NAMplatform, 2014). In the seismic risk study of Arup, the scales 3.6 to 5.0 M. and PGA-values of around 0.25 g are chosen for scenario-based calculations.

5.3 Earthquake characteristics

The earthquakes are different with respect to earthquakes over the world. The magnitudes of the earthquakes in Groningen are relatively low in comparison with earthquakes in for example Chili, Turkey or Japan. However, the hypocenter lies quite shallow at a depth of only 3 km beneath the surface. Therefore the earthquakes can have a relatively high intensity and effects at the surface, while acting on a smaller area (NAMplatform, 2014). The earthquakes in Groningen occur on a quite regular basis, which means that applied measures should be able to survive multiple seismic events. Earthquake loads are dynamic loads, generated by seismic waves. The sudden amount of energy which is released during an earthquake is converted into seismic waves. The horizontal S-waves, Love- and Rayleigh waves cause the most damage to buildings because buildings are more susceptible to horizontal than vertical acceleration (Charleson, 2008).

According to Charleson (2008), the three most important characteristics of ground shaking are:

- Value of the peak ground acceleration
- Duration of strong shaking
- Frequency content of shaking

Where Arup takes 0,25 g into account for the Seismic risk study (2013), for the structural upgrading study a PGA of 0,5 g is adopted, for upgrading measures with respect to life safety. Whereas the peak ground acceleration which are being measured in Groningen lie around 0,09 g. The earthquakes in Groningen have a relatively low magnitude, and therefore also a short duration. The shaking usually occurs in the range of 10 seconds.

The natural period of vibration is approximately similar to the amount of stories multiplied by 0.1. For low-rise masonry buildings in Groningen of 1-3 stories, the natural periods will lie between 0.1 and 0.3 seconds. Mainly the first mode of vibration is important.

Damping is the dissipation of energy; which leads to a decay of earthquake vibrations. In buildings, it is mainly caused by internal friction within building elements (Charleson, 2008).

5.4 Lateral force

Forces induced by earthquake accelerations are dependent on multiple factors:

- Seismic hazard;
- Ground conditions; and
- Characteristics and parameters of the structure (Wikipedia, 2014)

Earthquakes cause horizontal and vertical ground shaking. Of main importance are the lateral (horizontal) forces induced by the quakes. The accelerations due to the shaking of the ground are transferred through the superstructure of the building. Seismic forces are inertia forces which arise when the mass of the structure resists the acceleration. Inertia forces can be assumed to act at the center of mass. For a schematizatin see fig. 9.

A consequence of this is that buildings with heavy concrete floors or roofs attract more seismic forces than buildings which are provided with light timber floors.

The buildings in Groningen are 80% unreinforced masonry structures, which is a heavy form of construction. The building can be seen as a cantilever. Therefore inertial forces are higher at higher floor levels. The horizontal force at the base (base shear) is an accumulation of the inertial forces above (Devdas Menon, 2008).

For calculations, a static equivalent force can be used, in which dynamic effects are taken into account (nonlinearity and plasticity). It is an elaboration on Newton's law (F=M·a), which reads as follows:

F_b=m·PGA·DAF·/q>R
F_b=equivalent load on superstructure
m=mass of the structure
PGA=peak ground acceleration
DAF=dynamic amplification factor
q=behavior factor

The q-factor is applied to take into account plastic behavior of the structure; a higher q-factor will decrease the value of the earthquake loading. If the structure has low plasticity q values are in the range of 1 to 2. If the plasticity is average or high, q values are 2 to 6.

Since earthquake loads are directly proportional to building mass, resulting force is assumed to act from the center of mass of a building. However, buildings *resist* the horizontal loads through the center of stiffness. A difference of the Center of Mass with respect to the Center of Stiffness causes a rotational force in addition to the horizontal force which is called torsion (Goodwin, Tonks, & Ingham, 2011).

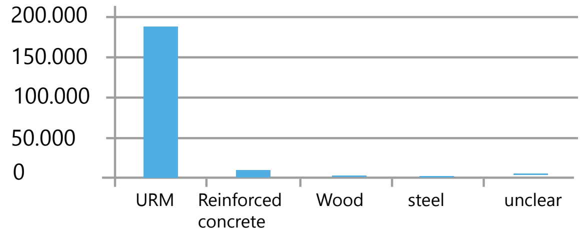


Figure.7: Percentage URM buildings in Groningen | Source: own image on the basis of data of Arup

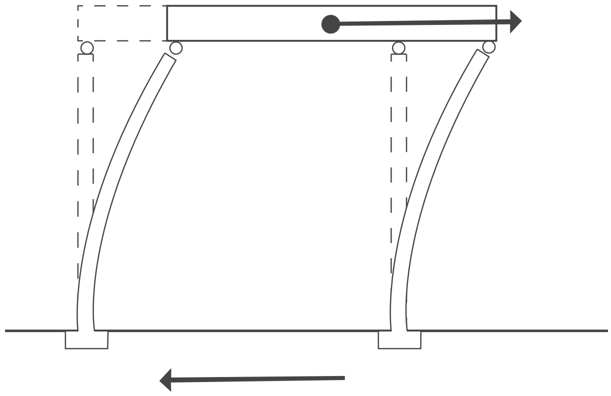


Figure.8: Inertia force due to acceleration at the base | Source: adapted from Charleson (2008)

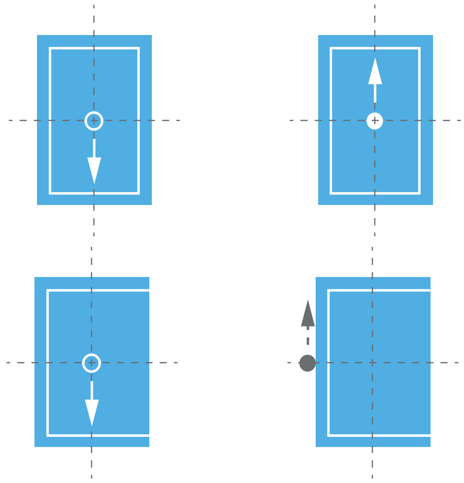


Figure.10: Favorable (a.) and unfavorable (b.) plans | Source: adapted from Arup (2013)

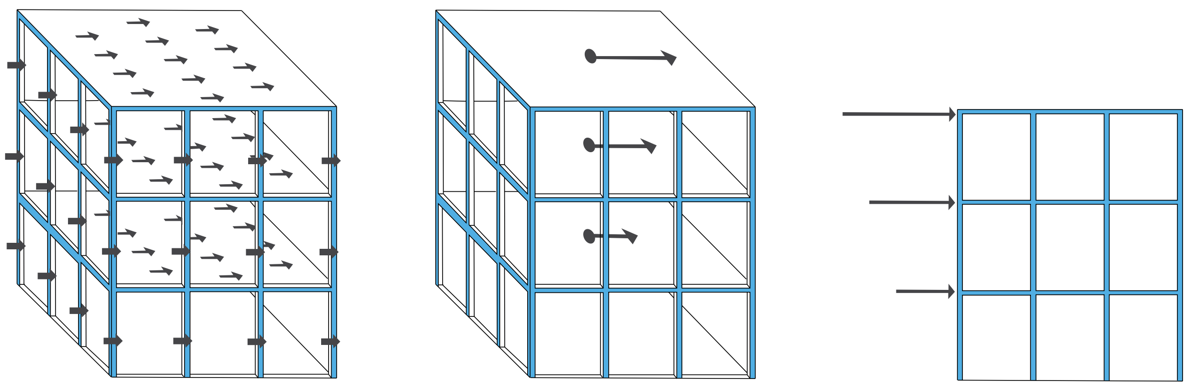


Figure.9: Simplification of the modelling of seismic loads in structures | adapted from Charleson (2008)

6. Seismic resistance

The first assesment is done by rapid visual screening. This external screening method is used to find immediate risks such as: falling hazards, immediate danger of collapse and walls with an inclination. After immediate risks are mitigated, for example by means of temporary shoring, research must be done into the physical condition of the building. By using the inherent strength of the existing building, the extent of intrusive measures can be minimized (Goodwin, Tonks, & Ingham, 2011).

Research must be done into the capacity of structural elements, the seismic resistance and the deficiencies (Khan, 2013), in order to set up measures which are tailored to the specific condition of the building. However, extensive research into the existing seismic resistance is complex and time-consuming. A trade-off has to be made between extensive research potentially resulting in less intrusion, or more superficial analysis resulting in quick implementation and presumably more intrusions.

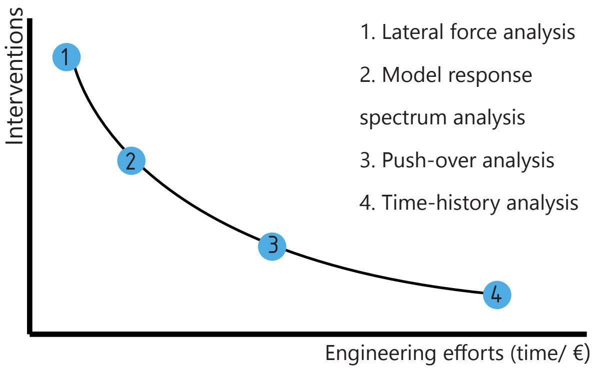


Figure.11: Costs-benefit consideration for calculation methods | Source: adapted from de Boer (2014)

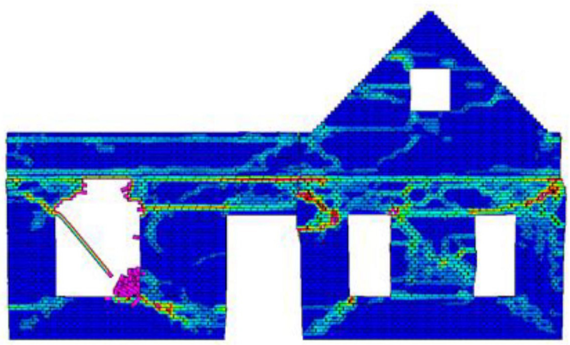


Figure.12: Non-linear time domain analysis | Source: de Boer (2014)

6.1 Assessment

Retrieve documentation

For the assessment of the existing condition, it is necessary to retrieve all available documentation (plans, sections, details, specifications, alterations) related to the building design. Also photographs of the construction before and after an earthquake prove to be very useful.

Analysis

For the estimation of the seismic performance, an assessment must be made of the structural behaviour; from linear to nonlinear failure (Khan, 2013), depending on the extent of the ground accelerations.

There are four general computational calculation methods proposed by de Boer (2014) which are listed in order of increasing complexity: the lateral force analysis, the modal spectral response analysis, the non-linear static push-over analysis and the non-linear dynamic time domain calculation. For calibration and validation of calculation models, shake table testing can be done with models of the building or building parts.

Ratio wind load / seismic load

When dealing with earthquakes, mainly horizontal loads are an issue. The lateral seismic loads are proportional to the mass of a building. Wind load is proportional to the size and shape of the building. Since both are lateral loads, a first estimation on the seismic resistance can be made by taking the ratio of the seismic and wind loads (Arup, 2013) because wind also requires lateral load resisting systems. However, the distribution of seismic and wind loads is quite different, and therefore this ratio does not always hold.

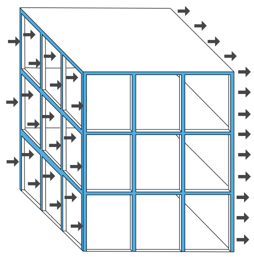


Figure.13: Windforces on a structure | adapted from Charleson (2008)

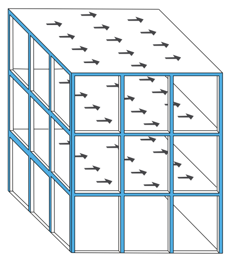


Figure.14: Seismic forces on a structure | adapted from Charleson (2008)

6.2 Seismic deficiencies

'Earthquakes do not kill, unsafe buildings do'. According to Charleson, (2008) the extent of damage depends 'not only on the magnitude of the earthquake, but also on the soil, the building configuration, the quality of design and the construction'. The unreinforced masonry buildings in Groningen perform poorly in earthquakes. Several deficiencies are listed below:

Seismic design

The buildings were constructed before seismic regulations were acknowledged to be necessary for the building stock. Therefore, the buildings are not seismically designed by an engineer.

Adjacent buildings

Buildings standing close or in contact with one another might be damaged due to pounding. However, the North-East of Groningen is built in low-density, masonry is quite stiff and the ground accelerations are relatively low. Therefore pounding may not be a major issue.

Building condition

The structural capacity of the building can be reduced by damage of prior earthquakes, and the condition of the building impaired by bad maintenance and deterioration of building materials. As stated by Khan (2013), cyclical maintenance is essential to

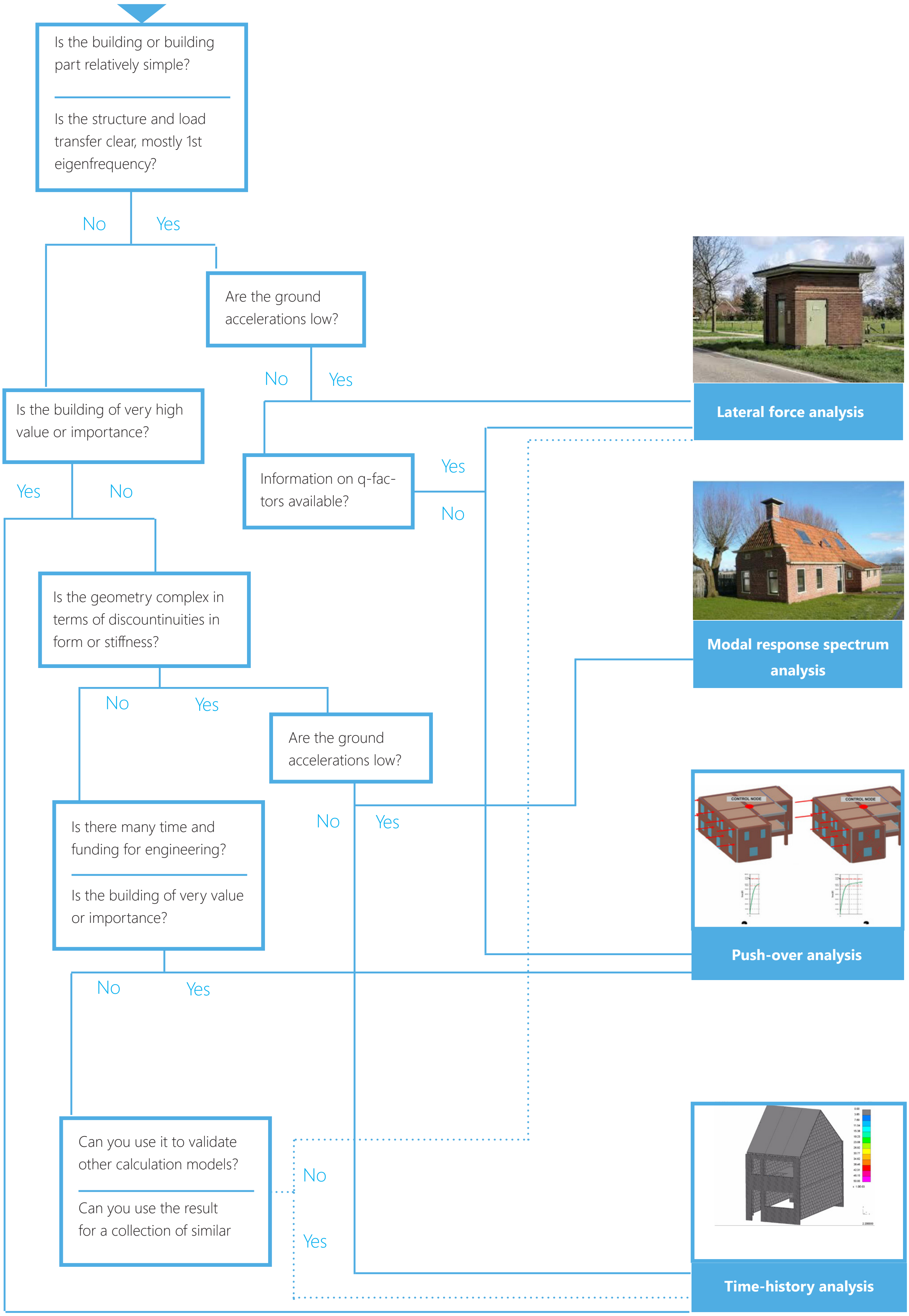


Figure.15: Decision tree for the choice of calculation method | Source: own image on the basis of pictures and criteria by de Boer (2014)

safeguard the building for moisture penetration and erosion of materials. Deteriorated mortar joints can weaken entire walls.

Building material

Important material variables are defined by FEMA (2006) as: the masonry unit type, the wall construction type and material properties of its constituents. The masonry building tradition has a wide variety of solid brick bond patterns, influencing the effective thickness of the wall and the response to in- or out-of-plane forces. The components have specific characteristics. Tensile, compressive and shear strength and –moduli can differ significantly between several types of masonry units, brick and mortar. Older mortars can be weaker than the masonry units. Newer mortars consist of more cement, and are therefore stronger, but also more susceptible to brittle cracking and consequently, they have a lower deformation capacity.

Building mass

Masonry walls are quite heavy, resulting in high inertial forces.

Parapets, chimneys and ornamentation

Non-structural elements as parapets, chimneys and ornamentation are frequently applied in the area of Groningen. These elements are called 'falling hazards' and are susceptible to damage.

Besides above mentioned characteristics; a building should be structurally assessed on the following qualities:

- **Lateral strength**
- **Lateral stiffness**
- **Ductility**
- **Integrity / stability**

Lateral strength

An assessment of the strength concerns the overall- and local strength, since strength depends on the capacity of each (or the weakest) component (Devdas Menon, 2008).

Masonry is quite strong in resisting vertical gravity loads which cause compression (Reitherman & Perry, 2009). Damaging earthquake loads are mainly horizontal, and therefore the building should have adequate later load resisting systems. Earthquake acceleration occurs in multiple directions, and causes the floor slabs to move rigidly in the horizontal plane. The slabs pass on their inertial forces to the masonry walls, which encounter forces in-plane and out-of-plane. The out-of-plane forces act inwardly and outwardly, causing plate bending or flexural stresses which result partially in tension and partially in compression. 'If the tension exceeds the compression induced by the dead loads, this can cause cracking, since masonry is weak in resisting tension' (Devdas Menon, 2008). Cracks due to out-of-plane bending tend to be vertical cracks.

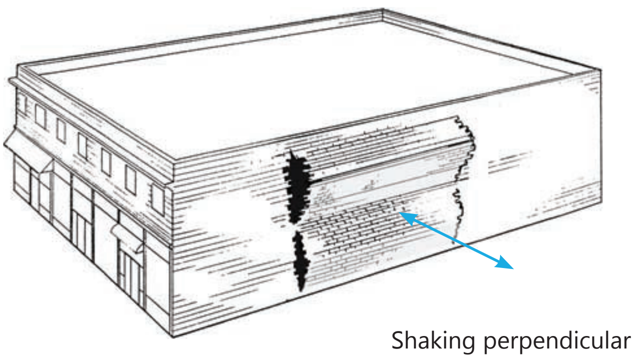


Figure.16: Out-of-plane failure of unreinforced masonry Walls | Source: Rutherford and Chekene

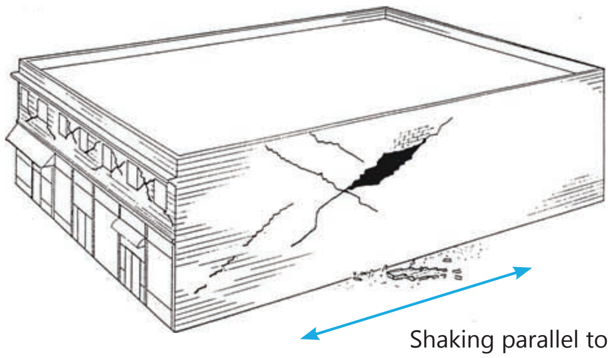


Figure.17: In-plane failure of unreinforced masonry Walls | Source: Rutherford and Chekene

The in-plane forces, acting parallel to the wall plane, cause shear. Shear forces attempt to push part of the wall to slide horizontally with respect to the rest. Shear 'forces a rectangular wall to take the shape of a parallelogram, in which one diagonal gets compressed and the other gets extended' (Devdas Menon, 2008). As a result, diagonal cracks are likely to occur.

Lateral stiffness

Structural elements resist force in proportion to their stiffness (Charleson, 2008). Because masonry walls are relatively stiff, they attract a lot of forces. The masonry wall should have enough resistance to withstand the effects of lateral loads perpendicular and parallel to its plane (Wijte, 2014). Stiffness is proportional to the structural height of an element. For buildings with cavity walls, only the slender inner leaf is load bearing. This means that the stiffness perpendicular to the plane is low. Older buildings with solid load-bearing walls contain walls with more structural height, which is favourable.

Ductility

Ductility is the degree to which a material allows plastic deformation. This characteristic allows the structure to deform and dissipate some of the earthquake energy without instantly breaking (without warning). Ductility is therefore a favourable characteristic when dealing with earthquakes. A building can have ductility, by material use, or detailing design. The unreinforced masonry buildings in Groningen, which are built out of a combination of bricks and mortar, are predominantly brittle. Mortar is the 'glue' that holds the bricks together and tends to crack in a brittle manner. 'Brittleness – being the opposite of ductility- is quite unfavourable and causes the structure to be designed up to 6 times the force of ductile structures' (Charleson, 2008).

Integrity

In order to transfer the inertia forces in the structure towards the foundation, the connections between the building components should be adequate. (Devdas Menon, 2008). When the connecting anchors become rusty, the integrity of the building is threatened.

The buildings in Groningen mostly have weak diaphragm-to-wall connections; the building lacks the connections to act together as one (Goodwin, Tonks, & Ingham, 2011). Buildings also have excessively flexible diaphragms.

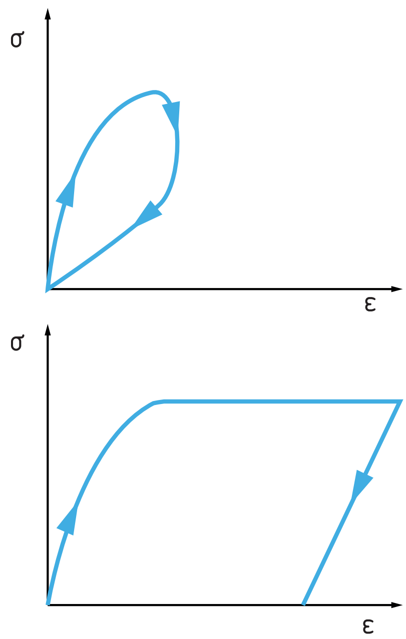


Figure.18: Plastic and elastic behavior | Source: adapted from TNO (2014)

Figure.20: Pharmacy in Loppersum | own image

Figure.19: Tensile anchor to prevent the facade from falling over | own image

Weak connections

This pharmacy building in the centre of Loppersum faces the problem of weak diaphragm to wall connections. This causes a threat of the front façade falling over. The applied temporary solutions are timber framing and a tensile chord fixed to the diaphragm anchors.

Figure.21: Entrance of a barn shed in Loppersum | own image

Figure.22: Tear at the lintel of barn entrance in Loppersum | own image

In-plane forces

Due to earthquake acceleration, the heavy concrete lintel is forced to move in the horizontal plan, passing on forces to the narrow corner transition. The rectangular opening is forced into a parallelogram, causing high stress concentrations in the corner. A temporary timber strut is placed as a relief for the structure, and to prevent collapse, since the support of the lintel is teared and unreliable.

Figure.23: Interior of barn with timber frames in Loppersum | own image

Figure.24: Tear in the wall due to out-of-plane forces | own image

Out-of-plane forces

This barn was built with a masonry base wall and a roof of timber frames. The thrust force in the timber frames induced an out-of-plane load to the masonry wall, causing vertical cracks at the location of the frames.

6.4 Repair

Before starting with structural upgrading, initial damage of the structure should be repaired. Repair activities will comprise mostly of the repair of cracks.

- Reinstatement of repointing mortar

Effective reparation can be done by a pressure injection of epoxy/ grout into the voids, in which the mortar should be properly cured.

- Adding rebars in joints

Adding embedded rebars in joints is a technique which is frequently applied by local structural firms in Groningen. One of these systems is called the HAS-system. A horizontal joint is grinded out, a rebar called a 'wokkel' is placed as reinforcement and the joint is filled up with mortar. For this part of the structure additional tensile strength is provided with minimum visual impact. The upgraded part will become a lot of stiffer; consequently attracting more forces. The area directly next to the upgraded zone will therefore be susceptible cracking due to the change in stiffness.

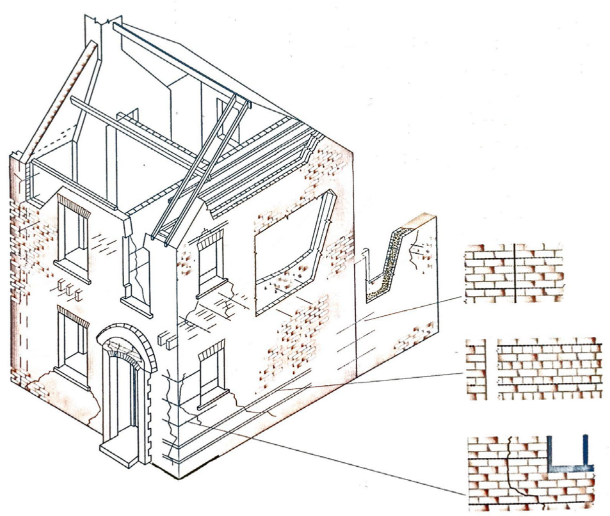


Figure.25: Repair of masonry | Source: adapted from Adamas

7. Design principles

A distinction can be made between resistant- and responsive measures. Resistant methods are seen as conventional, and are based on strength and stiffness and are therefore dependent on geometry and configuration, distribution and material used. Architectural decisions are bound and framed by structural objectives as avoiding torsion, discontinuities, set-backs and promoting symmetry, continuity and regularity (Beltran, 2014). This approach is based on appropriate structural configuration, the careful detailing of structural members and the connections between them (MCEER). Response-controlled methods on the other hand attempt to reduce the earthquake-generated forces (Harris, 2001) by means of energy dissipation by mechanical devices attached to the structure such as dampers or base isolation.

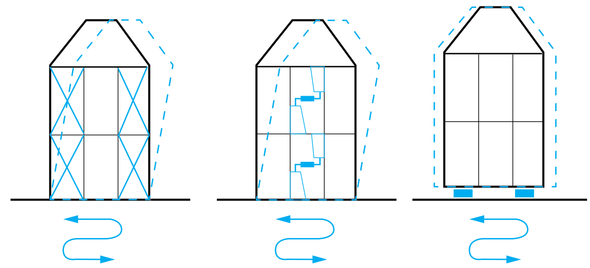


Figure.26: Resistant and responsive methods| adapted from Japan property central

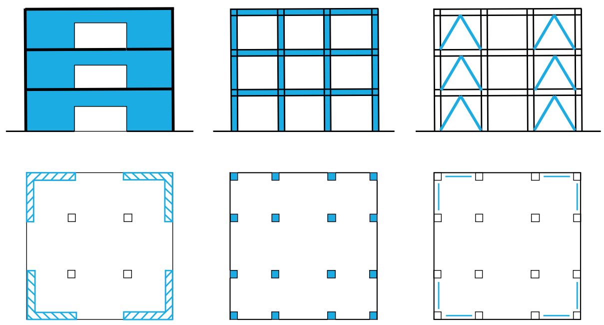


Figure.27: Resisting elements in the perimeter | adapted from Arup (2014)

7.1 Principles for new buildings

Firstly the aspects and principles with respect to new building design will be discussed.

A. Global strength, stiffness, stability, ductility

Distribution of seismic-resisting elements

By placing the resisting elements for seismic lateral loads, such as braces and shear walls, at the perimeter of the building, the greatest resistance is achieved since the lever arm will be the largest.

Choice of material and detailing

It is favourable to use materials with a high ductility, such as well-detailed steel, timber, reinforced concrete, reinforced masonry and to design details with enough ductility and deformation capacity.

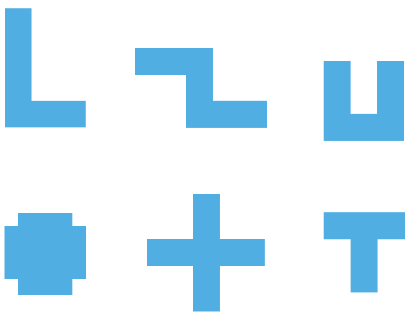


Figure.28: Unfavorable plans |

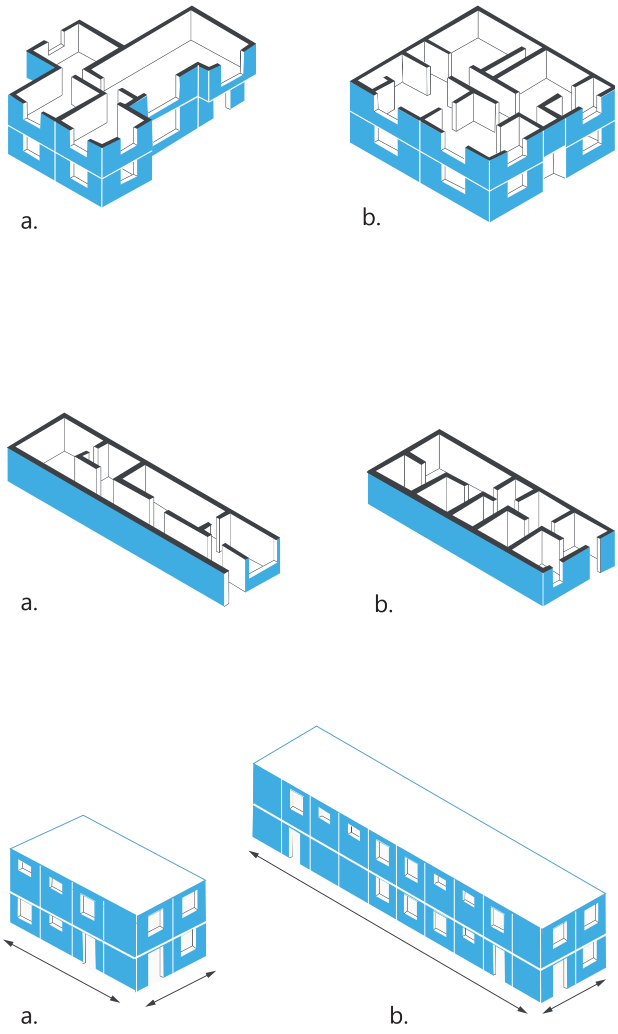


Figure.29: Favorable (a.) and unfavorable (b.) plans

Sources: all diagrams are adapted from Arup (2014)

B. Building configuration and mass distribution

The building configuration and distribution of mass influence the flow of forces.

Limited mass

Since seismic forces are directly proportional to the mass, it is beneficial to build as light as possible. For example with timber frame construction, a combination of timber and steel or even with fibre reinforced polymers.

Regularity in plan

Regularity and symmetry in plan is important for the load transfer. The resultant of the forces is located in the centre of mass, whereas the centre of rigidity withstands the forces. A difference in location of these centres results in torsion. The plan should be symmetric, including aspects as cut-outs of the floors. When designing the plan, one should avoid L, T, U, V, Z-shapes since these configurations introduce high shear stress and stress concentrations in the re-entrant corners. A plan setback of at least 15% to be considered re-entrant. Also the length of the walls should preferably be equal in both directions; in any case not more than 3 times the width.

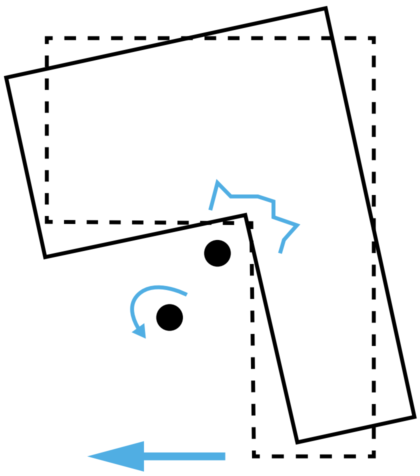
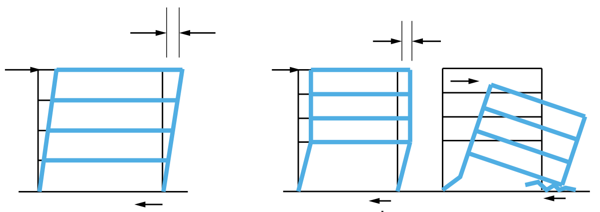


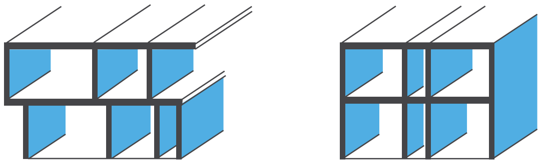
Figure.30: Re-entrant corners | Source: adapted from Nexus



a. b.

Figure.31: Weak story effect

Figure.33: Unfavourable elevations



a. b.

Figure.32: Unfavourable (a.) and favourable (b.) elevations

a. b.

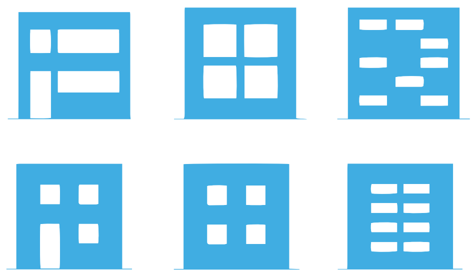


Figure.34: Unfavourable (a.) and favourable (b.) elevations

a. b.

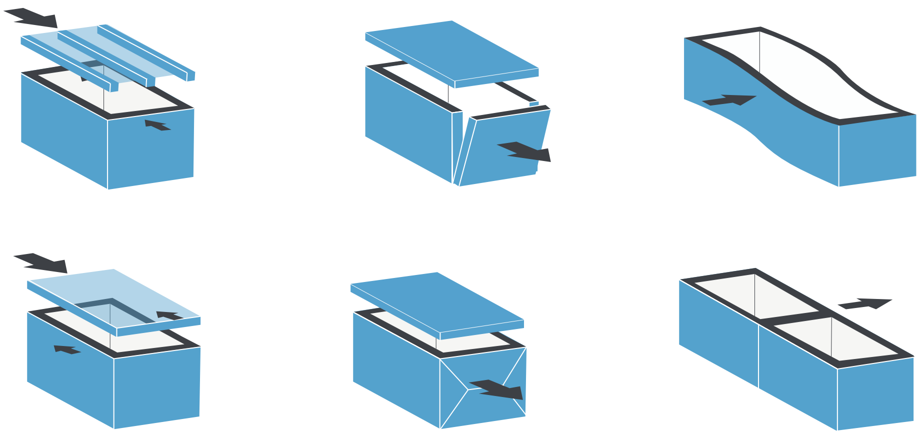


Figure.35: Unfavourable (a.) and favourable (b.) elevations

Sources: all diagrams are adapted from Arup (2014)

Regularity in elevation

The elevation should also be designed regular and continuous with respect to load transfer, since sudden changes of stiffness can induce a concentration of forces. When changing height in elevation, it is wise to provide a dilatation or split to the building. Flexible stories, open ground stories or ground floors with too many windows in combination with stiffer upper floors should be avoided and are problematic due to the difference in deformation. A disproportionate drift which is concentrated on a specific story can be the cause of collapse (Khan, 2013).

Distribution of live loads

Heavy loads should be placed lower in the building, to minimize the inertia forces. They should also be placed close to the centre of rigidity in order to avoid torsion.

C. Load path

Interconnection of members

One must also make sure that the connection between the walls and the diaphragms are sufficient. In this way, the building can withstand forces in a box-like manner.

Stiff diaphragms

Stiff diaphragms distribute forces related to the stiffness of each wall, whereas flexible diaphragms distribute forces on the basis of mass. This means that the walls perpendicular to the loading will experience significant loads in the weak-out-of-plane direction, possibly causing local failure. By creating stiff diaphragms, the forces can be distributed to walls that are parallel to the forces, and therefore resistant to those in-plane forces, which is more favourable.

Redundancy

By providing structures with a second load path, its redundancy will increase and it will not collapse immediately if some members fail.

D. Building components

In the design one should avoid long unsupported walls, by adding shear walls in short direction. Furthermore a wall should not have too large openings (see fig. 34); this will decrease its shear strength. In case of openings, take care of a direct transfer of forces between the cut-outs.

E. Non-structural elements

Carefully design possible falling hazards which are non-structural elements such as: chimneys, parapets, outer leaf of cavity walls, ornaments, balcony's and awnings. Therefore the detailing, connection and fixation of these elements should be done with great care.

F. Reduce demand

Instead of strengthening the building, one can attempt to reduce the demand. Building with ligher materials can also be seen as 'reducing demand'. Buildings have an inherent ability to dissipate energy, this is called damping. However, damping by the building itself results in a degree of damage, since it is based on friction between elements.

Enhance damping capacity

By equipping the building with additional devices which have a high damping capacity, the damage can be limited.

Isolate from ground

By setting the building on base isolators, the building will move, but it can retain its original shape (MCEER) without experiencing too much deformation. Furthermore, the natural period of the building will be longer, which reduces the acceleration of the structure.

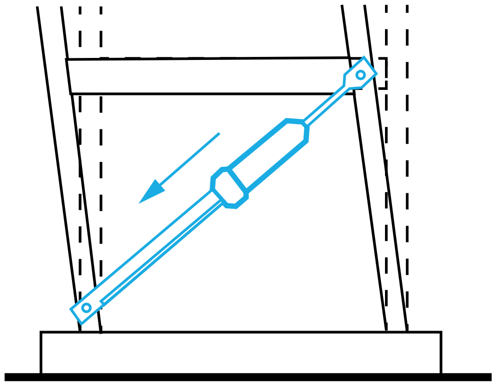


Figure.36: Damping device | Source: adapted from MCeer

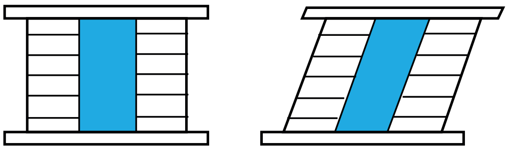


Figure.37: Lead-rubber bearing of base isolation | Source: adapted from MCeer

7.2 Seismic retrofit principles

The seismic principles with respect to retrofit are based on the seismic design principles, but adjusted for existing buildings. A summation will be given of structural objectives based on lists of the Seismic retrofit handbook of Devdas Menon (2008) and the structural upgrading report of Arup (2013);

A. Global strength, stiffness, stability and ductility

Increasing building strength / stiffness
Increase lateral strength by adding lateral force resisting systems. Making the building stiffer will reduce its need to be ductile.

Decreasing building mass
Seismic forces can be reduced by removing or replacing heavy elements by lighter versions such as non-structural masonry, heavy interior walls and heavy masonry chimneys.

Increasing building ductility
The building should be provided with more ductile connections. And if possible, brittle materials should be replaced by ductile ones, such as timber and well-detailed steel.

B. Building configuration and mass distribution

Removal of plan and elevation irregularities
Irregularities should be removed out of the plan and elevation. This can be done by rearranging or removing elements to align the mass and rigidity centres or by disconnecting and separating aberrant building parts.

C. Load path

Connection between the elements
Dutch building methods are based on stacking construction; therefore connections mostly rely on friction. By increasing the connectivity between the elements, the loads can be transferred in a more favourable way, through uninterrupted load paths. This can be achieved by upgrading the connection of the wall-roof and wall-floors by anchors.

Increase building redundancy
By enhancing the redundancy, the chance on progressive collapse is decreased.

Stiffen the floor diaphragms
By stiffening the floors, the diaphragm action is increased.

D. Building components

Local modification of structural elements
By improving the strength and deformation capacity of structural members, local failure can be prevented.

E. Non-structural components

Local modification of components
By improving the connection, strength and deformation capacity of non-structural members, falling hazards can be prevented.

F. Reduce demand

Enhance damping
The building can be equipped with extra damping systems to dissipate seismic energy to enhance the buildings damping capacity.
The existing building can be mounted on base isolators, in order to increase the building period and reduce seismic forces by employing damping.

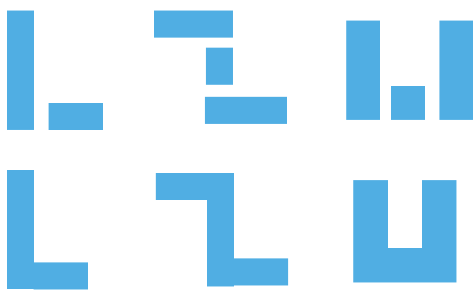


Figure.38: Removal of irregularities from plans | Source: adapted from Arup

Figure.39: Parapet strengthening with near-mounted FRP strips | Source: : Dizhur

8. Retrofit techniques

Solutions range from low-cost solutions to highly engineered methods. Arup has defined several levels of structural upgrading (2013). Techniques are ranked in levels, starting with the quickest and most cost-effective techniques, leading up to heavier and more radical interventions. >>

Level 0	Temporary measures e.g. shoring
Level 1	Mitigating measures for building parts at risk
Level 2	Strengthening of wall-diaphragm connections
Level 3	Stiffening of diagrams in the construction
Level 4	Strengthening of existing walls
Level 5	Replacing and adding walls
Level 6	Strengthening of foundations
Level 7	Demolition and rebuilding

8.1 Level 0: Temporary measures

Deficiencies

In order to mitigate immediate hazard, temporary measures can be applied to enhance global strength, provide stability and prevent collapse or to temporarily strengthen building elements against local failure.

Description

- *Temporary shoring*

External structures are placed perpendicular to the exterior façade. Shoring in the form of diagonal struts can be executed in timber or steel, potentially fixed into the ground. Shoring is particularly interesting if the building has limited lateral load resisting systems in a certain direction.

- *Temporary strong backs*

Temporary strong backs in the form of vertical bracing increase the out-of-plane strength and stiffness of structural elements.

- *Temporary vertical support*

Added columns or supports can be applied in order to relief the load on structural elements, prevent collapse, or protect inhabitants when collapse occurs.

- *Temporary façade anchoring*

Steel ties which are installed to connect the outer layer to internal walls can be rusted out (Russel, Ingham, & Griffith, 2006). Temporary anchoring of façade is applied to prevent the façade of falling over due to insufficient connection with the diaphragms

Temporary measures	
Disruption	Low (applied externally)
Visual impact	Temporary
Functional impact	Temporary
Reversibility	High
Costs	Low

Figure.40: Temporary timber shoring, Loppersum | Own image

Figure.41: Temporary steel shoring and removal of balcony, Onderdendam | Own image

Figure.42: Temporary tensile tying of the facade, Loppersum | Own image

8.2 Level 1: Mitigating measures for parts of the building at risk

Deficiency

Non-structural objects which are susceptible to falling off a building can form an even greater risk during earthquakes than the damage to the structure (Arup, 2013). These objects are already hazardous at low levels of ground acceleration and are very susceptible to earthquake damage due to their low bending strength and inadequate fixation (Rutherford & Chekene, 2006).

Description

Hazard can be mitigated by tying, removing or replacing the objects by lighter versions. Elements susceptible to damage are:

- *Parapets*

Parapets are simple to strengthen, by bracing them with steel angles towards the roof. The backside could also be strengthened with FRP strips.

- *Chimneys*

Chimneys are more complex to strengthen. An internal technique is to fix the chimney to the building diaphragms at each level or to add an internal supporting structure. External techniques include bracing the protruding part towards the roof structure with steel or timber angles or applying FRP-strips.

- *Balconies*

Balconies can be braced, or replaced by lighter alternatives, for example made of composite material .

- *Outer leaf of cavity*

Also the integrity and presence of cavity wall ties should be checked. If proven insufficient, for example by corrosion, they should be replaced or assisted by additional ties.

- *Decorative panels or roof tiles*

Brittle ceramic roof tiles or decorative panels with inadequate fixation also form a threat. A solution is to fix the tiles to the roof with mechanical fixers or to apply a snow guard fence.

- *Furniture and lightweight partition elements*

Furniture and light weight partitions can fall over. By adequately fixing the furniture to the structure, this can be prevented.

Figure.43: Parapet bracing | Source: Structural Renovations

Figure.44: Chimney braced towards the roof | Source: KGW

Brace element	
Disruption	Little (applied externally)
Visual impact	Parapet FRP: low Struts: low Chimney: FRP: may be suitable for plastered elements Struts: high
Functional impact	Low
Reversibility	FRP: low Bolted steel struts: high
Costs	Low

Remove or replace elements	
Disruption	Little (executed externally)
Visual impact	High: change of building character
Functional impact	Chimney: high Rest: depends on situation
Reversibility	Low
Costs	Low

8.3 Level 2: Strengthening wall-floor and wall-roof connection’

Deficiency

A very effective method of seismic upgrade is strengthening of the wall-floor and wall-roof connections. Decent connections allow the seismic forces to be transferred from floors to load resisting structural elements such as walls and ultimately to the foundation. The existing connections which are installed to connect the outer layer to internal walls (steel ties) can be insufficient for earthquakes or they can be rusted out through time (Russel, Ingham, & Griffith, 2006).

Description

An additional network of ties can be provided, which have to be able to cope with:

- Shear from the diaphragm trying to slide across the wall; and
- Tension from the diaphragm and wall trying to separate.

Steel slats, nailed to the beams of the floor can be anchored to the walls. The anchors, which run through the wall, can be embedded in a concrete topping on the floor and run to the reinforcement on the wall to enhance the connectivity.

Figure.45: Added walll-diaphragm anchors | Source: San Diego government

Strengthen wall-diaphragm connection	
Disruption	Little
Visual impact	Very low
Functional impact	Very Low
Reversibility	High: steel anchors and bolt connections However: anchors are drilled through the fabric
Costs	Low

8.4 Level 3: Stiffening of diagrams in the construction

Deficiency

Stiff diaphragms distribute forces related to the stiffness of each wall, whereas flexible diaphragms distribute forces on the basis of mass. This means that the walls perpendicular to the loading will experience significant loads in the weak out-of-plane direction, possibly causing local failure. By creating stiff diaphragms, the forces can be distributed to walls that are parallel to the forces and are therefore more resistant to the in-plane loads, which is more favorable.

Description

The existing diaphragms of the floors and roof can be upgraded, replaced, or assisted with an additional diaphragm. These interventions can be implemented on the ceiling or the floor

- *Mechanical fastenings* are added to take shear and tensile loads;
- *Ties at the periphery;*
- An extra layer of planks perpendicular to the direction of the existing planks;
- *Additional layer of sheeting* is added such as sheets of plywood or oriented strand- board
- *Casting a concrete screed* (light weight) topping over the existing floor. The concrete layer can be reinforced by a fine steel mesh or fibres;
- *Casting a concrete slab* over the existing floor. Reinforcing bars are placed in both directions. Extra weight will also induce extra inertial forces;
- *Steel truss system* below the timber floor in case it is not feasible to increase the existing floor;
- *New bracing* between roof beams;
- *Extra layer of sheeting* on the roof beams;
- *Create truss structure* or A-frames out of the roof beams.

Figure.46: Stiffening of a floor diaphragm by FRP | Source: Dizhur

Figure.47: Stiffening of a floor diaphragm adding steel frame | Nelson

Stiffening of diagrams	
Disruption	Moderate
Visual impact	Impact on either ceiling of floor
Functional impact	Very little
Reversibility	Overlay: low Sheeting: high Bracing: high
Costs	Low

8.5 Level 4: Strengthening of existing walls

Diaphragms are strengthened to provide a more favorable load transfer to the walls. The walls in turn, have to be able to withstand the seismic forces. An increase of the wall resistance comprises of an improvement of the in-plane flexural and shear capacity and ductility of the wall and the out-of plane flexural capacity. Heavy brittle walls, such as unreinforced masonry, are vulnerable to out-of-plane forces.

8.5.1 Steel exterior or internal elements

Deficiency

The wall span and its slenderness are too high. Measures are needed preventing the wall from bowing outward or inward.

Description

- *Columns/ strong backs*

Vertical structural members can be placed as bracing against the wall, in the form of steel posts or mullions;

- *Buttresses*

Additional buttresses can be constructed adjacent to the wall. The buttresses should be well integrated into the wall structure.

- *Diagonal struts*

The unsupported length of the wall can be decreased by placing diagonal struts from the wall to the ceiling diaphragm.

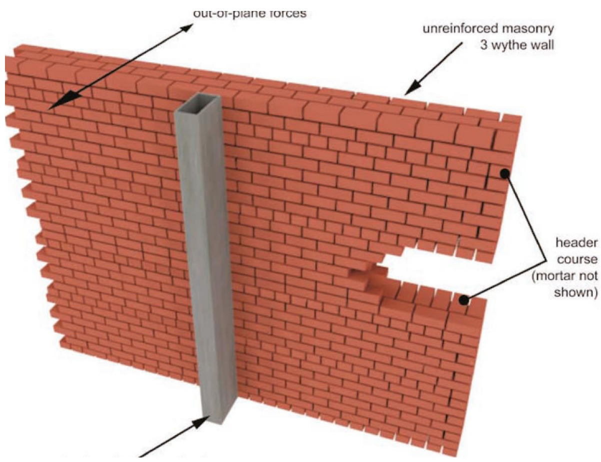


Figure.48: Steel strongback for a masonry wall | Source: FEMA

Figure.49: Steel strongbacks in the interior | Source: Dizhur

Figure.50: Diagonal struts from floor to wall | Source: Dizhur

Steel exterior or internal elements	
Disruption	against the wall: low in the wall: high
Visual impact	against the wall: high in the wall: low
Functional impact	against the wall: moderate in the wall: little
Reversibility	against the wall: high in case of steel low in case of in-situ concrete in the wall: very low, due to drilling into buidling fabric
Costs	Low

8.5.2 Concrete overlay

Deficiency

The in-plane flexural capacity and ductility and the out-of plane flexural capacity of the wall is too low.

Description

- *Shotcrete overlay*

The wall is strengthened by adding a layer of reinforced concrete inside and/or outside the wall. Due to the heaviness of concrete, this method adds weight to the structure.

- *Ferrocement with wire mesh*

The overlay can be done with ferrocement, and fine wire mesh. The mats are placed on both sides of the wall, creating a 'sandwich' wall.

- *Splint and bandage strengthening technique*

The ferrocement can also be applied in the form of vertical and horizontal belts (IS13935, 2005) which are placed between openings and at plinth level. This is called the splint and bandage strengthening technique.

Figure.51: FRP applied to a wall | Source: Dunning Thornton consultants

Concrete or FRP wall overlay	
Disruption	On both sides: high, requires relocation of inhabitants Externally: low-moderate
Visual impact	High, can be suitable for plastered walls
Functional impact	Very little
Reversibility	Low
Costs	Low

8.5.3 Fibre-reinforced polymer

Deficiency

The wall lacks in-plane shear strength and out-of-plane flexural capacity.

Description

The wall can be fully covered with FRP (fiber reinforced polymer) strips or in bands. Strips FRP have a very high strength and low weight, which is very favorable for seismic design.

8.5.4 Post tensioning

Deficiency

There can be tension in an unreinforced masonry wall, due to in-plane or out-of-plane bending. By inserting pre-stressing steel to create compression in the wall, the tension can be counteracted.

Description

Post tensioning can be installed in the wall by drilling cores, or be externally fixed to piers. Corrosion can be avoided by using plastic coated steel or FRP bars. A minimum thickness is necessary as a margin. Dutch (cavity) walls might be too thin to apply post-tensioning. Access is needed on top of the wall, for many Dutch houses with pitched roofs the top of the outer wall is not easily accessible.

Post-tensioning	
Disruption	Moderate
Visual impact	
Functional impact	Very little
Reversibility	Little
Costs	Moderate

8.5.5 Penetrations in wall

Deficiency

The shear resistance of the wall is influenced by the amount and size of penetrations (Robinson & Bowman, 2000). Near the presence of openings the section will have less shear strength than the full wall height. At this transition of stiffness the wall is susceptible to tearing.

Description

- *Infill of wall openings*

A solution could be to fill in the opening into a solid wall. This would have a negative effect on the experience of the space since the view is removed.

- *Enlarge openings*

The opposite action could also be an option; to enlarge the window opening. The change in pier slenderness could induce a switch to a more ductile rocking mechanism instead of brittle failure modes (Arup, 2013).

- *Strengthen window frame*

The window frame can be strengthened by adding a reinforcing lintel band. Furthermore, a steel window frame could be placed into the opening.

Figure.52: Strengthening of wall penetration by a steel braced frame | Source image: Nelson

Wall penetrations	
Disruption	Moderate
Visual impact	Infill: very high Enlarge: high Strengthen: high
Functional impact	Infill: very high Enlarge: - Strengthen: moderate
Reversibility	Infill: very low Enlarge: low Sterngthen: high
Costs	Moderate

8.6 Level 5: Replacing and adding walls

In case strengthening of the existing walls is not sufficient, one can choose to replace or add walls as addition to the lateral load resisting system. When adding walls, one should research if additional foundation systems are necessary, since the additional walls will transfer extra forces.

8.6.1 Add concrete or masonry shear wall

Deficiency

Additional global strength and stiffness is necessary, and a reduction on the demand of existing walls.

Description

Additional concrete or reinforced masonry walls can be placed. These walls can shorten the span of long, unsupported walls.

8.6.2 Add steel moment frame

Deficiency

Additional global lateral strength is necessary and a reduction on the demand of existing walls.

Description

- *Braced frames*

A way to strengthen walls is to add V-braced or X-braced frames. Frames with diagonals are far stiffer than moment frames.

- *Moment frames*

Moment frames can be added for additional horizontal resistance, out of reinforced concrete or steel. Concrete might fit better into the interior aesthetics, whereas steel has a higher degree of irreversibility and less weight.

One should be aware of the stiffness of the moment resistant frames with respect to the unreinforced masonry. The new system must be stiff enough to resist seismic forces before its horizontal drift damages the existing structure and fabric excessively (Reitherman & Perry, 2009).

Figure.53: Addition of a steel frame | Source: Dunning Thornton consultants:

Figure.54: Addition of concrete moment frames | Source: Dunning Thornton consultants

Addition of walls or frames	
Disruption	High, might demand relocation of inhabitants
Visual impact	High
Functional impact	Braced frame: high (intrusiv) Moment frame: low
Reversibility	In-situ: low Steel frames: high

8.6.3 Replacing of walls / façade

Deficiency

In the case the existing walls are of such a low-strength, that is not feasible or possible to upgrade them, they can be replaced by walls with more ductility or strength (Arup, 2013). This holds for interior and exterior walls.

Description

The wall which is placed back should have more ductility, for example reinforced concrete, steel or timber.

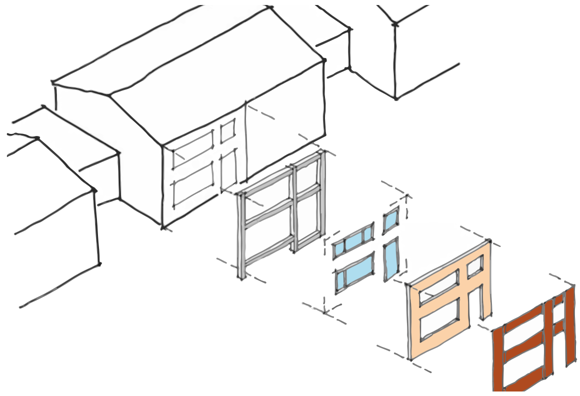


Figure.55: Replacing of the facade by a more ductile frame | Source: adapted from Arup (2013)

Facade replacement	
Disruption	High, might demand relocation of inhabitants
Visual impact	High: building appearnce changes
Functional impact	Moderate
Reversibility	Low
Costs	High

8.7 Level 6: Strengthening of foundations

Deficiency

The seismic forces must be led towards the foundation; therefore also the substructure must potentially be upgraded. The existing foundation or the soil capacity might be insufficient. At higher PGA levels, buildings can be susceptible to sliding of their foundation (Arup, 2013).

Description

Enhancement can be done by casting a new concrete footing, adding foundation piles and by enhancing the connection between the building and foundation to prevent it from sliding off.

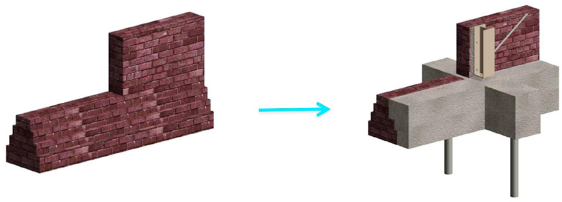


Figure.56: Strenghtening of the foundation | Source: Arup (2013))

Strengthening foundation	
Disruption	Very high
Visual impact	Very low
Functional impact	Very low
Reversibility	Very low, due to concrete placement
Costs	Low

8.8 Level 7: Demolition and rebuilding

If the future value of the building is too low, or the costs of seismic retrofit too high, the building can be demolished as the most radical measure.

8.9 Reducing demand

The following responsive methods were not captured in the list of Arup methods.

8.9.1 Reducing local stress concentration and torsion

Deficiency

Due to the building configuration and mass distribution high stress concentrations and torsional forces are induced in the building.

Description

- *Saw cut-ins*

Upgrading the overall structure may even include weakening parts of the structure in order to make the distribution of the stiffness more symmetric. Saw cut-ins can be made in walls, to counteract the shift between the center of mass and center of stiffness.

- *Split up*

Building parts can be split up into parts with regular building plans.

- *Removing elements*

The demand can also be lowered by removing elements, and so removing weight.

8.9.2 Dampers

Deficiency

Buildings have their own inherent ability to dissipate energy. However the capacity to dissipate without undergoing extensive damage and deformation is limited (MCEER).

Description

Dampers are devices that dissipate a portion of the seismic energy. Dampers can be installed as diagonals of a framework building. Dampers are most effective in flexible buildings. Damping systems can be expensive to install and difficult to cover.

Figure.57: Implementation of dampers into brick wall of an embassady building| Source: : DC 90

Figure.58: Implementation of dampers into brick wall apartement houses Source: DC 90

Dampers	
Disruption	Moderate
Visual impact	Depends on location
Functional impact	Depends on location
Reversibility	Depends on building material. For the examples above reversibility is very low
Costs	High

8.9.3 Seismic isolation

Deficiency

The building lacks overall strength and stiffness to withstand seismic events. The building type or aesthetics allow little intrusions.

Description

The implementation of shock absorbers (very flexible material) installed between super-structure and foundation. Base isolators are discs of highly elastic rubber. They are stiff and strong in vertical sense, but very flexible horizontally (MCEER). A lead plug in the middle undergoes deformation, and dissipates in this way some of the seismic energy into heat. Mounting the existing building on isolators is the most effective, however also most radical and expensive measure (Goel).

In Groningen, de Donut system is already applied for new housing , accounting for a seismic event of M=5.0. Discs can put in horizontal and vertical forces due to earthquakes. Mostly also a foundation upgrade is necessary; addition of new beams above the bearings.

Figure.59: DONUT-system base isolation | Source: Plegt-Vos

Seismic base insulation	
Disruption	High
Visual impact	Very low
Functional impact	Very low
Reversibility	Very low
Costs	Very high

On the next pages, the seismic retrofit techniques are organized in a matrix. The measures are ranked vertically by means of the levels of Arup, and horizontally in the main seismic design principles. The matrix is an adaption of the matrix of FEMA, (1990), which uses other categorization. >>

Level	Deficiency	Global strength, stability, stiffness (or ductility)	Building configuration or distribution	Load path	Building components	Non structural elements	Reduce demand
Level 0: Temporary measures	Risk of immediate collapse due to instability	Apply external diagonal shoring of timber or steel					
	Overloaded members	Temporary columns to protect inhabitants in case of collapse		Temporary columns for relief of structural elements			
	Inadequate out-of-plane strength				Temporary strong backs of steel or timber		
Level 1: Building parts at risk	Unbraced parapet					Brace parapet	Remove parapet
	Unbraced chimney		Replace chimney by a lighter version			Brace chimney	Remove chimney
	Balcony		Replace balcony by lightweight version				
	Loose lying rooftiles					Mechanical fixers or a snow guard	Remove appendages
	Poorly anchored appendages					Anchor appendages	
	Furniture and lightweight partition elements					Anchor furniture and lightweight wall	
Level 2: Improve connections between elements	Inadequate or missing wall-to-roof or floordiaphragm tie			Tension anchors Shear anchors Cross-ties and subdiaphragms			
Level 3: Stiffen existing diaphragms	Inadequate in-plane strength and stiffness of diaphragm			Mechanical fastenings Ties at the periphery Extra layer of planks or sheeting Concrete overlay			
Level 4: Strengthen existing walls	In-adequate out-of-plane and in-plane strength				Ferrocement overlay Shotcrete overlay Fibre reinforced polymers Post-tensioning Steel plates or straps Add butresses Add strongbacks		

Level	Deficiency	Global strength, stability, stiffness (or ductility)	Building configuration or distribution	Load path	Building compo-nents	Non structu-ral elements	Reduce demand
Level 4: Strengthen existing walls				Add diagonal struts from floor to wall to shorten the span			
	In-adequate out-of-plane strength				Add wood or steel strap reinforcemet Add a wood or steel braced window frame		
	Exessive stresses at openings and irregularities		Add steel moment-frames Add steel braced-frames Add shear walls				Fill up the wall penetration
Level 5: Replace or add elements	Soft or weak story						Replace facade by lighter panels
	Inadequate in-plane strength and stiffness of diaphragm				Add wood or steel strap reinforcement Add a wood or steel braced window frame		
	Lack of overall stability, strength, stiffness	Add steel moment-frames Add steel braced-frames Add shear walls					Add damping devices
	Heavy facade walls						
Level 6: strengthen foundation	Too little damping capacity					Add foundation peers	Seismic base isolation
Level 7: demolish and rebuild							Demolition of the building

Figure.60: NAM employee visiting owner of damaged fram | own image

9. Values and criteria

Beyond the minimum level of seismic performance and accepted risk (of seismic hazard) the remaining lifetime and future value of the building define the extent of the retrofit (Devdas Menon, 2008). The expected or intended lifespan of a building depends on its 'future value'. This value can be explored by assessing the following aspects: >>
These aspects are also design criteria which have implications on the performance objective of the design.

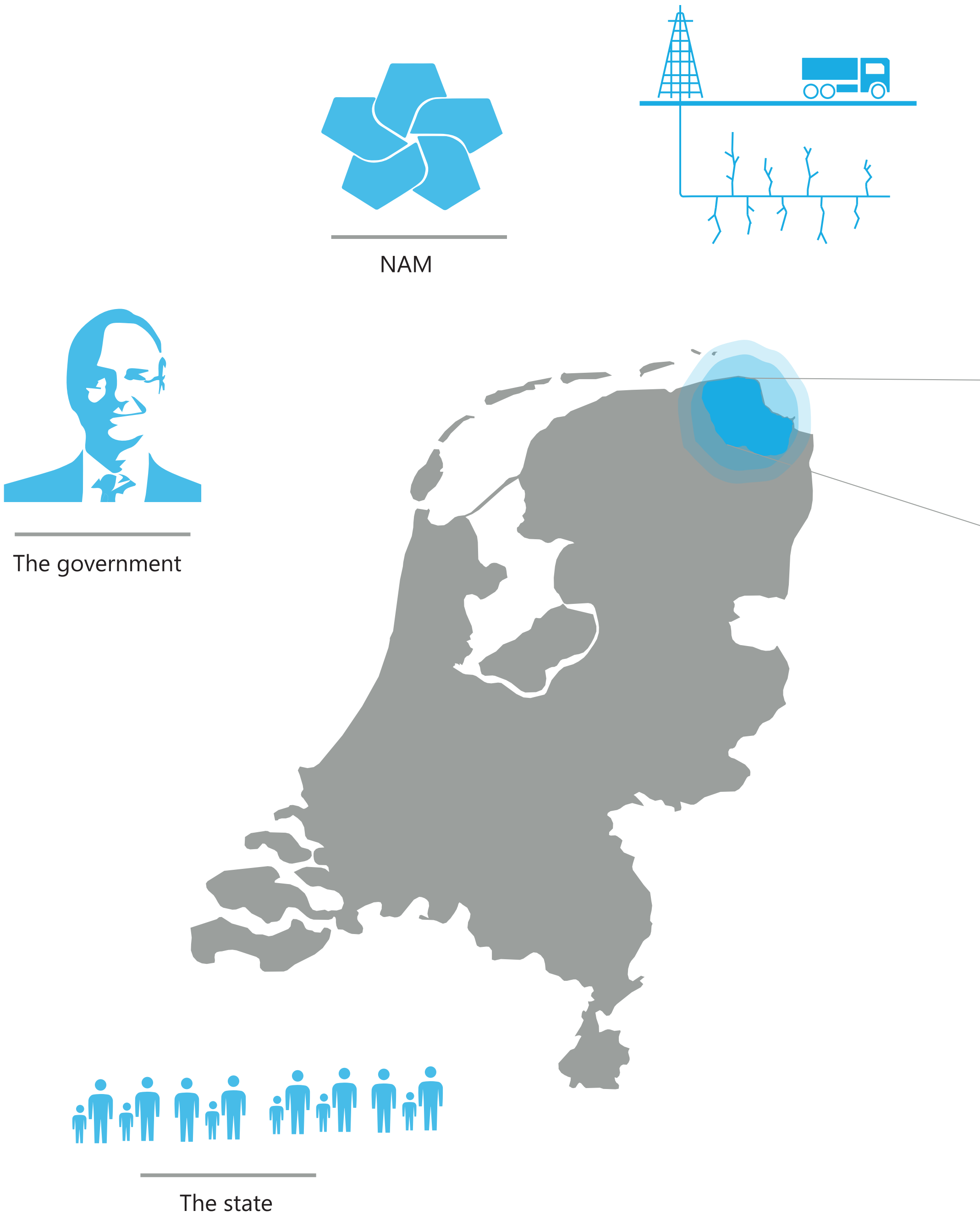
Seismic performance objective

Seismic retrofit can be defined by governing jurisdiction. In Groningen the minimum design standard is specified by new building codes. Seismic performance can also be voluntary; demanding further retrofit than the codes. A performance-based choice is integral. This means that other performance than seismic performance might be predominant in the retrofit.

Social / cultural
- Stakeholders
- The neighbourhood
- Building type
- Functionality
- Emotional value
- Architectural qualities
- Historical and cultural value

Technical
- Remaining life time
- Structural capacity
- Energetic quality

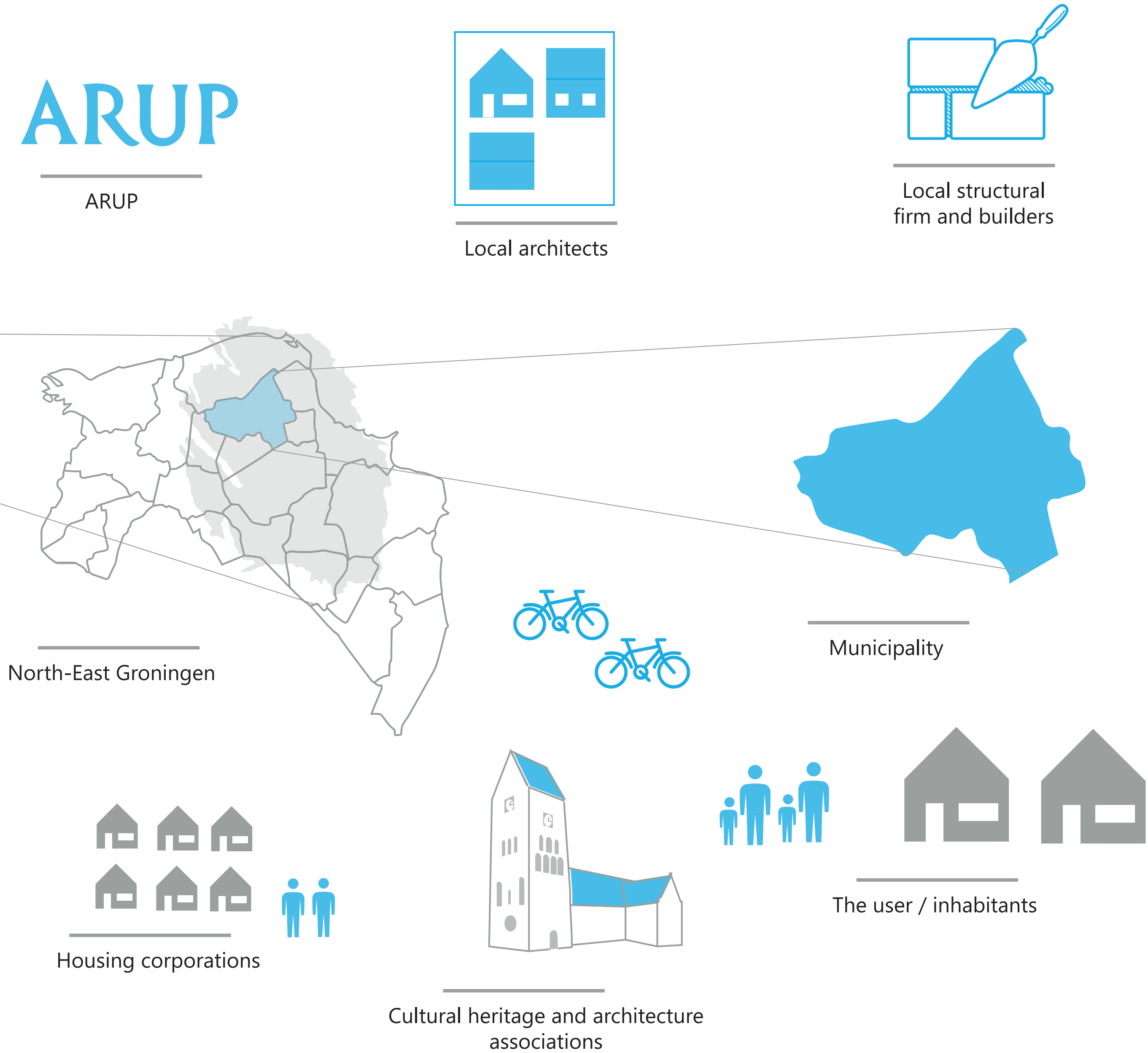
Implementation
- Costs
- Disruption
- Speed of implementation


NAM
The government
The state

Social and economical criteria

9.1 Stakeholders

It is important to make an overview of all the stakeholders, with respect to the situation in Groningen and the structural upgrading need. The interventions will affect several individuals and groups, and therefore it is essential to involve stakeholders in process as early as possible (Reitherman & Perry, 2009) . Involvement can lead to adjustments which will better fit the stakeholders' needs. The transparency of such a method might enlarge the trust and decrease frustration between parties. An overview of the stakeholders is made, in sequence of scale and operational level.



Stakeholder		
The state		• Population of the Netherlands • Owner of all underground mineral resources
	Stake	• Contribution to welfare to the Netherlands • 98% of the households run on Groningen gas for heating and cooking; • Installations tailored to low-calorie gas from Groningen
	Problems	• Interest of the whole population conflict with those in Groningen
Government		• Authority to define or limit production rate of natural gas
	Stake	• Gas earnings for the public treasury (up till now €250 billion, 2014) • Relation between decrease production rate and seismic events not clear • Safety, well-being and prosperity of the population as a whole
	Problems	• Decrease production rate will spread seismic energy over longer period • Considerations gas extraction – impact earthquakes • Distrust and frustration towards government policy
	Opportunities	• Compensation and investment in the area of North-East Groningen
NAM		• Engaged in the production of natural gas and petroleum • 75% of the total gas production of the Netherlands • Joint venture of Shell (50%) and Exxonmobil (50%) • Responsible for damage handling and economic loss
	Stake	• Redeem societal license to operate • Gas available for production up till 2080 • Allowed production rate of natural gas
	Problems	• Deteriorated image of natural gas, former 'cleanest of fossil fuels' • Cause of damage can be hard to establish (bad maintenance, sagging), which delays the damage handling process • Deteriorating reputation, and frustration towards NAM
	Opportunities	• Connect company image to sustainable development of the area • Generous damage handling and value compensation • Contribute to livability of the area • Enhance transparency and involvement
Arup		• Employed by NAM to perform a structural upgrading strategy, a seismic risk study, structural upgrading study, implementation study
		• Prioritization for implementation • Listing measures from most effective and fast implementation to intensive and radical • Priority for life-safety and severe damage
		• Standardization of solutions for large-scale implementation • Special assessment of cultural/ historical heritage
Housing corporations		• Organization for building, managing and renting housing accommodation • Aim to provide qualitative and affordable housing
	Stake	• Loss of value real estate and livability
	Opportunities	• Combine upgrading with other types of renovation • Energy efficiency upgrading

Stakeholder		
North-East Groningen		• The area of the Groningen Gas field
	Stake	• Safety of inhabitants • The livability of the area • Quality of buildings and facilities • Feeling of wellbeing
	Problems	• Earthquakes and subsidence • Population decline, aging, low employment • Leisure and tourism • Jammed housing market
	Opportunities	• Sustainable development of the area
Welstand		• Responsible for fitting form and aesthetics into building environment
	Stake	• Aesthetics criterion in seismic retrofit
	Problems	• Traditional building material masonry behaves poorly under seismic events • Ornamentation and non-structural elements form seismic risks
Cultural heritage		• Responsible for the preservation of cultural and historical heritage
	Stake	• How seismic retrofit might change the building • Sense of history and identity of cultural heritage
	Problems	• Most structural measures do not comply with strict rules
	Opportunities	• Provide future value – new functions?
The municipality		• Municipalities: Appingedam, Bedum, Bellingwedde, Delfszijl, Eemsmond, Groningen, Haren, Hoogezand-Sappermeer, Loppersum, Menter-wolde, Oldambt, Pekela, Slochteren, Ten Boer and Veendam
	Stake	• Safety is number one priority • Economics and tourism of municipality
	Problems	• Hard to set up policy, due to insecurities
Local structural firms and builders		• Repair and contra-expertise • Extra employment • Little knowledge and experience on earthquake engineering
The architect		• The designer of the specific building
	Stake	• Defending the architectural qualities and concept of the building
	Problems	• Costs and safety above architectural quality
	Opportunities	• Involve architect in seismic retrofit
Inhabitants		• Users, inhabitants, occupants of buildings at risk
	Stake	• Safety: prevent immediate risk • Value of buildings and financial situation • Livability, well-being • Damage repair and structural upgrading o Least disruption of their living or working activities o Structural upgrade/ safety of living environment o Preservation of emotional valued assets o Preservation of aesthetics o High indoor comfort and lower living expenses
	Problems	• Damage of personal affairs • Feelings of distrust, frustration, unsafety and insecurity
	Opportunities	• Compensation for loss • Sustainable subsidies for home upgrades • Involve users in seismic retrofit • Decrease fear, distrust and frustration o Involvement and transparency can redeem trust o Restore the feeling that their safety and well-being matters

9.2 The neighbourhood

The future value of the building depends partly on the surrounding neighbourhood.

- *Demographic situation*

Besides the earthquake tremors and subsidence the area of North-East Groningen faces other structural problems. The population is declining and aging. Youth and starters move towards the city in search for study or job, without returning. Due to the aging, there will be more pressure on the shrinking working class and the need for health care will grow (Simon, 2014). Families are growing smaller, while the amount of one-family households is increasing. (Simon, 2014)

Because of the declining population, there is less support for facilities for living, working, schooling and healthcare. This results in a concentration of facilities in cores, enlarging the distance to facilities for inhabitants, and thereby reducing the accessibility. Population decline has resulted in vacancy on the housing market and some impoverishment of the built environment. Next to this, inhabitants have a relatively low level of education income and a high level of unemployment (Stuurgroep PLUS Wonen en Voorzieningen Eemsdelta, 2012).

These problems have a negative effect on the quality of daily life and the attractiveness of the area for living, working or tourists passing by.

The earthquakes deteriorate these problems. People are anxious that North-East Groningen will not be attractive for companies to establish themselves, for people to live in or even for tourists to visit. The housing market is 'locked' and due to the indistinctness of the building codes, entrepreneurs are hesitant to expand or build. This development could harm the economy and employment of the area.

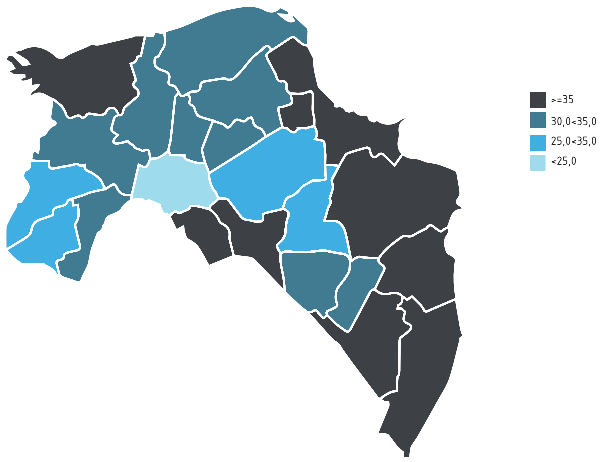


Figure.61: Grey pressure on neighborhoods in 2014 | Source: Sociaal planbureau Groningen

- *Living in an earthquake area*

Research (Haan, 2014) shows that one out of 5 inhabitants' feels that their house has lowered in value due to the earthquakes. One out of 4 persons experiences the earthquakes as a decrease of living comfort. However, the tendency to migrate is not that large in the area. Only 6% of the inhabitants feel a tendency to move. This low rate is due to social relationship with the living environment and presumably because of the decreased merchantability of the houses.

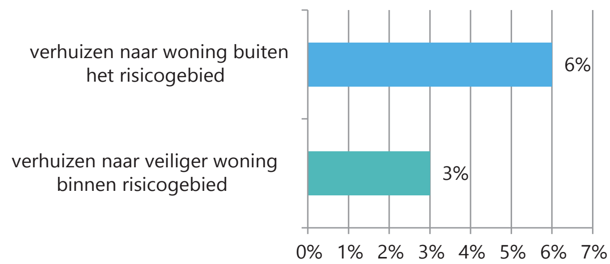


Figure.62: Tendency to move outside of the earthquake area | Source: Sociaal planbureau Groningen

- *Value drop of houses*

The decline of population is limited since the value of the houses is plunging. The decreased value makes the houses harder to sell. 'People simply cannot leave'. There is some selling of houses, but this happens mainly within the region itself.

- *Pleasant neighbourhood*

The area of North-East Groningen is characterized by space, nature and cultural heritage. Surrounded by outstretched green meadows for livestock and agriculture, lay picturesque villages. Many inhabitants enjoy living in such an environment. The area is a great attraction to tourists and cyclists, who celebrate the area for its quietness and spatiality.

9.7 Building type

It is important to choose measures which fit the specific building type (NAMplatform, 2013). Therefore Arup has mapped the most frequent occurring building types. The categories of building occupancy are defined as follows in the Seismic Risk Study of Arup (2013).

In the area of Groningen the main building occupancies are:

Occupancy category
Residential
Commercial - retail, banks
Commercial - medical office, hospital
Industrial - factory, warehouse
Agriculture - farm
Religious - church
Government - offices
Emergency response - police, fire, etc
Education - schools, universities

Of the residential buildings the following types are defined: free standing, two below one roof, villa, row house, farm, workers home, and the barn.

The building codes Eurocode 8 defines certain building classes, which are ranked in extent of damage consequence and risk. Buildings in which fewer people are exposed are of less risk than buildings which are occupied by many people.

Class	Desciption
IV	Vital importance for the protection of the population: hospital, fire station, ambulance, police
III	Earthquake resistance of importance due to consequences: school, retirement home, city hall
II	Houses
I	Minimal importance for safety: sheds, barns

The performance objective vary for different building types and consequence class. Some buildings are even vital in order to prevent risk and repair damage such as a hospital and a fire station. These buildings must stay operational even after a major earthquake; this means the seismic performance is higher and the level of allowed disruption is lower.

9.8 Functionality

It is important for the future value how well the building accommodates its use and facilitates its activities, and if it has enough capacity and flexibility to accommodate future use. As a retrofit criterion functionality is important with respect to flexibility of spaces, flow of circulation spaces, accessibility and usability.

9.9 Emotional value

The emotional value of a building is defined by the eagerness or dearness that people feel for a certain building and important memories attached to a certain place.

This value is created if the building provides a pleasant environment, experiential value, the feeling that the home is a home, a sense of safety and security, authenticity and flawlessness (Otter, 2008).

The occurrence of cracks obviously influences the feeling of safety and security and is an intrusion on the place people call home. Protecting emotional valued assets can be a higher performance objective than costs. In correspondence with the user, one can define the emotional valued assets and characteristics of a building.

Figure.63: Tear in the interior of a home | own image

9.10 Historical and cultural value

The area of North-East Groningen has a rich supply of cultural heritage in the form of churches, borgen (castle-like manors) and windmills. Estimation is made of 80-100 of these objects (Meijer & et al, 2013). Interventions on this cultural heritage should be applied with minimal intrusion. However, if nothing is done, buildings can be severely damaged or collapse, which will be even more harmful to the aesthetics than the renovations.

Cultural heritage provides identity and a sense of history. It is important for the stimulation of tourism. Nowadays monuments are popular establishments for cultural centers, information, tourist offices, hotels, restaurants, museums, and churches are valuable as meeting places which enhance social coherence. The heritage buildings function as icons which define the silhouette of a village. They have become part of the local culture and are unique in their nature, since no buildings are made alike anymore. (Goodwin, Tonks, & Ingham, 2011).

In order to preserve this heritage, buildings which are acknowledged to possess cultural or historical value, are subjected to strict rules. For these buildings the preservation defines and controls the seismic retrofit design. Consequently the following objectives are set:

- *Minimal intrusion*

Interventions should be applied with minimal intrusion. 'Additions cannot be allowed except so far as they do not detract from the interesting parts of the building, its traditional setting, the balance of its composition and its relation with its surroundings' (Venice Charter, 1964).

- *Invisible*

Interventions are only allowed when they do not harm the historical value, or if they are transparent enough .

- *In harmony with existing*

New seismic retrofit systems, should respect the character and integrity of the historic building (Charleson, 2008) and be visually compatible with the design. They should aim to preserve and reveal the aesthetic and historical value of the monument. This requires an in-depth study into the history and characteristics of the monument.

- *Preservation of historical materials*

Historical materials should be preserved and retained to the greatest extent possible and not be replaced in the process of seismic strengthening.

- *Reversible measures*

Since traditional techniques can prove to be inadequate, interventions should be done in the most reversible way, thus without harming the historical or cultural fabric. In case a modern, less intrusive technique could be applied in the future.

9.11 Architectural qualities

Retrofit techniques are executed because the building is too valuable to demolish, however, retrofit techniques can destroy the features that make such buildings significant and valuable. Therefore the applied techniques should be respectful for the character and architectural qualities of the building or have low visual impact.

First these qualities and characteristics need to be assessed. For newer buildings, the architect (or architecture firm) should be approached and involved into the process. Discuss with architect the important facets, the ideas and the concept.

Aesthetics are often a criterion for seismic retrofit. For historical buildings the importance of preservation of architectural fabric predominates. However, for non-historical buildings this objective can be sacrificed in favour of minimal disruption of inhabitants or saving costs (Rutherford & Chekene, 2006).

Technical criteria

9.2 Remaining life time

The future value of a building depends among others on the remaining or intended life time of the structure. A consideration must be made between the costs of the retrofit, and the timespan the building can still be used.

Newer buildings have less historical value, but they are accommodated to current use and have a lot of remaining lifetime and therefore are more profitable with respect to the prospect earnings of rent. For semi-old buildings, built hastily after the Second World War, the remaining life time is lower. These buildings are poorly built for earthquakes (narrow cavity walls) and are not accustomed to current demand.

Historical buildings have a lot of cultural value, and therefore are valued more, despite the lower rental prospects and accommodation to current use. There will be more motivation to maintain it and stretch its lifetime. For example, the municipality building of Loppersum was only built in 2007, and is fully accommodated to current staff and use.

Figure.64: The city hall of Loppersum

9.3 Technical or structural capacity

The type of structure and technical capacity influence the type of measures used. Some buildings are more suitable for retrofit than others for example with respect to their structural capacity and buildup. It is important to analyze the potential of buildings, not only their deficiencies (Otter, 2008).

- Unreinforced masonry

This paper focuses on unreinforced masonry buildings, which is the predominant building material of the area (80%). The basic components of masonry buildings are roofs, floor slabs, walls and foundations, spread wall footings. The most low-rise buildings exist of load-bearing masonry walls, which resist the gravity loads and lateral loads due to wind (Devdas Menon, 2008).
There are certain aspects which define the technical capacity/ value of the buildings

- Condition / maintenance

A building can already be in an ill condition due to bad construction, maintenance or sagging, which may have caused tears. These tears can enlarge during seismic events.

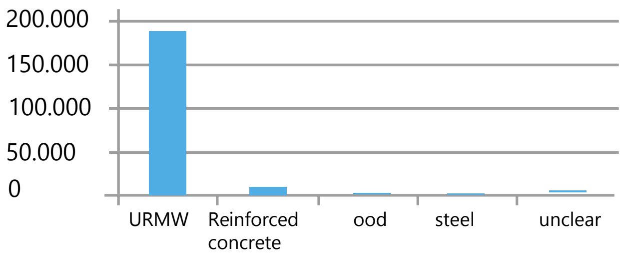


Figure.65: Distribution of building materials | Source: own image based on date of Arup (2013)

- Configuration

As described, the building configuration has a large influence on the seismic forces and stress concentrations in the building. Buildings with irregularities, discontinuities and set-backs will be harder to retrofit than buildings with symmetry, continuity and regularity.

- Wall type

A masonry bond is characterized by a pattern of headers and stretchers. Headers extend into the wall, indicating there is no cavity wall, but a solid wall. Solid walls are heavy, but have a relatively high construction depth for in-plane bending. A typical building method in Holland is the cavity wall; two narrow walls with a cavity space in between . Due to cavity walls, the structural depth is relatively small and the concrete floors induce higher inertia loads with respect to timber floors. Contemporary buildings are therefore more susceptible to earthquakes.

Traditional buildings are built with brick walls in several directions, adding to the global shear resistance. Newer buildings are built with long masonry walls in one direction, and relatively short ones in the other direction, which makes them weak in that direction.

- Floor type

Floor diaphragms can be stiff or flexible. Older buildings are equipped with timber floors. These are relatively flexible, but no so heavy, whereas newer buildings have relatively heavy concrete floors, resulting in large inertial forces (Wijte, 2014).

Figure.66: Masonry buildings in the Netherlands | Source: Wijte (2014)

9.4 Energetic quality

The energetic quality contributes to the value of the building. The quality is defined by on indoor climate (comfort) performance, energy efficiency and the capacity to generate renewable energy. Indoor climate increases the livability and energy efficiency and energy generation can decrease the monthly energy costs. In the map of Loppersum, the energy certificates are labeled, ranging from A++ to G, respectively green to red. Although it is clear that many buildings could use an energy upgrade, there are considerations which need to be assessed, in order to establish if an energetic upgrade is desirable or feasible.

Figure.67: Energy labesl of Groningen | Source: Energielabel atlatlas

- Value compensation

The idea for future policy is to combine the seismic and energy saving upgrade measures.
This initiative is meant to provide a value increase and compensation for the damaged buildings. Investing in sustainability will have positive effects on the value of the buildings and will on long-term lead to an energy-costs reduction for the inhabitants. This integral tactic seems to offer practical and financial benefits with respect to performing the two tasks individually. Furthermore, it fits into the targets of the government to fulfill the 2020 environmental goals.

- Increase of living comfort

Energy reduction can increase living quality, due to an increase of the internal climate such as better thermal comfort, less draught etcetera.

- Decrease of monthly energy costs

Increasing the energy efficiency or the energy autonomy of a building can decrease the energy bills. However, research (Majcen, 2013) suggests that for dwellings, up-grading energy efficiency does not necessarily mean a decrease in energy demand due to compensating behavior such as the rebound effect.

- Risk reduction has priority

The number one priority at the moment is structural safety. At this point, the repair of tears has the priority above energy saving measures.
Some feel that is not possible to compensate the value of the house by energy upgrade measures. As a farm owner in Groningen stated 'I received 4000 euro's for some sun panels on the roof of my barn. I'm not interested in that! My walls are scarred by tears and my house has dropped in value. Thát is what I care about, and will not get back'.

- Reluctance for extra concessions

Since owners of damaged property have experienced discomforts, they could be reluctant to make additional concessions. These concessions can include: increase of period of inaccessibility of the home due to renovation or potential changes in the aesthetics or build-up of the house.

- Feasible for building type

It is sometimes not possible or feasible to upgrade the energy label of a building (Raaij, 2014). In particular for old buildings, of which there is no space for extra insulation or extra insulation would harm the aesthetics.

- Logical combination/ synergy

Combining measures must be practical and integrated into the existing. By combining measures and finding synergies in the renovation one could yield financial and practical advantages and cause a minimal disruption with respect to performing tasks individually. Besides obvious synergies such as combining the renovation of specific building parts, the possibility of combining measures should be assessed per specific retrofit assignment.

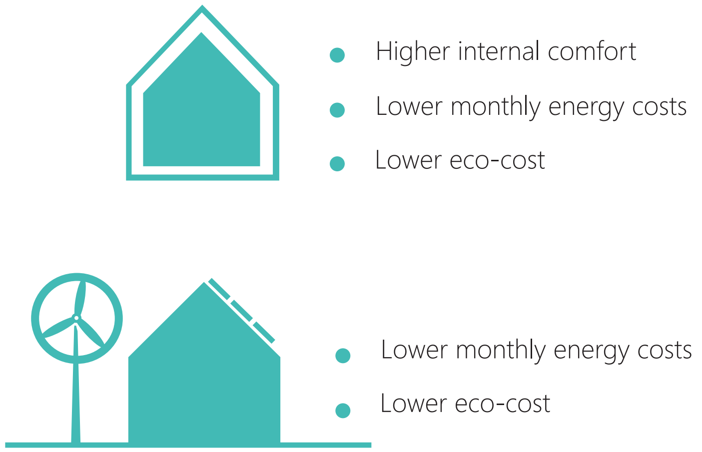


Figure.68: Energy demand reduction vs. renewable energy generation | Own image

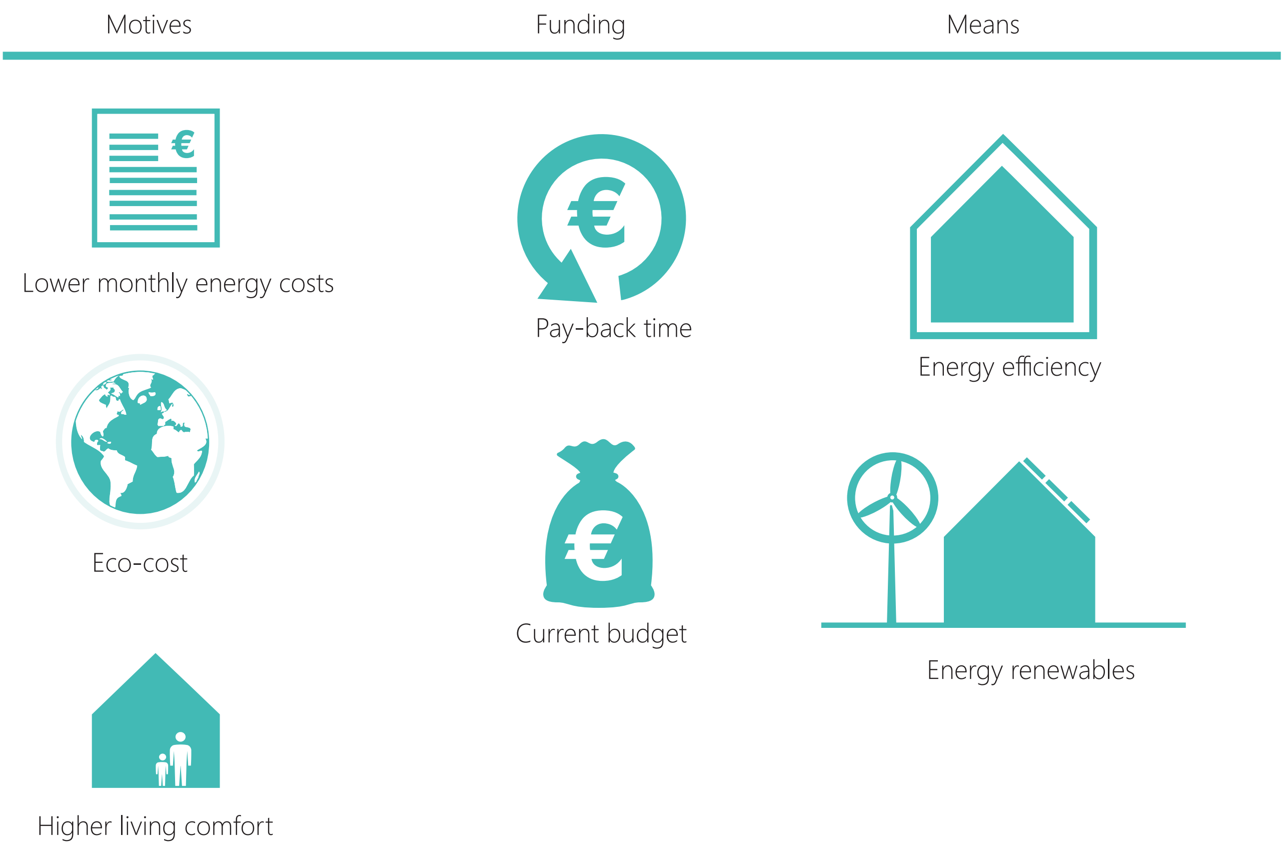


Figure.69: Potential motives, funding and means of energy savings. | Own image

10.Implications

The listed value assessment and criteria have implications for the chosen retrofit strategy and techniques. In the following section, examples of implications are given for the various criteria.

10.1 Seismic performance

Since not all criteria can be met for 100%, some kind of ranking needs to be defined stating which criteria are more important. This ranking is called the performance objective, done by the retrofit team in consultation with the relevant stakeholders.

Examples of high-ranked objectives are:

- For a historical building a minimum amount of intrusions.
- For house-owners the least amount of disruption and shortest relocation.

10.5 Stakeholders

First a value assessment of the existing is necessary to find out what is important for the relevant stakeholders. This can be done by in-depth interviews and brainstorm sessions with the help of a checklist. An appropriate way of communicating should be found, in order to provide stakeholders with enough understanding of the impact of the architectural or structural interventions.

10.6 The neighbourhood

- Demolition and rebuild

In case of demolition, due to population decline it might not be necessary to rebuild, since there might be existing buildings available. Or one might choose to migrate out of the earthquake area.

10.7 Building type

The type and function of a building and its consequence class influences the performance objectives. Furthermore, the type of building defines the importance of the criterion visual impact.

- Visual impact

Adding columns or strong backs is a low-cost solution. It can be visually displeasing, and cause a loss of interior usable space. Therefore, these measures could be suitable for agricultural buildings (Arup, 2013).

- Change the use

Another way of risk reduction is changing the use of the structure; a meeting or conference room which houses a lot of people could be reassigned to low-human presence functions such as storage, in which less risk is posed towards consumers.

- hange configuration and use

The change of plan or internal program could be an opportunity to change a building configuration

which is non-optimal seismic for seismic loads. Measures such as adding shear walls and braced frames can be performed while changing the plans and assigning new spaces.
Also the mass distribution can be optimised while renovating. Heavy walls can be removed from a plan; for example to accommodate smaller families, or to provide a more accessible space for elderly.

10.8 Functionality

For the functionality it is important that buildings are usable and accessible. Measures such as the addition of shear walls or braced in the interior of the building, have an impact on the functional use.

- Decrease in flexibility

The addition of these elements can lead to a decrease of flexibility to some extent. This might be harmful for specific buildings in which free passage is important such as retail spaces and parking garages. The extent of nuisance can be limited by placing the elements:

- Adjacent to existing walls

This might not be a useful option, since extra shear walls or braced frames are mostly placed because of the lacking of shear elements in that direction.

- In secondary spaces

Additions such as shear walls or frames can be placed in utilitarian or secondary spaces to reduce impact (Khan, 2013).

- Combined with functional elements

Measures can be combined or integrated with usable

Figure.70: Intrusive steel braced frame in a hallway | Source: Dunning Thornton consultants

elements. These steel braced frames decrease the accessibility of the hallway.

10.9 Emotional value

Implications will vary for specific building cases and stakeholders.

10.10 Historical and cultural value

High objectives for the preservation of historical buildings are: minimal intrusion, minimal visual impact, preservation of historical fabric, reversibility and in harmony with the existing.

- Non-structural elements

Non-structural elements are of high importance for the appearance and character of a building. For historical buildings one would rather chose to enhance the strength, than remove or replace.

- Connections

Enhancing connections between diaphragm and walls is a very effective measure with low visual impact and therefor quite suitable.

- Stiffening of diaphragm

Adding layers to the floor in the form of additional sheeting, or overlays can be complicating in the case that the historic floor material contributes to the character of the place. One could refrain from this measure, or assess which measure would be less harmful; floor or ceiling diaphragms.

- Strengthening walls

Adding steel posts is highly reversible, since the posts are fixed by bolts; however the visual impact is also very high. Post-tensioning consists of steel bars through the fabric, which makes the visual impact very low, but the reversibility too. Also overlays are quite intrusive and irreversible, however, perhaps an option for plastered walls.

- Adding walls

Adding walls will form an intrusion of the space and original configuration. Reversible steel frames do not fit into the character of historical buildings; perhaps they would be in industrial old buildings.

- Base insulation

Base insulation educes the load on the structure, and is placed beneath the building. This measure will result in the least amount of intrusion of the historical building. It is also a very expensive measure, so the budget and value will define if base insulation is a feasible option. Also other upgrades of the foundation will not be seen, and are therefore suitable approaches if the budget is sufficient.

10.11 Architectural qualities

- Masonry building tradition

Masonry appearance is deeply engraved in the emotional and cultural image of Groningen . Masonry is a poor building material for seismic resistance. Some masonry walls of existing buildings will need treatment or replacing.

Therefore measures with low-visual impact will be favoured such as anchoring walls to floors, stiffening of the floors and post-tensioning, and FRP on plastered surfaces. Unfavourable are wall-covering measures such as concrete wall overlays or FRP strips. Perhaps the architectural image can change integrating the FRP strips as a 'vakwerk-like' pattern.

Figure. 71: 'Vakwerk-building method'

- Integration of visible features

Visible features such as exterior buttresses should be designed in such a way that they blend in with the aesthetics of the building (Khan, 2013).

- Non-structural elements

Non-structural elements such as chimneys, balconies and parapets attribute to the character of the building. Removing or replacing would infringe their appearance. One should somehow brace with minimum visual impact. For plastered elements, FRP strips can be suitable.

When bracing non-structural elements this should be done without damaging the decorative details (Khan, 2013).

Figure. 72: House at stationsstraat in Loppersum. Adapted to asses the building respectively with chimney, with FRP chimney and without chimneys

10.2 Intended lifespan of a building

It might be more favourable (=less expensive) to demolish and rebuild, since the building constructed to new technologies might last longer than the previous building (Khan, 2013).

10.3 Structural quality

By analysing the existing structural condition one can define which measures are feasible, and which measure are necessary to tackle specific deficiencies.

Structural system:

New building

If the building is renewed, application of base isolation is significantly simpler than implementing base isolation in existing buildings. Furthermore; most buildings in Groningen have masonry line foundations. This makes the implementation of base isolation much more complex than if the foundation would be pointwise, which is the case for framework buildings. The consequence is that base isolation will mainly be applied in retrofit in the case of historical or very valuable buildings, whereas for new buildings it is also applied affordably for houses .

Application of dampers

The structural system defines which measures are most effective. For example; dampers are most effective for flexible buildings. For implementation, they are also more easily implemented into framework buildings. Dampers are not so applicable and hard to install in unreinforced masonry buildings.

10.4 Energetic quality

An objective can be to consider a combination of seismic measures with an energetic upgrade. Synergies are to be explored per building case; however there are some general potential synergies.

- When strengthening the foundation, one can implement thermal energy storage in the ground;
- While stiffening the ground floor, extra insulation can be applied;
- While stiffening diaphragms with an overlay, one could add floor or wall heating. However, this could be susceptible to damage and add too much weight to the floor;
- Replacing a heavy, brittle façade by a lighter, better insulated façade ;
- Stiffening the roof diaphragm and increasing insulation; and
- While removing broken windows, or insufficient openings or window frames one can replace with resisting frames and HR++ or triple glazing.

Implementation

The factors costs, disruption and speed of implementation are ascending parallel to the sequence of the Arup categorization of measures. Levels 2 and 3 are both cost-effective and least disruptive and therefore quite favourable with respect to implementation.

10.12 Costs

Cost-effective measures are found in the lower levels; such as removing falling hazards, enhancing connections between building elements, stiffening diaphragms.

10.13 Disruption and speed of implementation

Factors with least amount of disruption during construction also roughly follow the sequence of the Arup levels.

- Placement of elements

It might be necessary to place strengthening elements outside of the building envelope, in order to minimize disruption of inside activities. Elements could be placed adjacent to exterior walls; such as concrete shear walls, steel braced frames. Placing elements on the exterior will have serious implications on the aesthetics of the façade. Fig. x. is an example in which the integration has not been successful.

- Place panel on one side

If a panel can only be plastered on one side, a thicker layer of up to 200 mm reinforced concrete, cast-in-place or sprayed as shotcrete can provide adequate strength. This increases the in-plane shear strength and out-of-plane wall bracing.

- Continuous occupancy

When installing measures with continuous occupancy, there are factors to take into account such as acceptability of noise, dust, potential disruption of access and planning (Rutherford & Chekene, 2006).

10.14 Combinations with renovation of measures

The upgrade can be combined with other renovation methods, gaining a practical and financial advantage. Costs can be saved if multiple measures can be installed at the same time or if synergies are made. For example, synergies between seismic upgrade and regular renovation measures such as roofing replacement or energy efficient upgrading measures.

Figure.73: External placing of seismic resisting elements

Figure.74: External placing of seismic resisting elements

Periode Bouwdeel	**15 jaar**	**25 jaar**	**40 jaar**
Schil			
1. Dak		60%	
2. Gevel		10%	
3. Raamopeningen		38%	
Woning intern			
4. Keuken, douche, toilet	50%	90%	100%
5. Indeling			30%
Installatie			
6. Installatie-units	100%	100%	100%
7. Rest van de installaties		25%	75%

Figure.75: General need to replace building parts | Table adapted from Otter, Toolkit voor bestaande gebouwen

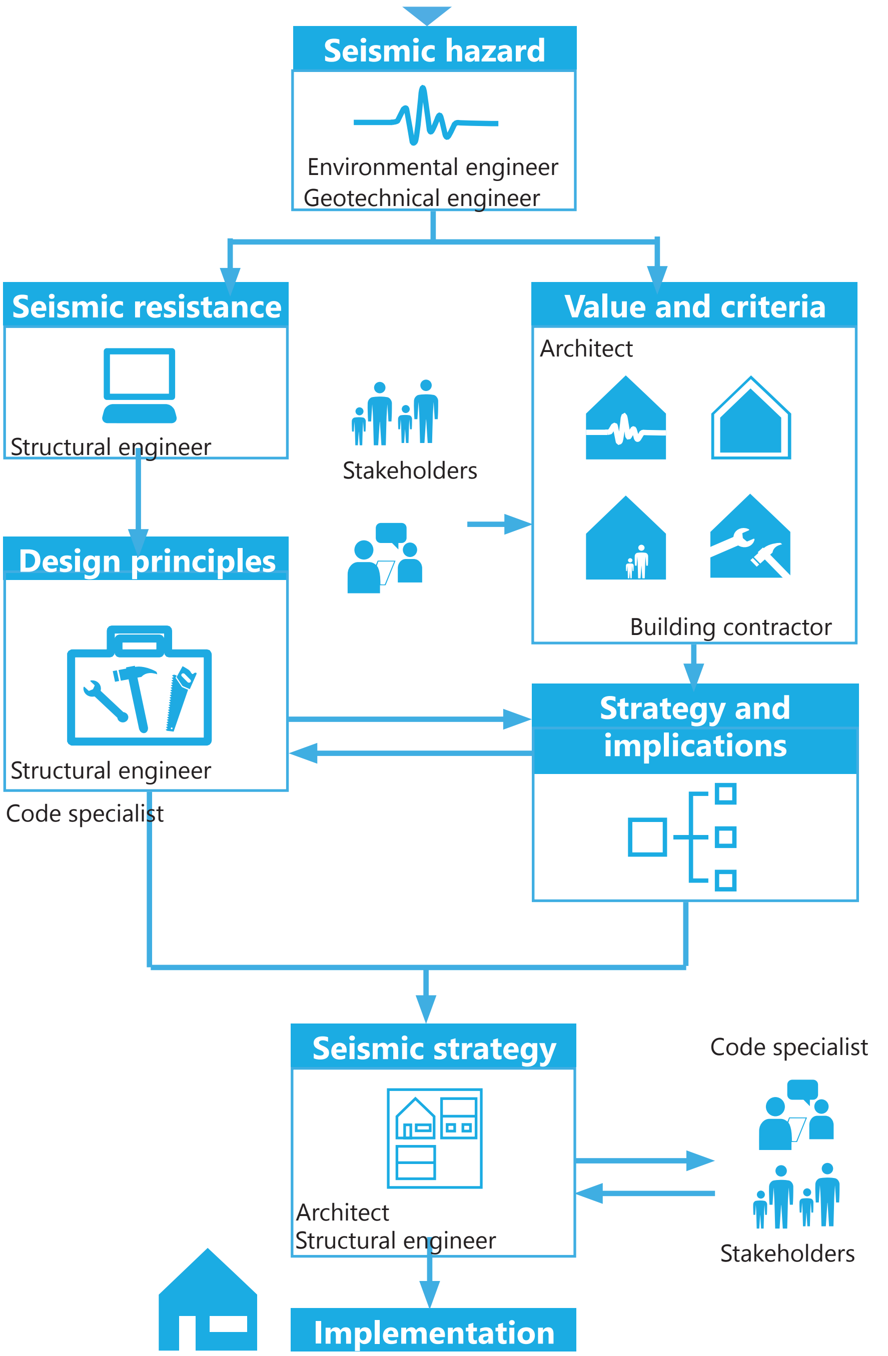


Figure.76: Proposal for a seismic retrofit scheme and sequence | Own image

12. Conclusion

In Groningen there are damaged buildings which need rehabilitation and undamaged buildings which need pre-emptive structural upgrading. At the start of a seismic retrofit case it is necessary to set up a team of specialists, according to Khan (2013) existing of: an architect, structural engineer, building code specialist, geotechnical engineer, environmental engineer and a building contractor. The main objective for the seismic retrofit lies in reducing risk. The objective for seismic performance is to not experience damage during frequent smaller earthquakes, and ensure life safety for rare, larger earthquakes.

In consultation with the environmental and geophysics specialist, the **seismic hazard** must be defined. Research shows that a tremor can be expected of a magnitude of 4,1 M, with a PGA of 0.12g. Chances on an earthquake with a higher magnitude are estimated on 10% (NAMplatform, 2014). For designing the scale 5.0 M is adopted and the PGA value of 0,5 g, for upgrading measures with respect to life safety. Seismic forces are mainly lateral inertia forces which arise when the mass of the structure resists the horizontal acceleration. Inertia forces can be assumed to act at the center of mass. For calculations, a static equivalent force can be used ($F_b=m \cdot PGA \cdot DAF \cdot /q>R$).

An **assessment of seismic resistance** can be done qualitatively by assessing the building condition, configuration, structural systems and -materials, and quantitatively with calculation methods. General seismic deficiencies are: bad building condition, high building mass, badly fixed parapets, chimneys and ornamentation, and inadequate lateral strength, stiffness, ductility and integrity. For calculation, the following methods are defined, listed in order of increasing complexity: the lateral force analysis, the modal spectral response analysis, the non-linear static push-over analysis and the non-linear dynamic time domain calculation (Boer, 2014). Unreinforced masonry structures are mainly damaged in the form of tears due to out-of-plane and in-plane loading. Before starting with structural upgrading, initial damage of the structure should be repaired.

Seismic engineering toolbox

For the choice of seismic upgrade, an engineering **toolbox of seismic design, retrofit and techniques** should be evaluated and assessed on amount of disruption during installation, impact on aesthetic, impact on functionality, reversibility and costs.

Design principles

- Distribute seismic-resisting elements at the perimeter
- Choose ductile materials and design ductile details
- Limit the building mass
- Design a regular and symmetric plan and elevation
- Provide adequate connection between the members
- Provide the building with second load paths and redundancy
- Reduce the demand by dissipating energy, or increasing the building period.

Retrofit principles

- Increase strength by adding lateral force resisting systems
- Decrease building mass by removing or replacing elements
- Increase ductility by replacing materials or adjusting details
- Remove irregularities from plan and elevation
- Stiffen the floor diaphragms
- Improve local strength of components
- Enhance connection of non-structural members or enhance connection.
- Reduce demand by adding damping systems or base isolation.

Techniques are ranked in levels by Arup (2013), starting with the quickest and most cost-effective techniques, leading up to heavier and more radical interventions.

Retrofit techniques:

Level 0 Temporary measures e.g. shoring
Level 1 Mitigating measures for building parts at risk
Level 2 Strengthening of wall-diaphragm connections
Level 3 Stiffening of diagrams in the construction
Level 4 Strengthening of existing walls
Level 5 Replacing and adding walls
Level 6 Strengthening of foundations
Level 7 Demolition and rebuilding

Values and criteria

In order to set up a multi-faceted performance objectives (which reach further than seismic performance dictated by the building code) the following aspects must be assessed with respect to the building and its context.

Stakeholders

Context

Building type

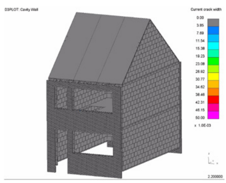
Functionality

Emotional value

Architectural qualities

Historical and cultural value

Remaining lifetime



Structural capacity

Energetic quality

Costs

Disruption

Speed of implementation

Figure.77: City hall of the municipality of Loppersum

11. Case study

11.1 City hall of the Municipality of Loppersum

The proposed framework will be tested on a case study as a research by design. The chosen case study is the city hall of the municipality of Loppersum.
The structural upgrading task of the building stock of Groningen is found to be so large, that proposal is done to set up a specialized governmental institution, the 'Rijksdienst voor aardbevingen' to manage and handle the task of upgrading the buildings. The municipality building of Loppersum is already a contact point and information center for earthquakes and it lies in the epicenter of the quakes. Therefore it is a fitting place for the institution.

From the research it became clear that alterations to the building by adding or changing its function also offer the possibility to adjust or change the building configuration with respect to seismic performance.
The program of the new institution does not fit in the existing building; therefore an additional part will be designed. The redesign will therefore be partially using the new building principles and partially the retrofit principles. An interesting option is to examine if the added building part can provide extra strength or stability to the existing building, or if it is more feasible to decouple the building parts.

11.2 Strategy

For the assessment of the building condition and its seismic resistance it is necessary to retrieve the relevant documents of the building: on the basis of these documents a quantitative and preliminary assessment is made of the seismic resistance and its deficiencies. The structure is yet undamaged. However, being a masonry construction it is susceptible to damage due to seismic actions.

Analysis of the existing

In order to set up multi-faceted performance objectives (which reach further than seismic performance dictated by the building code) the aspects of the existing building and its context which are addressed in this paper will be assessed.

Preliminary criteria

The users of the building are mainly the inhabitants of Loppersum and the employees of the municipality. It is a building in which many people come and go; accessibility is therefore a very important parameter.

The building houses many people; and will therefore be hplaced in a high-consequence class; demanding stricter seismic performance.

Since the building is relatively new, the architects can be contacted. Penta architecs, the designer the building can be questioned on the concept, important elements and characteristics of the building

The municipality is built in 2007, it is relatively new and is fully accommodated to current staff and use. Besides potential underperforming for earthquakes, the building is good shape. The municipality has stated their ambitions in sustainability; so combination with energy upgrade is an option.

Since the building will be used by multiple parties and interventions will be done in the old building, it is hard to define who will pay each share. Clear arrangements must be made on this.

Since the building is fully occupational, disruption caused by construction and installation must be kept to a minimum. It is necessary to evaluate the possibilities and costs of relocation of users.

In consultation with the stakeholders, values and criteria can be defined which serving as design conditions. Since not all criteria can be 100% fulfilled, weighing factors must be made, stating their importance. Then a strategy for seismic retrofit will be made.

Figure.78: City hall of the municipality of Loppersum

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