Traditional timber joint constructions as a solution for creating new residential buildings in the earthquake area of Groningen

An exploratory research into the possibility of using traditional timber joints as an earthquake resilient building method

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Preface

In front of you lies my graduation research. This thesis is the final part of my master Construction Management and Engineering at the Eindhoven University of Technology. The subject of this research is the application of traditional timber structures in the earthquake area of Groningen in order to build new earthquake resilient residential buildings. This subject is not a textbook example for this master track, but fits me very well.

For as long as I know I have been interested in building and working with wood. This is one of the reasons I have been enjoying my studies for the past seven years at the faculty of the Built Environment. When I started at this university I knew one thing for sure: ”I will not become an architect”. Luckily, the bachelor program provided me with a broad education into all the facets of this interesting and diverse work field. These courses even made me enthusiastic about some parts of architecture. The final years of my study I have spent on the master CME. This master track allowed me to specialize while simultaneously keeping a broad scope within the built environment. This wide characteristic of the master track allowed me to use my interest for timber structures in my graduation project.

The thesis which you are about to read has been the result of half a year of work. The process towards completing it has not been completely without struggles. I like to thank my supervisors for guiding me in the right direction when necessary. Furthermore, I like to thank my friends, family, housemates and especially my girlfriend for the support and motivating words when I needed them. With this graduation project I conclude my time at the university and start a new chapter. I like to thank everyone who made this time so amazing.

Tom Penninx
Eindhoven, 31-10-2019

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Summary

Over the past years the province of Groningen has been an increasingly bigger part of the news in the Netherlands and abroad. The area in the north of the Netherlands is struck by more frequent and heavier earthquakes. This has not always been the case whereas this seismic activity only started in 1986. The source for the earthquakes can be traced back even earlier to 1959 when the NAM discovered a big natural gas reservoir in the area. Soon the NAM, in cooperation with the Dutch government, started to pump the natural gas to the surface. For the first 25 years this did not have any consequences for the inhabitants of the area. However, this changed when the earthquakes started and caused damage to the built environment. The damage to the residential buildings of the citizens in the earthquake area is no only causing a devaluation of the property but also, a feeling of unsafety for the inhabitants.

The buildings in the area were not engineered to be able to withstand the seismicity and are therefore prone to damage. As a solution, the government and the NAM offer renovations and reinforcements to the existing buildings. This is regarded as a temporary solution whereas future earthquakes will still cause damage to the buildings. A long term solution to this problem is to build new residential buildings capable of withstanding the earthquakes and by doing this, prevent damage which devaluates the building. Moreover, by creating an earthquake resilient building, a safer environment is created for the inhabitants.

In contrast to Groningen there are countries around the world which design for seismic activity such as Italy, Turkey and Japan. Earthquakes are common and have been occurring for centuries in these areas. The built environment in these countries has been evolving over the centuries and is adapted to withstand the forces. What all of these old buildings have in common is that they rely on some sort of timber construction. The fact that a large amount of these wooden structures still exist and are capable of withstanding earthquakes, implies that building with traditional timber structures can be a solution in the earthquake areas of today, as well. This research will therefore explore the possibility of adding a traditional timber structure to new to be build earthquake resilient residential buildings in Groningen.

The available literature gave an overview of important aspects playing a role when designing in an earthquake area. An important characteristic which became clear is the usage of materials with a low mass, whereas this has a positive effect on the earthquake force on the building. Furthermore, ductility of the applied materials is a favorable characteristic since this allows for earthquake energy dissipation. Both these characteristics can be found in timber constructions when the wood is applied in a correct way. “This” correct way is important because wood is an isotropic material and will behave differently depending on the loading direction. Because of this it is important that the force is led into the wood as a compression in the longitudinal direction where it can show ductility. This is why connections and joints play an important role in the energy dissipating possibilities of an overall structure. The joints effect the way the forces are directed into the wood.

The timber joints were the focus of the analysis following the literature review. In the analysis three different types of timber structures were evaluated and scored on criteria. Two of these timber structures were of Dutch origin and can be found in traditional farmhouses over the country. The last alternative was based on a research by prof. Shiratori who proposed an improved Japanese joint method for usage in earthquake areas. The criteria on which these

structures were scored were derived from the literature. It captured the possibility for ductility and energy dissipation, the overall theoretical displacement of the structure, the usage of different types of fasteners and scored the structure on the level of embedment in the environment of Groningen. These scores were then used in a multi criteria decision analysis to find the best fitting alternative for the earthquake area in Groningen. The method used was the analytic hierarchy process (AHP). This method allows for a pairwise comparison between the different alternatives and uses the cardinal scores from the evaluation to find the best fitting alternative. The alternative which came out of the analysis as the best option was the Shiratori inspired timber structure. This timber structure has the highest potential of energy dissipation and would allow for little displacement of the construction.

In the final part of the thesis, this traditional timber structure was applied to a case study. This case study was used to verify whether the traditional timber structure could be used to build a residential building. Because the residential building should fit in with the current built environment, a building in the area was selected which would be used as a reference. The case study provides a detailed description and illustration of the newly designed residential building and shows that a traditional timber structure can be combined with additional earthquake resilient methods to design a building. The case study shows that there is a possibility for these type of timber structures in new to be build earthquake resilient residential buildings. However, further research into the exact behavior of the timber structure in an earthquake situation will be necessary before the method can be applied to the built environment.

Samenvatting

Sinds de laatste jaren is de provincie Groningen meer in het landelijke en internationale nieuws. De meest noordelijke provincie van Nederland wordt steeds vaker opgeschud door lichte en zwaardere aardbevingen. Dat er aardbevingen voorkomen in dit gebied is niet altijd het geval geweest. Pas sinds 1986 zijn de eerste aardbevingen gevoeld in het gebied. De oorzaak van de bevingen kan in het jaar 1959 gevonden worden. In dit jaar ontdekte de NAM een groot aardgas veld in de provincie. Al snel na deze vondst begon de NAM, in samenwerking met de Nederlandse staat, met het omhoog pompen van het aardgas. Voor de eerste 25 jaar gaf dit geen enkel probleem voor de inwoners van het gebied. Echter, dit veranderde met de start van de aardbevingen die de gebouwde omgeving beschadigden. The schade aan de woningen heeft niet enkel een waardevermindering tot gevolg, maar ook het gevoel van onveiligheid groeit bij de inwoners.

The gebouwen in het aardbevingsgebied zijn niet ontworpen om weerstand te bieden tegen aardbevingskrachten en ontvangen daardoor schade. Als oplossing bieden de Nederlandse overheid en de NAM versterkingen aan de huidige bebouwing aan. Dit wordt echter gezien als tijdelijke oplossing aangezien het gebouw nog steeds schade zal oplopen bij de volgende beving. Een langdurige oplossing voor het probleem kan echter worden gevonden in het bouwen van nieuwe woningen die weerstand kunnen bieden tegen de aardbevingskracht en hiermee waardevermindering kunnen voorkomen. Bovenal, door het bouwen van aardbeving bestendige woningen wordt er een veiligere gebouwde omgeving gecreëerd voor de inwoners.

In tegenstelling tot Groningen zijn er landen zoals Italië, Turkije en Japan waar er rekening gehouden wordt met aardbevingen bij het ontwerp van een gebouw. In deze gebieden komen aardbevingen al eeuwen regelmatig voor. De gebouwde omgeving in deze landen is dan ook ontwikkeld door de eeuwen heen om deze krachten te kunnen weerstaan. Wat al deze oude gebouwen gemeen hebben is dat ze allemaal gebruik maken van een soort houtconstructie. Het feit dat deze gebouwen na al deze eeuwen en meerdere zware aardbevingen nog steeds staan geeft aan dat er een mogelijke oplossing ligt in het toepassen van deze traditionele houten constructies. Dit onderzoek kijkt daarom naar de mogelijkheden om deze traditionele houten constructies toe te passen in een nieuwbouw woning in het aardbevingsgebied van Groningen.

De beschikbare literatuur gaf een overzicht van de belangrijke aspecten die een rol spelen bij het ontwerpen in een aardbevingsgebied. Een belangrijk kenmerk is het gewicht van een toegepast materiaal. Een laag gewicht heeft een positieve reactie op de aardbevingskracht. Verder is de taaiheid van een materiaal een belangrijke eigenschap. Deze eigenschap maakt het opnemen van aardbevingsenergie in de constructie mogelijk. Zowel het lichtgewicht als de taaiheid zijn te vinden in houten constructie indien goed toegepast. Deze juiste toepassing is van belang aangezien hout een isotroop materiaal is en daarom de richting van de kracht van invloed is op de reactie van het hout. Bij hout is het van belang dat de kracht in de vorm van druk in de lengte richting van het hout wordt geleid. Op deze manier kan het hout taaiheid vertonen. Om deze reden spelen verbindingen in houtconstructies een belangrijke rol, de verbinding kan de krachten op een juiste manier in het materiaal leiden.

Deze houten verbindingen waren het belangrijkste onderdeel van de analyse die volgde na het literatuur onderzoek. In deze analyse worden drie verschillende houtconstructies geëvalueerd en beoordeeld aan de hand van criteria. Twee van deze houtconstructies komen voor in Nederland en worden veelal toegepast bij traditionele boerderijen verspreid over het land. De andere houtconstructie is afgeleid van een onderzoek door professor Shiratori. Hij stelt een verbeterde traditionele Japanse houtverbinding voor in zijn onderzoek die speciaal toegepast wordt in aardbevingsgebieden. Deze constructies worden beoordeeld op grond van uiteenlopende criteria van de taaiheid en mogelijkheid tot energie opname, de verplaatsing van de constructie, de toepassing van verschillende verbindingsmiddelen en de toetsing of de constructie past in het Groningse landschap. Vervolgens werden deze scores gebruikt in een multi criteria decision analysis om de best passende oplossing te vinden. De specifieke methode die hierin is toegepast was het Analytische Hiërarchie Proces. Deze methode maakt gebruik van een pairwise comparison om de alternatieven te vergelijken aan de hand van de kwantitatieve scores van de constructie evaluatie. Het alternatief wat het beste uit de vergelijking kwam was de houten constructie geïnspireerd op de Shiratori verbinding. Deze constructie heeft de meeste potentie voor het absorberen van de aardbevingsenergie en zorgt voor een kleine verplaatsing van de constructie.

In het laatste onderdeel van het onderzoek is de traditionele houtconstructie toegepast in een casus. Deze casus is toegevoegd om te verifiëren dat de traditionele houtconstructie kan worden toegepast in een nieuwbouw woning. Om een goede toepassing te kunnen maken is een woning uit het aardbevingsgebied gekozen als referentie. De casus bevat een uitgebreide en gedetailleerde weergave van de toepassing van de houtconstructie in combinatie met andere aardbevingsbestendige bouwmethode. Alhoewel de casus laat zien dat de houtconstructie toegepast kan worden in een nieuwbouw woning, is er toch verder onderzoek nodig naar de precieze effecten van aardbevingen op de constructie alvorens het gebruikt kan worden in de praktijk.

Abstract

The built environment in Groningen, the most northern province of the Netherlands, is prone to damage because of induced earthquakes. These earthquakes are a result of an under pressure in the gas reservoir, three kilometers below the surface. The damage to the residential buildings of the citizens in the earthquake area are not only creating a devaluation of the property but a feeling of unsafety as well. Because the earthquakes are relatively new, the buildings in the area are not engineered to be able to withstand the seismicity. In contrast to Groningen there are countries around the world which design for seismic activity. What these countries have in common is that the traditional buildings rely on some sort of timber construction. The fact that a large amount of these wooden structures still exist and are capable of withstanding earthquakes, implies that there can be a solution in building with traditional timber structures in earthquakes areas in the present time. This research explores the possibility of adding a traditional timber structure to new to be build earthquake resilient residential buildings in Groningen.

The timber joints were the focus of the analysis. In the analysis two Dutch and one updated Japanese traditional timber structures were evaluated and scored on criteria. The criteria on which these structures were scored were derived from the literature. It captured the possibility for ductility and energy dissipation, the overall theoretical displacement of the structure, the usage of different types of fasteners and scored the structure on the level of embedment in the environment of Groningen. These scores were then used in a pairwise comparison using the analytic hierarchy process (AHP). The improved Japanese timber structure turned out to have the highest potential of energy dissipation and would allow for the smallest displacement of the construction.

Additionally, a case study was used to verify whether the traditional timber structure could be used to build a residential building. This case study showed that there is a possibility for these type of timber structures in new to be build earthquake resilient residential buildings. However, further research into the exact behavior of the timber structure in an earthquake situation will be necessary before the method can be applied to the built environment.

List of Abbreviations

AHP	Analytic Hierarchy Process
CI	Consistency Index
CLT	Cross Laminated Timber
CNC	Computer Numerical Control
DAF	Dynamic Amplification Factor
GLT	Glue Laminated Timber
K-N joint	Kusabi-Nageshi joint
MCDA	Multi Criteria Decision Analysis
NAM	Nederlandse Aardolie Maatschappij
PGA	Peak Ground Acceleration
RI	Random Index

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Equation 1:

$$M_L = \log(A) - \log(A_0)$$

Equation 2:

$$M_w = \frac{2}{3} log_{10}(M_0) - 6.0$$

Equation 3:

$$F = m * a$$

Equation 4:

$$F = m * a * DAF$$

Equation 5:

$$a_{jk} * a_{kj} = 1$$

Equation 6:

$$\bar{a}_{jk} = \frac{a_{jk}}{\sum_{l=1}^{m} a_{lk}}$$

Equation 7:

$$w_j = \frac{\sum_{l=1}^{m} \bar{a}_{jl}}{m}$$

Equation 8:

$$v = S * w$$

Equation 9:

$$CI = \frac{\lambda - m}{m - 1}$$

Equation 10:

$$\frac{CI}{RI} < 0.1$$

1. Introduction

1.1. Problem definition

On the 22nd of May this year the province of Groningen was struck by yet another earthquake (Kerstens, 2019). This earthquake had a magnitude of 3.4 on the Richter scale and was therefore listed as one of the top three heaviest earthquakes in Groningen. The earthquakes in the province of Groningen are not only getting heavier but more frequent as well (Algemeen Dagblad, 2018). Over the course of 2018, a total amount of 87 earthquakes with a magnitude over 1.5 on the Richter scale were measured. These earthquakes damage the built environment and give a feeling of unsafety to the residents.

The residential buildings in Groningen are not designed to withstand seismic forces. This is because earthquakes did not occur in the province until 30 years ago. The first earthquake occurred in 1986 and its cause was unknown at that moment in time, however it was believed that the gas production in the area could be linked to seismicity. In 1959 a large gas reservoir was found in the soil of Groningen, the largest in the world at that moment (Vlek, 2018). Shortly after the discovery the gas extraction was initiated by the NAM (Nederlandse Aardolie Maatschappij), a joint venture of Shell and ExxonMobil. The company extracted natural gas from the sandstone layer in the soil for over 25 years without any problems. However, since 1986 the amount of earthquakes and damage to the built environment has been increasing (Gerrits, 2018). This increase can be explained by taking a look at the cause of the earthquakes. When the gas is extracted from the sandstone layer it reduces the pressure. The pressure difference which is then formed within the layers makes the soil compact and lowers the overall soil height. When this occurs evenly, no harm is done. However, when the soil compacts suddenly, an earthquake can be the result.

Recently, the NAM and the gas extraction in the province are covered more extensively in the news because of the increasing amount of earthquakes in Groningen. The residential buildings are more damaged and show cracks in the traditional masonry structures. This visible damage to the inhabitants houses makes the residents feel unsafe (Vlek, 2019). Some buildings are in a near collapse state and need to be reinforced to withstand future earthquakes (Gerrits, 2018). This way of reinforcing buildings is merely a temporary solution and leaves the residents with a devaluation of their property. The gas production is reduced gradually over the years and will be brought to a complete stop. However, the seismicity will not just stop by doing this (Vlek, 2019). It is therefore important to look for a structural solution.

1.2. Research question

The previous paragraph shows that the current built environment of Groningen is not prepared for the earthquake forces. The buildings were not engineered to be able to withstand the seismicity and therefore are prone to damage. As a solution, the government and the NAM offer renovations and reinforcements to the existing buildings. This is regarded as a temporary solution whereas the buildings will still be damaged with future earthquakes. A long term solution to this problem is to build new residential buildings capable of withstanding the earthquakes and by doing this, prevent damage which devaluates the building. Moreover, by creating an earthquake resilient building, a safer environment is created for the inhabitants.

In contrast to Groningen there are areas around the world which design for seismic activity. In countries such as Italy, Turkey and Japan (Gülkan & Langenbach, 2004; Langenbach, 2014), earthquakes are common and have been occurring for centuries. The built environment in these countries has been evolving over the centuries and is adapted to withstand the forces. What all of these old buildings have in common is that they rely on some sort of timber construction. The type of timber structure is different for every location and depends on tradition and local resources (Zwerger, 2015). The fact that a large amount of these wooden structures still exist and are capable of withstanding earthquakes, implies that there can be a solution in building with traditional timber structures in earthquake areas in the present time. Because of this, the following research question is formulated:

"How can a traditional timber structure be used to build new earthquake resilient residential buildings in Groningen?"

This research question can be roughly divided into two parts: the building and the earthquake. First of all, the earthquakes occurring in Groningen are the cause for the problems. To be able to find a solution to these problems it is important to first have a better understanding of the cause and effects of these earthquakes. This will be covered in the sub question:

> "*What causes the earthquakes in Groningen and how does it cause damage to the built environment?"*

The usage of traditional timber joints in structures to withstand earthquake forces could form a solution in the built environment of Groningen. The province contains historical buildings which rely on a timber frame structure (van Cruyningen, Goudeau, Grovestins, Viersen, & van Zuijlen, 2003). The centuries-old barns which are spread across the area, contain large bent structures carrying the roof and providing stability. These barn structures, as part of the built environment of Groningen, are not initially designed to withstand earthquake forces. However, by analyzing the joints in the structure it would be possible to determine the capability for earthquake resistance. This needs to be done in order to find an answer to the sub question:

> "What traditional timber structures can be found in the earthquake area of Groningen and are these earthquake resilient?"

The usage of traditional timber structures should not be limited to the ones which can be found in Groningen alone. As mentioned, the structures in the province were not initially designed to withstand seismicity. A solution could be to apply the structures from international earthquake areas in Groningen. However, a system which works in Japan for example does not necessarily have to work in Groningen. Therefore, the following sub question is formulated:

> "How can international earthquake resistant traditional timber structures be used in Groningen?"

This research will take a look into three different building parts to be able to design an earthquake resilient residential building; The load bearing timber structure, walls and floors of a residential building. As mentioned before, the current built environment of the province relies mainly on masonry walls. These buildings show cracks when struck by an earthquake. The cracks scare residents and lower their property's value (Vlek, 2018). The problem lies within the materialization of the walls. The walls which are used in most of the houses in Groningen consist of unreinforced masonry work (Sarhosis, Dais, Smyrou, & Bal, 2019). The masonry wall reacts brittle and therefore cracks. When designing a new residential building this behavior of walls have to be taken into account and applied to the solution. The following sub question is formulated to solve this problem:

> "What wall type can be used to build residential buildings in the earthquake area of Groningen?"

The other main element in a residential building is the floor. This building element has a large influence on the way the building behaves during an earthquake. The mass of the floor has a big influence on the size of earthquake force the building has to endure (Sucuoğlu & Akkar, 2014). To find a fitting solution for the new to be built residential buildings the following sub question is asked:

> "What floor type can be used to build residential buildings in the earthquake area of Groningen?"

1.3. The social and scientific importance of the thesis

The increasing frequency of earthquakes in Groningen calls for a structural solution. The temporary solutions provided by the NAM and the Dutch government help residents momentarily but do not solve the problem (Gerrits, 2018). The seismicity in this region will continue as long as the gas production lasts and is not likely to stop immediately when the production stops (Vlek, 2019). Therefore, the built environment should adapt to be able to withstand these forces and give the inhabitants of Groningen a feeling of safety. This research aims to propose a possible solution for the inhabitants of the earthquake area who are willing to build a new house in the area.

The need for this solution requires investigation further than just the usual building methods found in Groningen. There are several areas around the world were earthquakes are a regular phenomenon, and have been for centuries. In these areas timber structures can be found which survived earthquake forces for over centuries. The timber structures which can be found in these seismic active countries such as Turkey, China and Japan show that there could be a function for these traditional building methods in modern time and different location. New modern manufacturing possibilities such as CNC milling create a new chance for the former labor intensive building method (Roche, Robeller, Humbert, & Weinand, 2015). This creates the possibility for researchers to understand (Bulleit, Sandberg, Drewek, & O'Bryant, 1999; Parisi & Piazza, 2008; Xue, Xu, & Xia, 2018) and possibly improve (Takeshi Shiratori,

2010) the empirical knowledge of these building methods. This research analyses whether it would be possible to use these kind of structures in the context of Groningen.

1.4. Research design and reading guide

This research is divided into two main parts: the literature review and the analysis. The latter requires the information form the literature review in order to be carried out properly. This literature review can be found in chapter 2. In this chapter it is aimed to find answers to some of the sub questions and provide the necessary information for the analysis.

Before this analysis will be carried out, the methodology for this part will be first elaborated in chapter 3. In this chapter the evaluation method for the traditional timber structures will be explained which uses the information from chapter 2. After this evaluation the process which will take place to select the best fitting alternative using a multi decision criteria analysis (MDCA). In the last step of chapter 3, the information derived from the literature on earthquake resilient wall and floor systems will be used in combination with the result of the MCDA. This validation step combines all the previous information in a case study to answer the research question. The complete information flow for this research is shown in Figure 1.

When all the information is available, chapter 4 will conclude this research and reflect on the process and outcome.

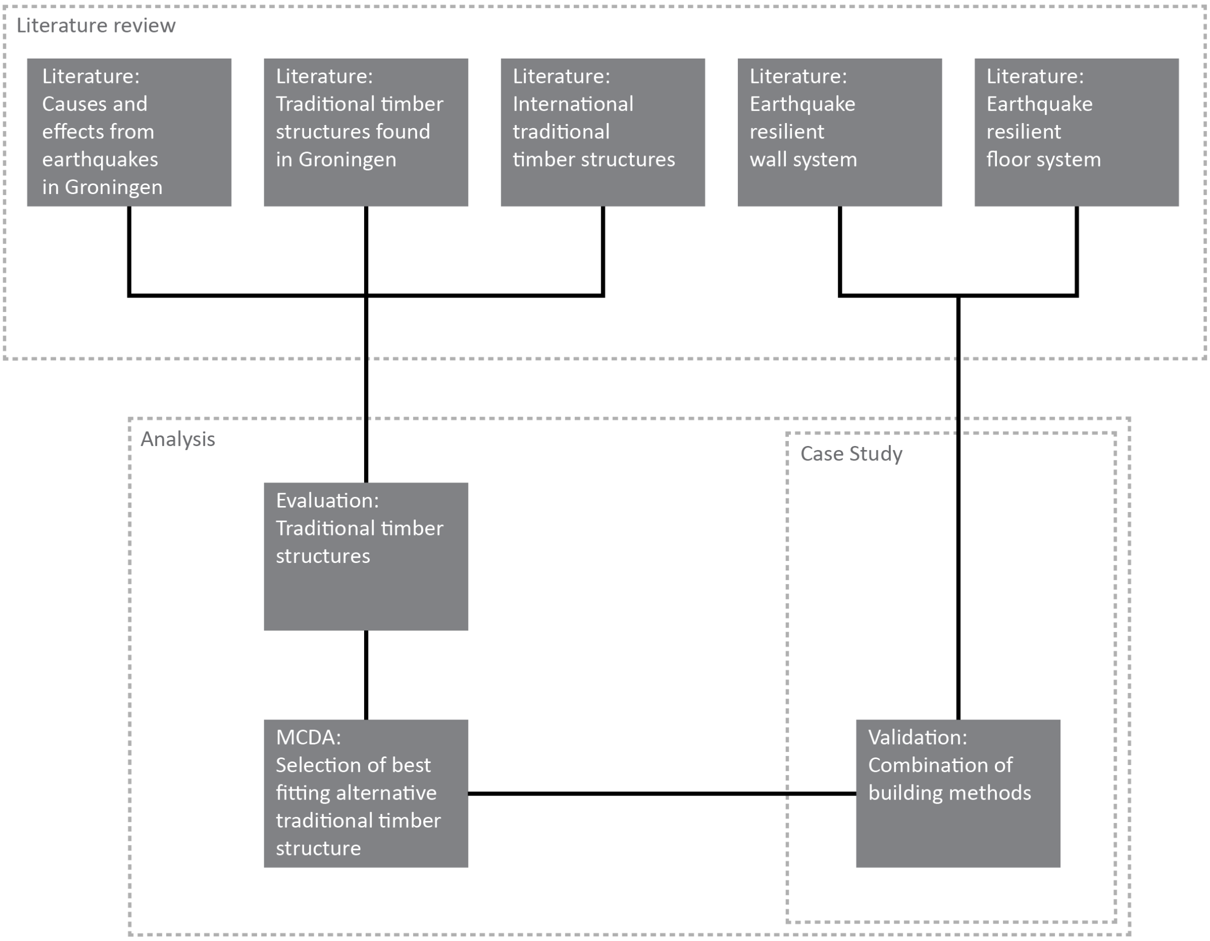

Figure 1. Research model

2. Literature review

In this chapter the literature on the subject will be covered. Existing research is used to find answers to a selection of the sub questions.

2.1. Earthquakes

2.1.1. Characteristics of earthquakes

Earthquakes are phenomenon in which friction energy of soil layers is suddenly released causing a seismic wave in the earth. The point in the earth's crust from where the energy is released is known as the hypocenter, directly above this point on the surface of the earth the epicenter can be found. This is the location where the earthquake has the biggest effect. Further away from the epicenter the earthquake will lose its energy. The initial energy can be created by two causes: movement of tectonic plates or induced in the earth by human activity. The first one is the most commonly known and occurs the most often (Sucuoğlu & Akkar, 2014). However, even though tectonic earthquakes are still the most common, induced seismicity has been happening more often over the last decades and in areas which are not known for earthquakes.

An earthquake is a combination of seismic waves which travel through the earth's crust. There are three different waves which can be distinguished: compressional waves (P), shear waves (S) and surface waves. The P-waves create a compression in the surface parallel to the epicenter. These waves travel the fastest and are therefore the first to reach a seismograph warning for an earthquake. Secondly, the S-waves arrive which create a sinusoid shear wave perpendicular to the surface. Lastly, the surface waves which create the most damage due to a complex rotational movement which is created in the earth's crust. The surface waves give the largest amplitude on the seismograph which defines the magnitude of the earthquake.

The power of an earthquake is described either by its magnitude or the intensity. The magnitude can be quantified by different scales of which the Richter scale is the most commonly known (NAM, 2019). The Richter scale which measures between 1-10, was formulated In 1935 by Charles Richter. He did this in California, by using the amplitude of a base earthquake measured by a Wood-Anderson seismograph and subtracted that from the amplitude created by the occurring earthquake (Sucuoğlu & Akkar, 2014). It is important to notice that this local magnitude (M_L) only works for this type of seismograph and the area of California. Therefore, when using the M_L on a global scale to describe the magnitude of an earthquake the seismic agency must be aware of the location and type of seismograph used. The equation formulated by Richter is on a logarithmic scale, this means an increase on the scale by one point is the result of an increase in energy by the earthquake of $10^{1.5}$ (a factor ≈ 31,6) (NAM, 2019). The equation for the Richter scale is written down in equation (1).

$$M_L = \log(A) - \log(A_0) \qquad (1)$$

In the 1970s further research was done to formulate an improved scale. The Seismologists Thomas C. Hanks and Hiroo Kanamori proposed an equation to calculate the magnitude of an earthquake independently from the area in which it took place (Sucuoğlu & Akkar, 2014). This Moment magnitude scale (M_W) is defined using equation (2).

$$M_w = \frac{2}{3} log_{10}(M_0) - 6.0 \qquad (2)$$

In equation (2) the value of M_0 is the seismic moment in Newtonmeters. The constants in this equation are used to keep the calculation of the M_w consistent with the Richter scale. This means the outcome will lie in the same range as the scales (Richter) used previously. However, a big difference is that the outcome is not limited to a value between 1 and 10, meaning that heavier earthquakes can be measured. Because the Richter scale is widely known by the public, misconceptions occur in the usage of this scale. Media often refers to the Richter scale where in fact they mean the moment magnitude scale. All the magnitude values used in this report will be on the moment magnitude scale, being the most accurate measurement scale. The Moment magnitude scale is an objective representation of the magnitude (energy) of an earthquake and does not give information on the intensity of the earthquake. The intensity contains the damage caused to the surroundings as well. This description of damage was created by Mercalli in the early 20th century. This proposed scale quantifies the strength of an earthquake according to observations. The effect on people, objects, the built environment and landscape are taken into account in a 12 points scale (I-XII). The intensity scales from I: not felt (but measured by instruments) to XII: Completely devastating (NAM, 2019). The Mercalli scale can give a total different view on the effects of an earthquake than the magnitude scale. This is because the measured magnitude is the amount of energy released which travels in waves through the soil. This soil can have different compositions which effects the wave by absorbing or increasing the travel distance and energy of the earthquake. This can result in a low magnitude earthquake on the moment magnitude scale but a high level on the Mercalli scale in case the soil amplifies the energy.

2.1.2. Earthquake types

As mentioned before it is possible to distinguish two types of earthquakes: tectonic and induced. The first type of earthquakes are the ones caused by the constant movement of the earth's crust (a short explanation of this type is added to appendix A). Different to tectonic seismicity is induced seismicity. The study on anthropogenic or non-natural seismicity has started in 1894 after earthquakes were felt in Johannesburg, South-Africa (Mcgarr, 1994). Eight years prior to this research the gold mining production at Witwatersrand had started, however it would take until 1908 for the research to find the connection between the mining in the area and the start of the earthquakes. Since this first incident, multiple other causes of earthquakes were found. In traditional non seismic areas in North America and Europe earthquakes were felt, caused by processes such as reservoir impoundment, fluid injection and fluid withdrawal (Keranen & Weingarten, 2018). These induced earthquakes caused by human activity have reached high magnitudes in strength and have had big impacts on the built environment in the area. The largest earthquake caused by oil and gas extraction since 1929 took place in Uzbekistan with a magnitude of 7.3 (Beirlant, Kijko, Reynkens, & Einmahl, 2018). This large magnitude is not rare whereas magnitudes of about 6 on the Richter scale were measured in France close to a gas field (Beirlant et al., 2018).

In the 1980s the first seismic activity was recorded in the province of Groningen. The province has had no history of tectonic earthquakes until that point (Dedontney et al., 2016). This raised the question whether the seismicity was caused by a different reason. Research was done to find the cause of this seismicity. The gas extraction, which had started 20 years prior to the first earthquake, was found to be the reason for the increasing level of seismicity. The gas extraction causes a lower pressure in the reservoir which makes the soil compact (Sucuoğlu & Akkar, 2014). When this compaction happens evenly no major problems occur. However, when soil layers get stuck they build up friction stress. This movement of soil layers among each other occurs at the so called faults. These faults are the natural edges in soil layers. When the friction stress reaches a certain threshold the energy is released and creates an earthquake (Sucuoğlu & Akkar, 2014). The frequency with which earthquakes occur has risen ever since the 1980s. Other than the increase in frequency, an increase in strength of the earthquakes can be seen (Dedontney et al., 2016).

As mentioned earlier, the magnitude of an earthquake is not the only factor influencing the devastating effect on the built environment. The composition of the soil has a big influence on the shaking of the earth as well. At a location where the soil mostly consists of rock the earthquake will have a less devastating effect on buildings than when the same magnitude earthquake would occur in areas with soft soil (Sucuoğlu & Akkar, 2014). The situation in Groningen is a good example of this; softer soil types such as bog, sand and clay amplify the waves created during an earthquake. Within the province of Groningen these soil types can be found in different locations, this is the reason that some areas are more sensitive to the effects of an earthquake than others. Due to the different effect from area to area a different quantity is used, the Peak Ground Acceleration (PGA). The PGA is the maximum value of the grounds acceleration and is measured in m/s^2. This value is used as the acceleration in calculating the forces on a building using Newton's second law (3).

$$F = m * a \qquad (3)$$

From equation (3) it becomes clear that there are two factors influencing the force which the building has to endure. The 'a' is the acceleration of the ground on which the building is located and the 'm' is the mass of the building. When designing a new building the mass of the building can be calculated using the masses of the individual elements. This gives the value for the equation to determine the forces on the building. The acceleration is different for every location and earthquake. This is why the Peak Ground Acceleration is used to calculate the forces on a building. The PGA is the estimated maximum ground acceleration to be expected in an area.

2.1.3. Earthquakes in Groningen

On the 22nd of May this year the province of Groningen was struck by yet another earthquake (Kerstens, 2019). This earthquake had a magnitude of 3.4 on the Richter scale and because of that was added to the top three heaviest earthquakes in Groningen. The earthquakes in the province of Groningen are not only getting heavier but more frequent as well (Dedontney et al., 2016). Over the course of 2018 a total of 87 earthquakes with a magnitude over 1.5 on the Richter scale were measured (Algemeen Dagblad, 2018). These earthquakes harm the built environment of Groningen and with that the safety of the residents. Larger growing cracks in walls and entire buildings coming to a state of (near) collapse leave the people of Groningen desperate.

The earthquakes found in Groningen are not of a natural cause, but induced by human activity. The reason for the start of the earthquakes in 1986 can be traced back to the discovery of natural gas near the city of Slochteren in 1959 (NAM, 2018). In that year the NAM, a joint venture founded by Shell and ExxonMobil, discovered one of the biggest natural gas fields in the world. This gas field spreads over 900 km^2 and contained 2.8 billion cubic meters (bcm) of natural gas, which was at that point in time the biggest in the world (Vlek, 2018). After this discovery the company immediately started to pump the gas to the surface in cooperation with the Dutch government. Over the past 50 years the NAM and the Dutch government have extracted 2.1 bcm of gas from the reservoir. This gas can be found within a porous layer named Rotliegend sandstone in the soil of Groningen. When the gas is extracted a pressure difference occurs, creating an imbalance in the soil (Ellsworth, 2013). The pressure reduction which has been created over 50 years has already added up to 250 bar (Vlek, 2018). The sandstone layer compacts, causing the ground to drop. When this compaction happens gradually and evenly no harm is done. However, when the soil compacts uneven it can cause friction stress within the different layers in the soil. When the different soil layers suddenly come lose the stored friction energy is released causing an earthquake. This earthquake is created by human interference in the soil and is therefore called an anthropogenic earthquake (Beirlant et al., 2018). In the next chapter the characteristics of these kind of earthquakes will be further elaborated.

Since 1986 these man-made earthquakes have been occurring in Groningen and will not stop until the state of stress in the soil is in balance again (Beirlant et al., 2018). The easy solution, according to the inhabitants of the earthquake area, seems be stopping the production of gas in Groningen in order to stop the earthquakes as well. However, besides the big national and international economic dependency of the gas from Groningen (Gerrits, 2018), just to stop the production of gas will not give a direct solution (Waterval, 2018). It took 25 years for the earthquakes to start since the first year of gas production in this area and, as mentioned the stress built up in the soil does not vanish by just stopping the production. The soil of Groningen needs to come to a phase in which the disturbance of the stress is reduced and brought to a minimum (Ellsworth, 2013). This process can take years and will involve more earthquakes in the process. The earthquakes will not disappear overnight, neither will the safety hazards for the users of these buildings and the devaluation of their property. It is therefore important to find a solution to the unsafe and damaged built environment in Groningen.

2.2. Building in an earthquake area

2.2.1. Designing for earthquakes

Earthquakes are the only natural disaster, such as tornadoes and tsunamis, engineers take into account when calculating buildings (Langenbach, 2014). However, making a building completely earthquake proof will not be economically interesting, nor practical in use. This is because of the large amount of material required to achieve this. Therefore, when taking earthquakes into account the calculations will be done to establish a certain level of safety instead of complete earthquake resistance. The material will give in, but will not collapse to provide an escape for the people inside. The destruction of buildings by an earthquake, causes the biggest threat to occupants of a building. This is also mentioned by Prof. Langenbach in his keynote at the 2014 World Conference on Timber Engineering: "Earthquakes do not kill people, buildings do" (2014). For this reason it is important to create a construction which gives the users time to escape the building. This approach, however, does have a downside. It allows the buildings to come to a near collapse stage and repairs after an earthquake are often very expensive, or even impossible. This building for the short term contradicts the trend of sustainable building (Pessiki, 2017). However, the safety of the users of the building is regarded more important as described in the design code Eurocode 8. Residential buildings need to protect human life in a way that an earthquake will not take human life or cause serious injury due to the failure of the building. Therefore, the design strength of the building should reach the so called no-collapse requirement. This requirement states that there should be no local or total collapse in the structure of the building (Sucuoğlu & Akkar, 2014).

As mentioned earlier, earthquake forces were not taken into account by Dutch engineers when designing a building. In most parts of the Netherlands this is still not necessary, however the situation in Groningen does require for this destructive force to be considered. The effect of seismic forces is not like any other kind of force currently used in the design process such as wind or permanent action. When an earthquake occurs the acceleration in the soil creates both horizontal and vertical forces which affect the building (SKH, 2017). Even though both horizontal and vertical forces occur, when designing a building, the forces in x and y direction are considered the most important. These forces can be calculated using the earlier mentioned Newton's second law in eq. (3). Equation (3) shows the importance of the mass of the building in relation to the acceleration of the soil. This is where wooden structures get their advantage over concrete and brick buildings for example. The lower mass gives lower forces on the building when exposed to seismic activity. Newton's second law gives a good indication for designing earthquake resisting structures. However, it is not completely capturing every aspect. The seismic waves during an earthquake take place in different frequencies. During a specific frequency the peak ground acceleration reaches its highest value. When the frequency matches the natural frequency of the building, a collapse of the structure is possible. This phenomenon can have such devastating results an additional factor is multiplied to Newton's second law: the dynamic amplification factor (DAF), resulting in equation (4).

$$F = m * a * DAF \qquad (4)$$

The mass of the building can be calculated using the masses of the individual elements. This gives the value for the equation (4) to determine the forces on the building. The acceleration is different for every location and earthquake. This is why the Peak Ground Acceleration is used to calculate the forces on a building. The PGA is the estimated maximum ground acceleration to be expected in an area. It can then be used to calculate the maximum force a building should endure. In Figure 2. the seismic hazard map for Groningen, made by the KNMI, is shown. This map shows the area of the gas field in Groningen and gives the expected PGA for the locations within the reservoir area. The values range from 0.05 m/s^2 near the edges to 0.24 m/s^2 in the center of the reservoir. These values for the PGA are calculated with a probability of exceedance for once every 475 years.

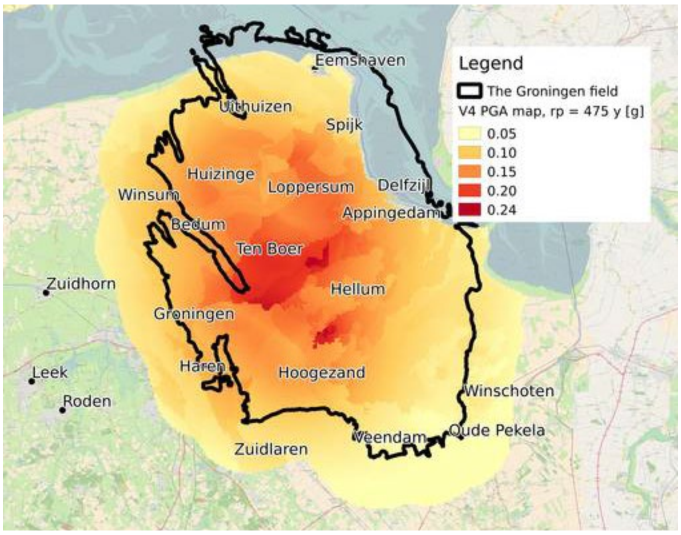

Figure 2. Seismic hazard map Groningen 2017 (KNMI, 2017)

2.2.2. Energy dissipation in a construction

An earthquake is a sudden release of energy. This energy travels through the soil in the form of waves and reaches the built environment in that way. When a building gets struck by a part of the earthquake energy, the energy will create a force on the construction. The force which reaches the structure is calculated as described in the previous paragraph. However, some structures have the possibility to dissipate parts of the energy. When this energy is dissipated it will not create a force on the construction, but lowers the amount of force the construction has to endure (SKH, 2017). The ability of a structure to dissipate energy is therefore very welcome in a seismic active area. This ability of dissipation is different for every material.

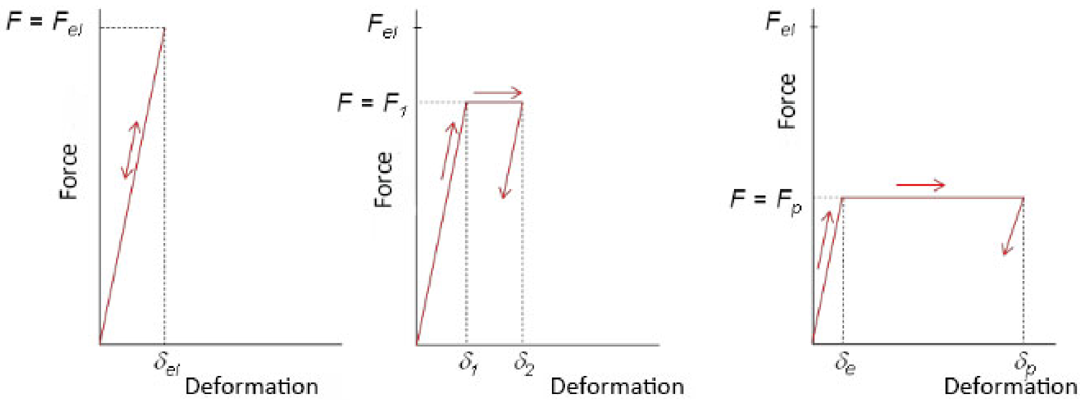

Figure 3. Force and displacement (SKH, 2017)

In Figure 3 the graphs show the displacement of a construction on the horizontal axis in relation to the force on the vertical axis. The first graph shows a construction which reacts completely linear elastic to the force. The displacement of the construction is small and it will go back to its original state after the force is gone. This type of behavior does not allow for dissipation to happen and therefore the full energy of the earthquake will cause damage to the construction. The amount of energy is calculated by calculating the surface under the graph (SKH, 2017). The second graph shows a construction which is characterized as limited plastic. The graph shows that the construction can take a lower amount of force in comparison to the first graph. Nevertheless, the construction can dissipate some energy, lowering the force it has to endure. After the earthquake has taken place the construction shows a small permanent deformation. The final graph shows a material which reacts highly plastic. Again, the force the material can take is lower compared to the other two. The material can dissipate a large amount of energy, lowering the force, but has a large deformation because of it. The latter material/construction is, due to its energy dissipating property, very suitable for earthquake areas since it lowers the force the construction has to endure. When designing a building for seismic resistance this energy dissipation should be considered.

2.2.3. Building shapes

When designing buildings to resist earthquake forces an easy advantage can be gained by taking the shape of the building into account. Buildings with a rectangular floorplan with little irregularities are the most fitting in seismic areas (NEN, 2015; SKH, 2017). Buildings with a corner shape have to endure larger forces during an earthquake and need extra structural reinforcement to create a stiff structure. Another possibility is to detach the different building parts from each other, creating multiple rectangular shaped building parts. Additional to these floorplan design decisions the section of a building influences the sensitivity to earthquakes as well. The base of the building should be the widest part, narrowing down towards the top. This is based on the mass of the building being placed at the bottom. When creating a narrow base with a wider top the chances of swinging of the construction get higher. In Figure 4 an overview of suitable and less suitable building shapes is shown (SKH, 2017).

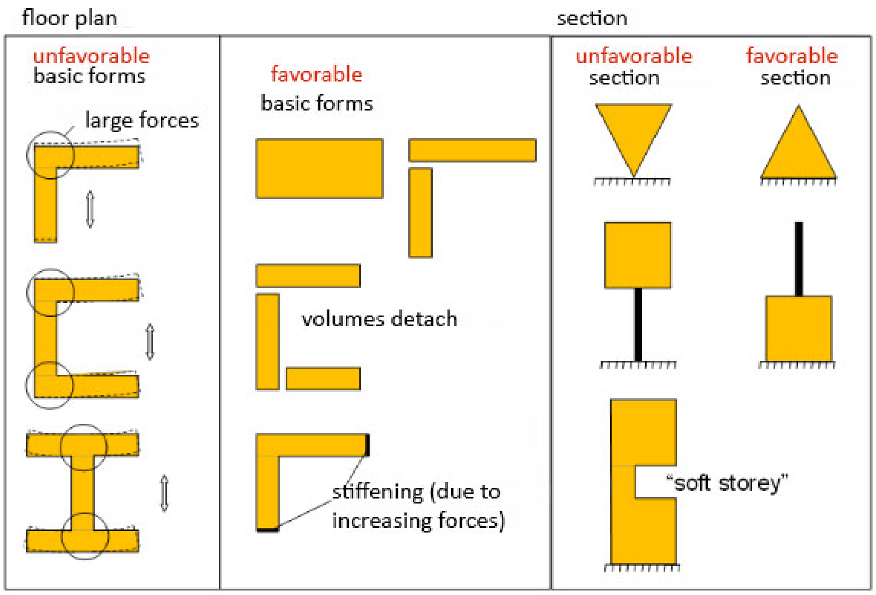

Figure 4. Overview of suitable building shapes in earthquake areas. (SKH, 2017)

2.3. Timber structures

Following from the previous chapters, buildings in an earthquake area should have a low mass and ideally be able to dissipate energy. The low mass will keep the earthquake forces smaller on the building. A material which has been widely used in earthquake areas is, therefore, wood. The light weight material has beneficial characteristics for the applications in a seismic active area. This chapter explore further the characteristics of timber structures.

2.3.1. Timber characteristics

Timber structures have been used to create buildings for over thousands of years. They vary from ordinary houses to temples and churches (Zwerger, 2015). Wood has proven to be a diverse material which is also easily accessible. However, when large scale concrete and steel made their entry into the construction world in the 20th century, new opportunities arose for building higher and bigger as to what was possible before. Timber lost ground in the construction world, but this all changed again roughly 20 years ago with new research and innovation in timber structures. The empirical knowledge about wooden structures was researched and new innovations such as glue laminated timber (GLT) made it possible to create larger spans. This put timber back on the map as a possible construction material for different kinds of structures. In this chapter the characteristics of wood in timber structures will be explained further as this knowledge is necessary for timber.

The characteristics and behavior of timber in a construction can be led back to the growth of the tree. Due to the large surface of leaves or needles on a tree, it will catch high amounts of wind. These horizontal forces create a moment in the trunk of the tree resulting in high compression and tension stresses along the length. The natural need for the tree to withstand these horizontal forces requires the tree to be able to take these forces in longitudinal direction. In contrast to these high forces in longitudinal direction the tree has little force to endure in the direction perpendicular to the grain and therefore can suffice with a lower strength in this direction. Hence, wood can be characterized as an isotropic material, meaning that it has different properties within the material itself (Pirinen, 2014). Important in this characterization is the grain of the wood. The grain is running along the length of the tree. Wood can take high compression strengths in the direction parallel to the grain (longitudinal) but approximately 40 times less perpendicular to the grain. The exact value of compression strength is dependent on the type of wood being used. When designing a structure it is therefore important to know which type of wood to use for which project and purpose. In the case of tensile strength, again the direction of the grain plays an important role. Similar to compression strength, the tensile strength is 10-20 times greater parallel to the grain in comparison to perpendicular to the grain.

An important factor to take into account when designing with timber elements is the ductile and brittle behavior of wood. Most materials are either ductile (capable of deformation before breaking) or brittle (breaking without deformation). However, wood is a isotropic material and therefore can be both depending on the loading direction of the wood. In Figure 5. the stress strain diagram for wood is shown. This diagram shows the behavior of wood in the possible loading directions. The figure shows in the top right quadrant that wood behaves brittle in tension both parallel and perpendicular to the grain. in tension, both parallel or perpendicular to the grain, behave brittle. The material will bear the force until sudden brittle failure. In the lower left quadrant the material is shown under pressure loading. Perpendicular to the grain wood is capable of deformation but only at a low loading force. This gives the wood the opportunity to dissipate a little amount of energy. However, wood loaded under pressure parallel to the grain performs differently. The material acts much more ductile in this direction, making it possible to dissipate energy.

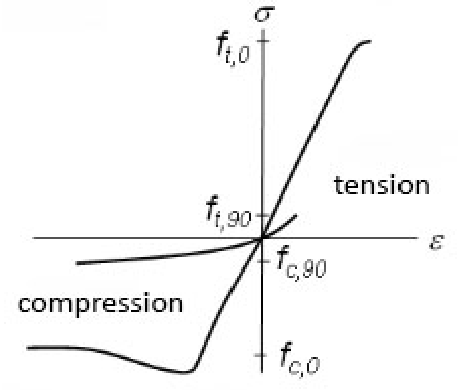

Figure 5. Stress strain diagram of wood (SKH, 2017)

This ductility is described by Jorissen and Fragiacomo (2011) as follows: "Ductility is the possibility to attain large displacements without losing too much strength in a material specimen/joint/member/structure loaded in displacement control". This possibility for displacement describes the favorable behavior as mentioned in paragraph 2.2.2. Constructions in earthquake areas showing ductility make it possible to lower the force the building has to endure due to the dissipation of parts of the energy in the construction.

When considering elements loaded in tension, a more brittle behavior will occur, bending or shear. A typical example of these elements are beams loaded in tension. The beams will show a small deformation followed by visible fractures in the material (Malo, Siem, & Ellingsbø, 2011). Due to the brittle behavior in beams it is necessary to design these elements with overstrength (Jorissen & Fragiacomo, 2011). This way of designing is not economical but necessary for the safety of the construction. Contrasting to the brittle beams are elements in compression, either parallel or perpendicular to the grain. These elements can show ductility. The definition by Jorissen and Fragiacomo (2011) recognizes the capacity of displacement within joints as part of the ductile possibilities within a construction. This behavior of ductility within joints is important to achieve in order to compensate for the brittle behavior of the beams. Ductility is a favorable characteristic of an element. Before fracture the element will displace and warn the users of a building for possible failure of the construction. Especially when creating a design for a seismic active area this warning function of a ductile connection is highly important. Furthermore, the displacement of the material and joint lowers the force the building has to endure. This means the building is able to take heavier earthquakes before coming to a state of collapse.

The above shows that ductility within the construction is of high importance. Reaching a level of ductility in a timber joint raises the ability of the construction to endure earthquakes of higher force. Since elements such as beams are not able to show any ductility the joints are the part of a timber construction to gain an advantage. In the next chapter the tradition of timber joints is elaborated as a possible solution to build safe buildings in the seismic active area of Groningen.

2.3.2. Traditional timber joints

Timber structures can be found all over the world. This is due to the fact that this natural material grows almost everywhere and provides a relatively easy material to work with (Zwerger, 2015). The tradition of building with timber reaches back centuries and results in true mastership in countries such as China, Japan, Norway and Austria. Despite the usage of roughly the same material, there are major differences in joinery and usage of the timber (Zwerger, 2015). These differences are not only caused by the species of trees and environmental qualities in the areas but the tradition of the people in these areas as well. The knowledge of building with these timber joints was passed on by master to apprentice for centuries. However, that changed when the industrialization and mass production became more important in the economy of the last century (Erman, 2002). The declining interest in the traditional joinery was caused mainly by this need for faster and cheaper construction methods. By the end of the 20th century this started to change again. During the 1980s the demand for renovation of traditional wooden structures started to rise causing a growing interest in timber joints and their mechanical properties (Bulleit et al., 1999). The knowledge up to that point was mostly empirical. Simultaneously with the rise of renovation, a growth could be seen in the demand for traditional wooden structures in newly build buildings. Because the understanding of this construction method was mainly based on empirical knowledge, multiple researches have been conducted on these topics over the past years to get a better understanding of the mechanical properties of these joints and structures (Parisi & Piazza, 2008; Xue et al., 2018). Another reason why the timber joint had disappeared out of the general building methods is the high level of craftmanship and crafting hours. The usage of timber joinery is laborious and therefore expensive. However, with the usage of modern computer numerical control (CNC) the precise crafting of timber joints can speed up the process and make it cheaper (Pirinen, 2014; Roche et al., 2015). This creates the opportunity for timber joints to make a comeback into the construction world.

Timber joints come in different forms, as mentioned earlier. A main difference can immediately be made when looking at different construction systems. Roughly three systems can be distinguished: light framing as can be found in most American houses, post and beam which create a frame of the timber building as done in The Netherlands, and solid timber constructions such as full wooden walls in Scandinavian cottages (Erman, 1999). In this research the focus will be on the second building method: the post and beam frame structure. This type of construction is historically used in the Netherlands as main structure for churches, farmhouses and residential buildings (Hillinga, 2009).

When working with a post and beam structure not only the geographical location in which the structure was built affected the type of joints but the required functionality of these connections as well. The functionalities of these joints have been researched by multiple parties over the past century. Because the joints are created according to tradition and geographical locations most researches are influenced by the background of the researcher. Other than this, the point of view of the researcher can be on different subjects like structural, esthetic and functional aspects of the joint (Erman, 1999). In this research the aim is to find a solution for the province of Groningen. This means the joinery should fit the style which can be found in this province. However, because the area is not used to earthquakes influences from other traditional joinery from abroad will be used.

The research by Zwerger (2015) makes a classification on the functional aspects of the joint. The joints can be roughly characterized by permanent or flexible (Zwerger, 2015). Both these types have their own advantages. The flexible joints can be used when the building needs to be reassembled because of relocation or in case parts need replacement because of damage. The permanent joints cannot be dismantled without damaging them. This downside is compensated by the higher strength these joints have (Zwerger, 2015). Other than the difference in permanent or flexible it is possible to classify the joints on several other characteristics such as: the direction of the joint, the number of components, the force bearing type of the joint, the position of the joint in the structure and the applied fastener types (Erman, 2002).

When regarding the direction of the joint it can be characterized according to the joining angle: either orthogonal or diagonal. Common examples of orthogonal joints are corner and 'T' joints as shown in Figure 6. The T joints are formed by an element which connects to a second element perpendicular to the first one in a 'T' shape (Erman, 2002). This way of joinery can be found in both European and Asian countries. However, the geometry of the joints differ from each other because of tradition.

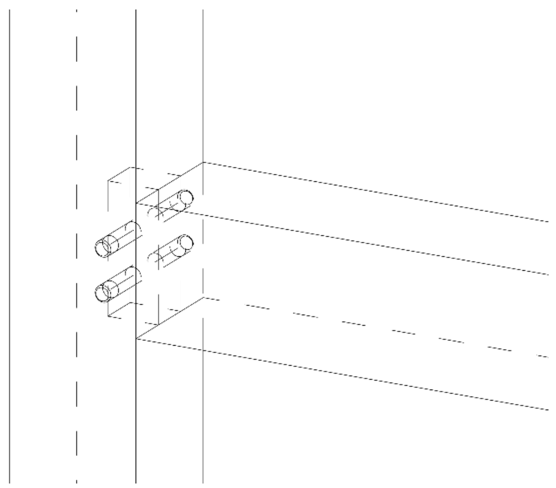
Figure 6. T shaped joint mortise and tenon

In Japan, most of the joints are created with orthogonal connections forming a complex geometry. The few diagonal joints which can be found in Japan are used for roof constructions. In contrast, the European joinery tradition relies on diagonal joints, not only for roof structures but for bracing in walls and frames as well. The European joints are less complex in their geometry and rely on the diagonal connections for stability.

The joint in a column and beam structure is the place where elements come together. The amount of elements coming together in a joint influences the possible joinery. Too many elements in one joint can limit the choice of a joinery type. Erman (2002) provides a directional breakdown structure to organize these elements and their position in the joint. The breakdown structure makes a rough distinction between three different kind of joints: corner, 'T' and multiple component joints. Forming a joint requires a minimum of two elements but can contain as much as six elements in case all orthogonal directions are used. The direction and amount of elements is important for selecting a suitable joint. To illustrate this an example can be given for a 'T' joint as can be seen in Figure 7. Consider a 'T' joint with a column in the vertical direction. The design requires for a horizontal beam on top of this column running in the same plane. This horizontal beam can be formed in two different ways, either with two elements or one single element. The choice affects the possible joinery which can be applied. Because of this, it is important to get a clear overview of the required amount of components and their directions.

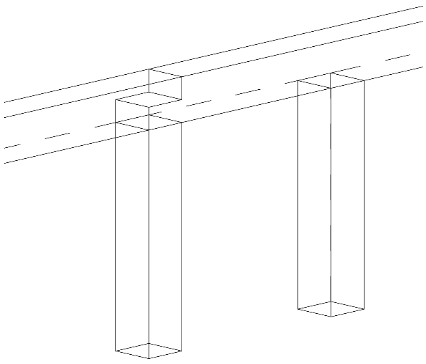

Figure 7. T joint example options

In European joinery additional fasteners are used such as wooden pegs or steel bolts to reinforce a joint (Erman, 2002). Traditionally wooden pegs and wedges were used in the connections but over the centuries steel fastener types came widely available. The behavior of these pegs needs to be analyzed when creating a timber joint. Research by Bulleit et al. (1999) shows that especially the wooden pegs can be normative in some cases. The failure of these fasteners can result in the instability of the overall structure and damage of other elements. Even though these wooden fasteners can ultimately cause instability when they break, in some cases the traditional aesthetics of a construction is considered more important and therefore the wooden fasteners are used (Rumlová & Fojtík, 2015). Steel fasteners such as bolts are capable of showing large plastic deformation and are therefore preferred in earthquake situations (Malo et al., 2011). The plastic deformation adds to the energy dissipation and warning function of the joint (Jorissen & Fragiacomo, 2011). Even tough wooden fasteners are considered not favorable in earthquake situations because of their brittle behavior, the research of Shiratori (2009) found a way to use wooden wedge beams in his advantage. The wedge beam is used as embedment in case of an earthquake, dissipating energy in this way. Additionally, the advantage gained by the wedge beam is the possibility to replace parts. After an earthquake occurred the wedge beam could be easily replaced and therefore the construction would come back to full strength (T. Shiratori, Leijten, & Komatsu, 2009). This different approach shows that there is not one single solution for a connection, but that the used solution is highly dependent on the conditions in which it needs to perform.

When designing a fitting construction for a building, the selection of proper joints is important. The joints in a timber structure are assumed the weakest parts of the construction (Erman, 2002). However, as mentioned in the previous chapter the joint can provide the construction with necessary ductility (Jorissen & Fragiacomo, 2011). Especially in areas where earthquakes are common, a well-designed joint can make the difference. In case a non-suitable type of joint is used it can amplify the weakness of the connection, however when a joint is stiff and capable of ductility it improves the overall structure.

The direction of the force and the deformation caused by this force need to be reflected in the joint (Erman, 2002). For instance, when the tensile strength is normative in a 'T' shaped connection, a dovetail joint can provide a solution as seen in Figure 8. The wide tail of the connection protects the tenon to come lose when being pulled at (tensile force). This is an example in which the joinery fits the purpose of the joint and the forces it has to endure. Especially in cases where the wooden structure is placed in a seismic active area the joints form the key elements in the structure. When the joint is well chosen and manufactured correctly it can provide dissipation of energy through the structure to some extent. When this is not the case it can amplify the fragility of the structure (Parisi & Piazza, 2008).

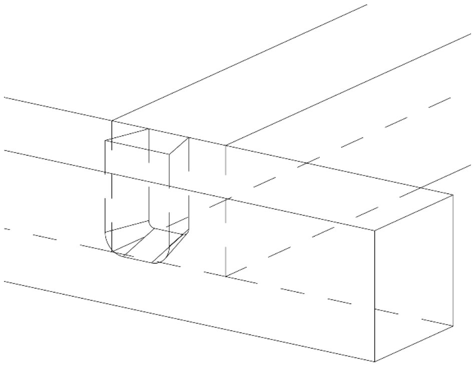

Figure 8. T shaped dovetail connection

Other than the selection of the right joint, the craftmanship and manufacturing determine the stiffness and durability of the joint (Erman, 2002). The level of accuracy in the connection affects the effectiveness of the joint. The transmission of forces is regulated by the direct contact and friction between the wooden elements in a connection (Parisi & Piazza, 2008). Therefore the level of precision of the joint increases the contact area and with that enlarges the amount of friction.

Joints are formed by adding one or more cuts in a piece of timber creating an extension which is counter fitted in a second element. This process of joinery can create a wide variety of connections, all with their own strengths and weaknesses. The precision of these cuts are important whereas the contact surface of the joint will be larger when the joint fits tightly. Over the course of history the craftmanship of the carpenter was necessary to make sure that a high level of precision was reached (Zwerger, 2015). In recent times innovations such as computer numerical control, or CNC for short, make it possible to reach an even higher level of precision (Pirinen, 2014). However, the knowledge possessed by the master carpenters on their material should not be underestimated. Not only the level of precision while working on the joint determined the end result but the material knowledge played a key role. Knowing the moisture level in the used elements and using this to the advantage of the joint can make a connection even more precise due to the shrinkage and swelling of wood (Zwerger, 2015).
Traditional timber joints can transmit only a small amount of moment, therefore they need to be modeled as a pinned/hinged connection (Bulleit et al., 1999). To improve a connection on its moment transmitting, an additional brace needs to be added. This results in a more moment resistant overall connection. The amount of moment which can be transmitted depends heavily on the precision of the joint: the better the elements fit together, the higher the level of transmitting of moment (Bulleit et al., 1999). The larger friction area which is the result of higher precision in the joints is the reason for this increase in moment capacity (Erman, 2002). However, in contrast to the little amount of moment found by the research of Bulleit et al. (1999), when modeling a total frame it must be assumed that the joints carry no moment. The addition of bracing and other diagonal elements do not chance this.

As mentioned the orthotropic behavior of timber has influence on the loading capacity in different directions. The research of Shiratori (2010), shows that it is possible to utilize the strengths of timber while diminishing the weaknesses. In his research the traditional Japanese Nuki joint (through tenon joint) and Nageshi joint were used as reference points. Both rely on a tight fit and friction to transfer force through the joint. Due to embedment of the beam into the post as a result of forces caused by earthquakes and the shrinkage of the material the joint loses its friction and with that a big part of the strength. As a solution to this, Shiratori proposes a new joint, namely the K-N joint as shown in Figure 9 and Figure 10. This joint is formed by triangular shaped Nageshi beams (black in Figure) on both sides of a post directed towards the center using Kusabi wedges (dark grey in Figure). The posts (in the colors green and light grey) are locked between the two elements and forced into prestress using a bolt fastener. Because of the shape of the Nageshi beam in combination with the Kusabi wedges any rotation which will occur in the system is now translated to compression forces along the grain of the post, resulting in an optimal usage of the isotropic behavior of wood (T. Shiratori et al., 2009). Both embedment and friction play a key role in the functioning of this K-N joint system. The embedment of the post into the beam is a way of absorbing the energy led into the construction by the earthquake. This is why it is important to use a wood type which has a high density value, able to take as much force perpendicular to the grain as possible. Because of this embedment the joint will lose strength gradually over time due to loss of friction. This can be countered by tightening the bolt to increase stress on the joint again. However, after severe damage or a long time span it may be necessary to replace the Kusabi wedge beams. The K-N joint allows for this replacement relative easily because of the fastening due to the bolt, creating a non-permanent joint.

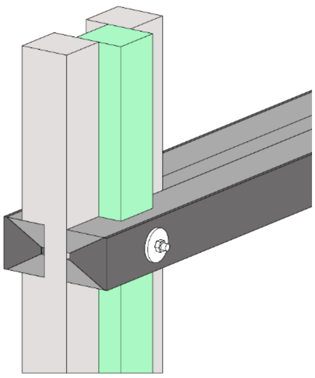

Figure 9. K-N joint assembled

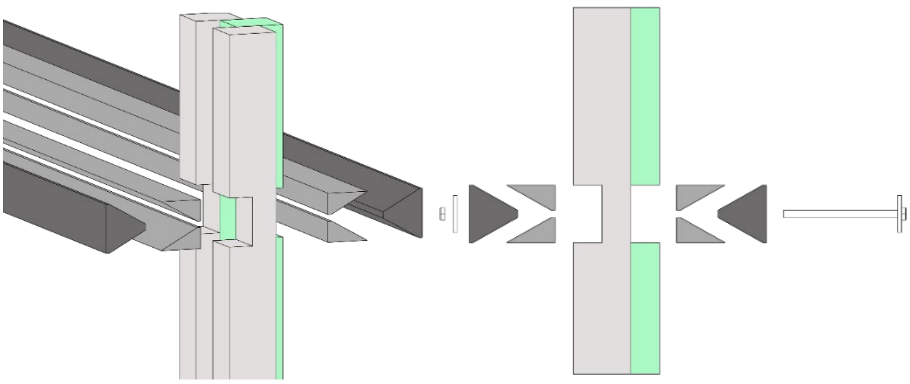

Figure 10. Exploded view of K-N joint

2.3.3. Traditional timber structures in the Netherlands

The province of Groningen is the most northern province of The Netherlands. When earthquakes are felt in the province it is near or above the gas reservoir which is located to the north-eastern part of Groningen. In this area, mostly smaller villages and agricultural land use can be found. A building type which can be found frequently in this area is farmhouses. Within the farmhouse typology there are still different shapes and sizes depending on the location within the province. The popularity for this kind of building is clear since the farmhouses and barns can be found in the villages as well. In the countryside, farmers use farmhouses or residential and commercial use, whereas, in villages the traditional barn building is used as a workshop, factory or even as local priory (Hillinga, 2009). These barns are mainly shaped by their bent structure, the load bearing construction of the building (van Cruyningen et al., 2003). The bents are formed by posts connected by horizontal beams to create a frame. These bents can either be placed within the depth of the building or along the width. In the Netherlands the bents are mostly placed along the width. The amount of bents determined the depth and size of the farmhouse and with that showed the wealth of the farmer. Along the length of the farmhouse horizontal beams and bracings are added to connect the multiple bents into a sturdy structure. The area between two bents is known as a "Gebintvak" (inner bent area) as can be seen in Figure 11. These areas had different functions for the farmer ranging from storage for food and tools to living area for cattle.

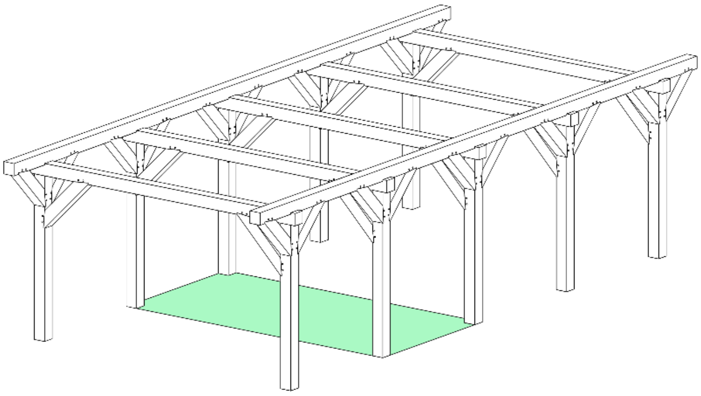

Figure 11. Gebintvak of a bent structure

Bent structures come in different shapes and sizes within the Netherlands. The most commonly used is the "Ankerbalkgebint" (van Cruyningen et al., 2003) this type of bent is formed by two posts connected by a beam which goes through the post with a through tenon locked by wedges and pegs as can be seen in detail in Figure 12. The braces are connected using an oblique tenon joint to the column and beam. To connect multiple bents the horizontal beam is connected by a mortise and tenon connection fastened by pegs. This type of bent is found in most areas around the Netherlands, except from large areas in Friesland, Noord-Holland and Groningen.

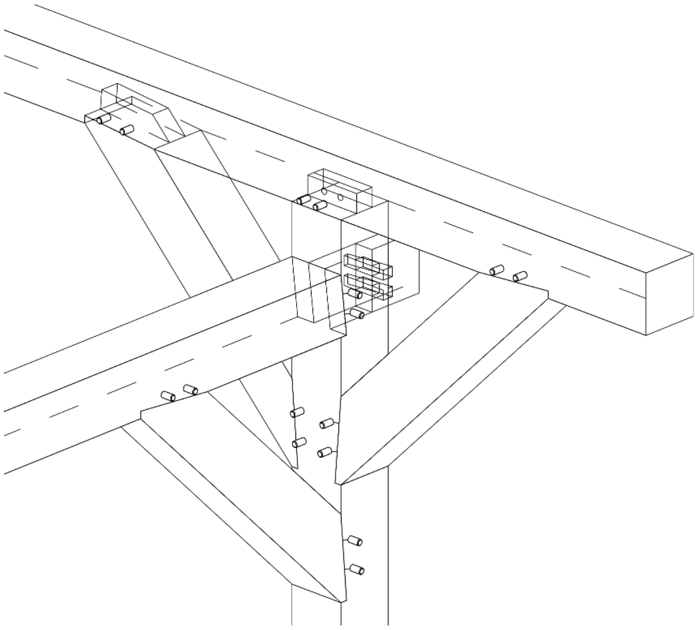

Figure 12. Ankerbalk joint detail

In these areas a different kind of bent can be found: the “Dekbalkgebint” (van Cruyningen et al., 2003). The horizontal bent beam is connected on top of the columns using a mortise and tenon connection as illustrated in Figure 13. The braces are connected in a similar way to the “Ankerbalkgebint”. A difference can be found in the connection of multiple bents. This is done by a beam connected to the top beam of the bent using a halved dovetail joint as shown in the detail.

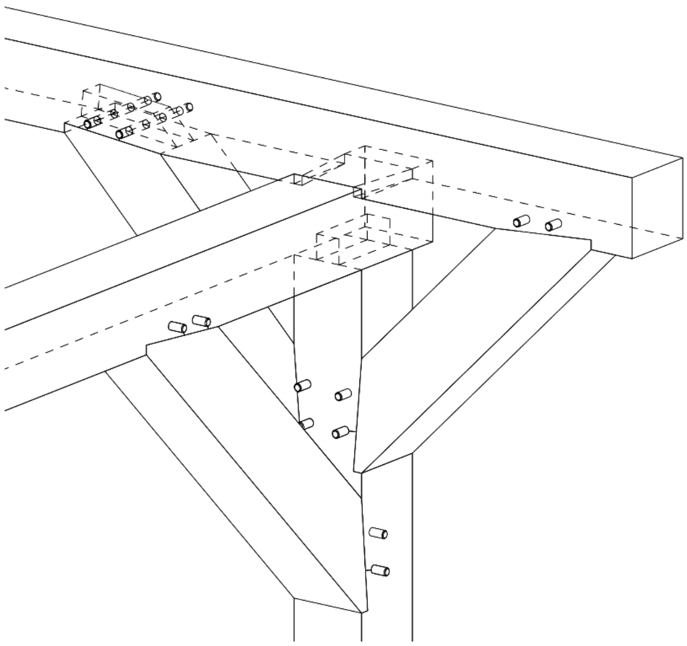

Figure 13. Dekbalkgebint joint detail

2.4. Design of walls and floors

The residential built environment of Groningen consists mainly of houses with masonry walls and concrete floors. These materials are heavy and behave brittle (Sarhosis et al., 2019), and are therefore not ideal in a seismic active areas. The weight of the material influences the earthquake force in accordance to Newton's second law. The heavy materials cause a higher force in contrast with a situation with lighter materials.

In the earthquake area, buildings can be found from different ages. Technology has changed over time, so have the building methods for the residential buildings. This difference over time can be seen in the masonry work in the area. Older buildings are built with lime mortar and buildings from the late 19th and 20th century on with modern cement based mortar. Between these mortar types there is a difference in structural behavior. Lime based mortar is more flexible than the cement based one. The lime mortar allows the masonry work to settle in case of a gradually shifting ground over time. The cement based mortar is stronger but less flexible. Because of this difference in mortar the walls will react differently to earthquakes as well. When the mortar is of lower strength than the masonry as with lime mortar, the wall will crack over the mortar alongside the bricks. In case the mortar is stronger than the masonry work, the wall will crack over the bricks itself. These cracks create a devaluation of the property in Groningen and a feeling of unsafety for the inhabitants (Gerrits, 2018).

This occurrence of cracks is a result from the wall functioning as a whole. The combination of bricks and mortar, not as single elements but in a wall, creates an element with different materialization characteristics (Sarhosis et al., 2019). A masonry wall does not show ductility but rather behaves brittle and gives a plastic deformation at a low force. When the earthquake force gets stronger due to the weight of the element, the weakest link in the combination will show fractures. This low amount of ductility in the brickwork of the built environment of Groningen is a problem. Finding a solution for the built environment of Groningen should therefore focus on a more ductile solution for the walls.This solution can be found for example in cross-laminated timber (CLT) (Brandner, Flatscher, Ringhofer, Schickhofer, & Thiel, 2016). This material is a composite of timber boards in a glued layered system. The CLT elements are formed of an uneven amount of layers with timber boards which are turned by 90° every layer. The low weight of the timber elements in comparison to the masonry work result in a lower earthquake force to start with. Additionally, the high strength to weight ratio of the CLT wall elements make them a fitting solution to replace the masonry as a structural element. Even more important is the capability of the CLT elements to show significant ductility and with that, energy dissipation (Izzi, Polastri, & Massimo, 2014). Additional to the usage of CLT for the walls, the material can be used for floor systems as well. Because of the cross laminating the floor can take forces in both directions (Brandner et al., 2016). This is in contrast to traditional wooden elevation floors which used beams to span the desired space. These beams are able to coop with forces in plane to their spanning direction but will have less strength in the other orientation. However, these more traditional wooden elevation floors could already form an improvement to the current situation. The heavy concrete floor slabs, used in most Dutch residential buildings, give a high earthquake force due to their weight. Moreover, similar to the masonry walls in Dutch residential buildings, these concrete floor slabs behave brittle and show little ductility. In normal situations this building method would suffice, only as result of the more frequent earthquakes the problem with the weight shows. As a solution to this height weight, the Finnish manufacturer Metsä Wood has come up with an alternative to the concrete hollow-core slab. The Kerto-Ripa floor (Figure 14) is a system made out of a glued together CLT plate and beams to form a hollow-core floor. Because of the usage of wood in this system, it has an at least 5 times lower weight than the concrete hollow-core slab (Metsä Wood, 2016). This reduction in weight translates to a 5 times lower force caused by an earthquake following Newton's second law.

Figure 14. Kerto-Ripa floor system (Metsä Wood, 2016)

The Dutch tradition of building relies heavily on masonry work. When new residential buildings would be built with CLT only, this brickwork characteristic of residential buildings in Groningen would disappear. However, this does not have to be the case when improved masonry systems are used. An example of this can be found in the research by Yamaguchi, Matsufuji, & Koyama (2007). This research proposes a system named SRB-DUP in which the elements are not bond together, as would be the case with traditional brick and mortar. The construction method as can be seen in Figure 15 is made out of specially designed bricks with holes in them. The holes are used for vertical steel reinforcement which provide the system with prestress. Between each different layers of brick a steel plate is placed which provides horizontal reinforcement. The holes in the brick are wider than the bolts and nuts which connect the steel plates. In this way the bricks can move within the limits of the holes diameter. Due to this prestress the system can use shear friction to dissipate earthquake energy (Yamaguchi et al., 2007). This prevents the system of plastic deformation as which is the case with traditional masonry and results in cracks. The result of this masonry system is a wall which can dissipate energy but maintains the appearance of a traditional brick wall.

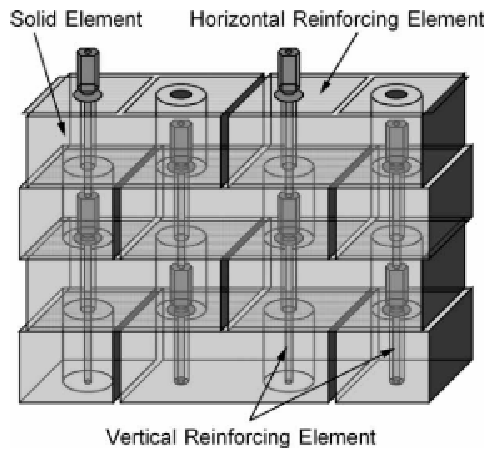

Figure 15. Prestressed reinforced brick wall (Yamaguchi et al., 2007)

3. Methodology

3.1. Introduction

The literature review shows that changes have to be made in the built environment in Groningen. Residents feel unsafe in their current houses and are faced with damages which devaluate their property. Repairing and reinforcing the current built environment is merely a temporary solution. The building will still be prone to damage from the set of small and larger earthquakes which are occurring in the area. The solution to this can be found in new to be built residential buildings which are able to withstand earthquake forces. These buildings do need a different approach whereas the current building method does not suffice for earthquakes. For this new method a combination is tested with known earthquake wall and floor solutions in combination with a new approach using a traditional timber structure as main load bearing construction element. The literature shows that timber structures are able to perform ductility and energy dissipation but this depends highly on the used connections (Jorissen & Fragiacomo, 2011). Examples from other countries show that structures using traditional timber joinery can show these favorable qualities as well (Nakahara, Hisatoku, Nagase, & Takahashi, 2000; T. Shiratori et al., 2009; Takeshi Shiratori, 2010). However, there is no research done in the ability for energy dissipation and ductile behavior of traditional wooden bent structures which can be found in the Netherlands. To be able to see whether these traditional timber joint structures are usable and not only add visually but also structural qualities to new to be built residential buildings in the seismic area, an analysis will follow on the structural behavior. This analysis will then be used to select the most suitable structure which then can be used in a case study along with the known earthquake resistant wall and floor systems.

3.2. Method

3.2.1. Research approach

The literature review described possible timber structures: the Ankerbalk bent, Dekbalk bent and the construction by Shiratori. The first two are constructions which have not been tested on their earthquake resistance. The latter of the three is a construction designed especially for the Japanese earthquake area but is not applied as a load bearing structure. Because there is no research available it is necessary to analyze the structures first on their theoretical structural behavior. The behavior is evaluated using knowledge gained from the literature. The joints, which connect the elements of the bents and the bents to each other, are of most interest since this is the place ductility and energy dissipation can take place (Jorissen & Fragiacomo, 2011).

After the structures are evaluated the best fitting solution for the situation in Groningen needs to be selected. For this selection process a multi criteria decision analysis (MCDA) will be used. This qualitative research method is use to be able to rank the alternatives and come up with a non-arbitrary result (Harker, 1989). Because of this diversity it is necessary to select the MCDA which fit the goal the best. The article by Montis et al. (2000) provides a tradeoff between the different MCDA methods. The goal of the analysis is to make a ranking of the alternatives to show the difference between the most favorable solution and the runner ups. In the evaluation of the timber structures a rubric matrix will be used to score the structure on different criteria. The weights of the different criteria will receive a cardinal value and are regarded important for the overall outcome. According to the article by Montis et al. (2000) this would mean the AHP method would fit this analysis the best. This Analytic Hierarchy

Process (AHP) was created by Thomas L. Saaty (Harker, 1989). The AHP is used in a design process to make and explain design decisions in an analytical way. The process part of the AHP refers to the process of decision making. The MCDA method cannot completely replace the decision making for the decision making party but it creates an insight in the priorities of the criteria and it gives a comparison between the alternatives. By doing this, the creativity involved in a design process is not limited but merely scientifically founded by the analytical analysis (Harker, 1989).

The last step of the analysis is to implement the best fitting structural solution together with the wall and floor systems in a case study. For this case study a residential building in the earthquake area will be used as a reference to create a new earthquake resilient residential building. The aim of this case study is to show that the separate systems can work together in achieving the earthquake resilient goal.

3.2.2. Design

The AHP method gives the opportunity to compare alternatives with each other on set criteria (Saaty, 1980). This makes it possible to create a tradeoff between alternatives by using a pairwise comparison of criteria. This is done in order to break down a complicated decision into smaller comparisons. To be able to compare the alternatives it is necessary to set criteria on which the options can be rated. The criteria are drawn from the literature research and form the basis for selecting the best alternative. To be able to perform a structured analysis the criteria are combined in a rubric matrix as can be seen in Figure 16. This rubric matrix allows for a scoring of the individual alternatives without comparing them yet to one another. In this scoring process it is assumed that every person who has a basic understanding of structural design and has read the literature research should come to the same individual scores.

Earthquake resistance and Safety	0	1	2	3	4
Ductility capacity	No ductility is possible in the joints	Low amount of ductility is possible in some joints	Low amount of ductility is possible in all joints	High amount of ductility is possible in some joints	High amount of ductility is possible in all joints
Displacement in x and y direction	Structure is not stable in any direction after displacement	Structure loses some stability in one direction after displacement, lost all stabilty in the other direction	Structure loses some stability in both directions after displacement	Structure loses some stability in one direction after displacement, remains stable in the other direction	Structure is stable in both directions after displacement
Ductility in fasteners	No fastener has possibility for ductility	Some fasteners have low possibility for ductility	All fasteners have low possibility for ductility	Some fasteners have low possibility for ductility and some have high possibility for ductility	All fasteners have high possibility for ductility
Possibility for repair	No elements can be replaced without breaking down the entire structure	Fasteners can be replaced by breaking down the structure	Fasteners can be replaced without breaking down the entire structure	Fasteners and minor elements can be replaced without breaking down the entire structure	All elements can be replaced without breaking down the entire structure
Traditional embedment in environment	**0**	**1**	**2**	**3**	**4**
Joinery used	No traditional joinery is applied in the construction	The construction contains a combination of tradional joinery and non traditional joints	All connections contain non European tradition joinery	All connections contain a combination of European and non European tradition joinery	All connections contain European traditional joinery
Fasteners used	No tradional fastener is used in the construction		The construction contains a combination of tradional fasteners and non traditional fastners		All fasteners used are tradional fasteners

Figure 16. Rubrics structure analysis

The rubric matrix contains six individual criteria which can be grouped into two main categories. The two categories cover the subjects of earthquake resistance and traditional embedment.

The literature research showed that the ability for ductility and dissipation of energy can provide the structure with the necessary earthquake resistance (Jorissen & Fragiacomo, 2011; Pirinen, 2014; SKH, 2017). The ductility has both a warning function and gives the construction the possibility to dissipate earthquake energy and with that lowering the force the structure has to endure. This is why the ductility capacity is regarded the most important criteria for scoring the structure. As described by Jorissen and Fragiacomo (2011) the focus should be on the joints of a construction to reach ductility. The criteria is scored in five levels from no ductility possible in any construction elements to ductility possible in all the construction elements. The exact level division can be seen in Figure 16.

The second criterion covers the stability of the building. When an earthquake occurs, the acceleration in the soil creates both horizontal and vertical forces which affect the building (SKH, 2017). Even though, both horizontal and vertical forces occur, when designing a building the forces in x and y direction are considered the most important (SKH, 2017). Therefore, only the displacement in the horizontal direction is covered. The theoretical displacement which occurs in both directions is analyzed for this criterion. Because an earthquake can create such a displacement in the elements of a construction the structure can become instable. This instability forms a treat to the users of the building and jeopardizes their safety. This safety of the users is the most important feature the structure has to provide. The displacement in x and y direction is scored from instability in any direction to stability in one direction and ultimately stability in both directions as shown in Figure 16.

In a timber post and beam structure the fasteners play an important role in locking the joint, making it a strong connection. Traditionally wooden pegs and wedges are used for this but these were replaced with steel connecters such as nails and bolts over the centuries. Within these fasteners different levels of ductility are possible. The ductility in the fasteners create another possibility for the dissipation of energy and therefore lowering the overall force on the structure. Furthermore, a fastener with ductile behavior does not break brittle and therefore can give a warning to the users of the building. Ductility within fasteners is highly dependent on the material used for these fasteners. In this research the two materials steel and oak are considered as fasteners, which are the most widely used. Oak can show low amounts of ductility in compression and no ductility in tension whereas steel is considered to have a high level of ductility in both directions. In the assessment of the structure the rating will add up from no ductility possible in the fasteners to a high level of ductility possible in all fasteners. In between these two extremes a combination is found where some fasteners are capable of ductility and some not as can be seen in Figure 16.

Lastly within the earthquake resistance category the possibility for repair is regarded. In the literature it is mentioned that designing a construction to completely resist earthquake forces is uneconomical and material wise not feasible (Langenbach, 2014). When a building comes to a near collapse stage it is in most cases not beneficial to repair the building and therefore go for demolition and rebuild (Gerrits, 2018). However, in case of multiple smaller earthquakes, such as the case in Groningen, it can be beneficial to be able to repair and replace parts of the construction. This criterion scores this possibility within the structures to replace elements. The structure will be put in the lowest level when no elements within the construction can be replaced, this can be either because the structure holds merely permanent joints or the replacement would mean the entire structure has to be replaced. The construction will be classified in the highest level on this criteria in case all elements can be replaced as described in Figure 16.

The second subject covers the traditional embedment in the environment. This subject is added to guarantee that the building fits in with the environment of Groningen. This embedment is already largely achieved by using the barn structure which provides the shape of the building. However, to achieve the traditional character of the building on the inside as well this part of the assessment will score the usage of traditional joinery and fasteners. This subject is mainly about the esthetics and therefore regarded less important over the earthquake resistance category.

The first criterion in this subject rates the usage of traditional joinery, with which the usage of wood on wood connections is meant. In this criteria the origin of the type of joint is considered which means that European originated joints are rated higher over others. This is done to reach a level of embedment in the environment and the history of construction in the Netherlands and particularly Groningen.

The final criteria in this rubric considers the usage of traditional fasteners. As mentioned in the article by Rumlová and Fojtík (2015) in some cases the aesthetics of the connection are considered important for the design. Because the embedment in the traditional environment of Groningen is scored here, the usage of traditional joinery is rated higher over steel connections. With the addition of this last criteria the rubric matrix, as can be found in Figure 16, is completed.

The rubric matrix will be used to score the alternatives individually. This is done to have a basis on which the pairwise comparison, needed for the AHP, can be based on. This pairwise comparison is filled in by the decision maker and is the basis for the AHP (Harker, 1989). The process is then used to calculate weights for the criteria according to the pairwise comparison. These weights indicate the level of importance of the criteria; a higher weight value indicates a more important criteria. The decision maker then needs to make a pairwise comparison of the alternatives on the separate criteria. The AHP scores these alternatives then again according to the pairwise comparison resulting in higher values for better performing alternatives. Finally, these scores and weights are combined by the AHP resulting in a weighted global score giving the best performing alternative in relation to the criteria.

As can be noticed in the description above, the pairwise comparison is a major part of the AHP. The decision maker has to score the alternatives and criteria in a matrix using a numerical value. In his research, Saaty (1980) proposes a table of relative scores which can be used for scoring the criteria and alternatives. This table, as can be seen in Table 1, will be used throughout this research.

Value	Interpretation
1	j and k are equally important
3	j is slightly more important than k
5	j is more important than k
7	j is strongly more important than k
9	j is absolutely more important than k

Table 1. Table of relative scores (Saaty, 1980)

The first step in the analytical hierarchy process is the creation of a pairwise comparison matrix which allows for the calculation of weighs for the criteria. This matrix needs to be created to proceed in the AHP and is of a size m x m, in which m is the number of evaluation criteria. Because the scores are filled in as a pairwise comparison they will be of the form a_{jk} and a_{kj} in which j is the criteria in the row of the matrix and k in the column. The scores need to satisfy the rule as can be seen in equation (5).

$$a_{jk} * a_{kj} = 1 \qquad (5)$$

By applying the rule above the matrix can be filled. The next step in the process is to normalize the pairwise comparison matrix by using equation (6) to calculate the normalized scores.

$$\bar{a}_{jk} = \frac{a_{jk}}{\sum_{l=1}^{m} a_{lk}} \qquad (6)$$

When the normalized pairwise comparison matrix is formed this matrix can be used to calculate the criteria weight vector *w.* This is done by calculating the average of the rows in the normalized pairwise comparison matrix, adding them up and dividing by the amount of columns as can be seen in equation (7).

$$w_j = \frac{\sum_{l=1}^{m} \bar{a}_{jl}}{m} \qquad (7)$$

After computing this, the so called matrix *S* can be created which holds the scores of the alternatives to the separate criteria. The matrix *S* is formed by the normalized vectors from each criteria matrix. In these criteria matrices a pairwise comparison is performed between the alternatives scored to the criteria. The matrices can be created in roughly the same way as described above by creating a pairwise comparison matrix, normalizing this and then creating a vector out of the matrix which shows the order in which the alternatives score on that specific criteria. These vectors are then combined into the new matrix *S*.
At this point the AHP is almost finished, the only part remaining is creating the so called global scores. These are the end result of the AHP and give the scores and ranking of the alternatives. The global scores are calculated by multiplying the alternative score matrix *S* by the weight vector *w* resulting in a vector *v* containing the global scores as can be seen in equation (8).

$$v = S * w \qquad (8)$$

This vector *v* then can be read in a decreasing order to show the alternatives from best scoring performance to the least.

The AHP relies heavily on the pairwise comparison which need to be filled in by the decision party. This is a human task and therefor sensitive to errors. Because of this, Saaty (1980) describes a consistency check to test if the scores are consistently filled in. This is done by computing a Consistency Index (CI) for the matrix. The CI is calculated with the following equation:

$$CI = \frac{\lambda - m}{m-1} \qquad (9)$$

In equation (9) the λ represents the summation of the consistency vectors (C_v). These vectors are calculated by multiplying the pairwise comparison matrix by the weight vector *w*. In the equation above the *m* describes the number of criteria again. When the CI is computed it becomes immediately clear whether the matrix is filled in consistent, this would mean CI=0. However, small inconsistencies are allowed in case the rule in equation (10) is satisfied.

$$\frac{CI}{RI} < 0.1 \qquad (10)$$

The RI value in equation (10) above is the Random Index as described by Saaty (1980). This index covers the consistency in case the matrix is filled in completely at random. In his book Saaty (1980) provides a table of RI values which can be used up to matrices with $m \leq 10$. This table is shown in Table 2.

m	2	3	4	5	6	7	8	9	10
RI	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.51

Table 2. Random Index values for small problems

3.3. Analysis

In the following analysis three alternatives will be evaluated on the set criteria. The characteristics of the different structures will be filled into the rubrics to have a systematic evaluation. These rubrics will then be used to further analyzed the alternatives using the analytical hierarchy process.

3.3.1. Reference construction Dekbalkgebint

The reference option is formed by the bent structure which is the mostly likely to be found in Groningen. The barns rely on the "Dekbalkgebint" as shown in Figure 17.

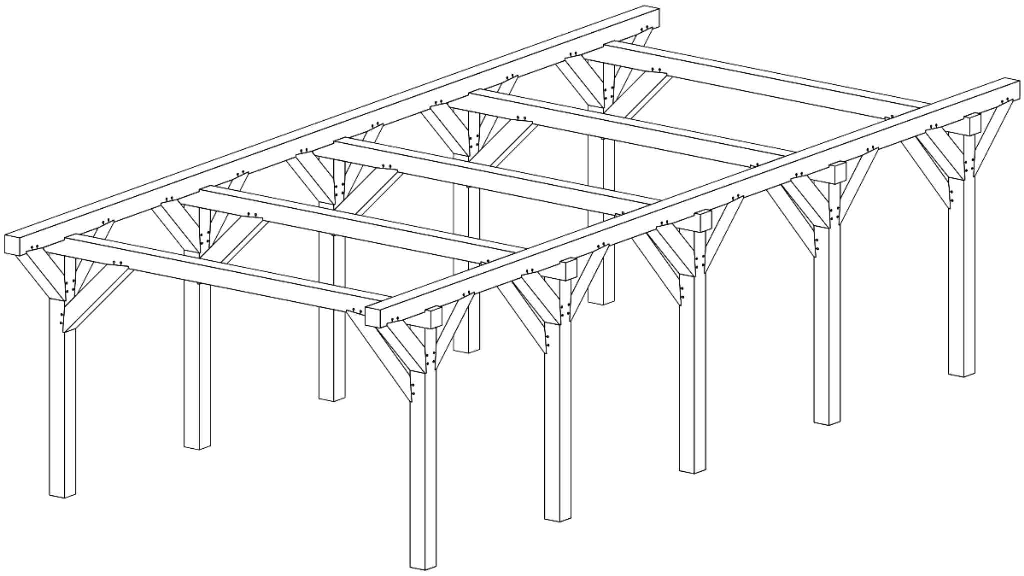

Figure 17. Dekbalkgebint

The "Dekbalkgebint" is formed by a horizontal bent beam which is connected on top of the posts using a mortise and tenon connection running in the width of the bent as illustrated in Figure 18 (van Cruyningen et al., 2003). On top of this bent beam a beam is added to connect the different bents. This beam is connected using a minimal depth halved dovetail joint. The joint keeps the beam from rotating and moving too much under normal circumstances. In this structure the stability is provided by braces connected to both of the beams. These braces use an oblique tenon joint for connecting the beams to the post. The fasteners used in locking the braces in place are oak pegs running through the post and beam.

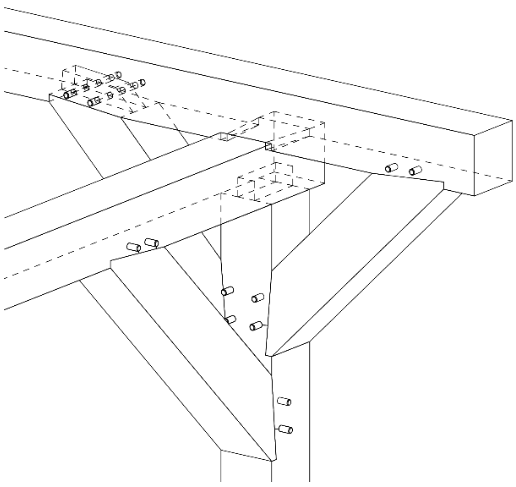

Figure 18. Dekbalkgebint detail

When an earthquake occurs, the forces can be placed on the construction in x and y direction. According to Eurocode 8 (SKH, 2017) it is allowed to place the forces at the floor levels, or in this case at the level of the beams. Figure 19 shows the schematic displacement in the x direction caused by a force from the left side. Because an earthquake shakes the building from both sides the figure can be used in mirror to show the displacement caused by a force from the right side. The figure is used to analyze where the displacement will occur but does not show the exact displacement. For this exact displacement it would be necessary to perform (scale) tests which are not covered in this research.

Ductility for timber structures is possible in compression parallel to the grain and in some lower amounts in compression perpendicular to the grain (Jorissen & Fragiacomo, 2011; Pirinen, 2014). Figure 20 shows the force caused by the earthquake on the bent beam, the force creates a displacement in the brace on the right side of the bent. This displacement forces the lower part of the brace in the post creating a compression force to the post. This compression makes a low amount of ductility possible whereas the force is not purely in the direction parallel to the grain. This ductility implies a dissipation of energy resulting in a lower force the structure has to endure. The energy dissipation works in both the x and y direction of the construction using the braces, however this ability of dissipating energy is limited to the displacement of the construction. With every shake of an earthquake the fasteners which hold the braces in place get weaker, until brittle failure. When this brittle failure occurs the braces which are exposed to tension will come lose from their post and cause instability. Losing the braces means the construction will not only lose its stability but the possibility of dissipating energy as well. This effect on the braces will be visible the most in the x direction whereas only two braces hold the construction stable. The multiple braces in the length direction will hold the structure stable for a longer time whereas more braces can counter the earthquake forces.

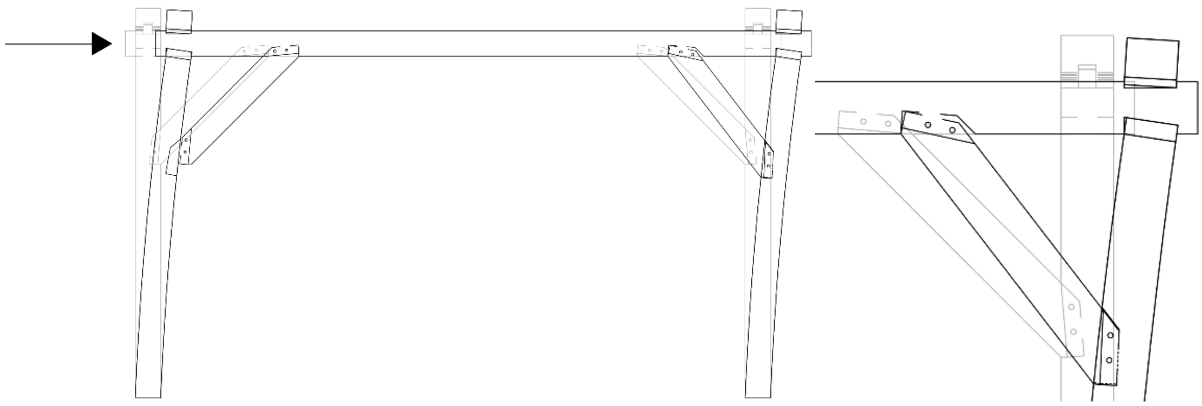

Figure 19. Dekbalkgebint in x direction

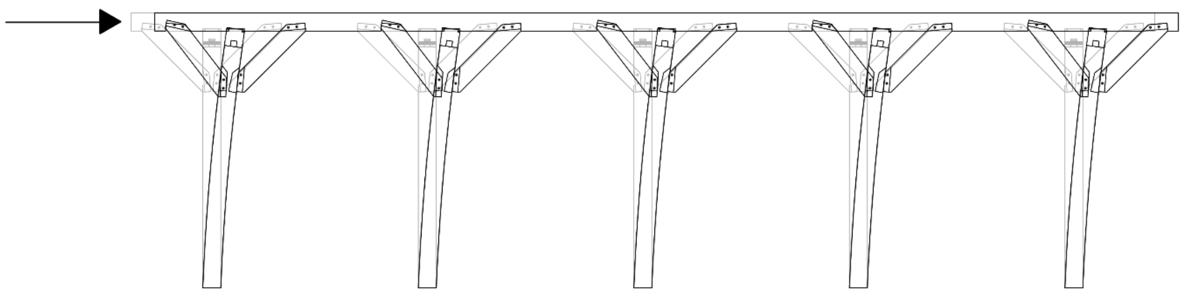

Figure 20. Dekbalkgebint in y direction

The construction of the Dekbalk bent relies on oak pegs to hold the braces in place. These pegs are loaded in tension perpendicular to the grain of the peg and therefore do no hold a possibility for ductile behavior. When the tensile strength of the peg is reached it will fail brittle.

The last of the earthquake resistance and safety criteria is the possibility for repair of the construction elements. The braces of the Dekbalk bent rely on oak pegs for locking. In case of a heavy earthquake resulting in the collapse of the building it is likely the following will happen. The pegs will fail brittle before the earthquake damages the construction elements. This failure will make the braces come lose and therefore the braces will stay relatively unharmed after the earthquake. However, because the structure will lose its stability the other joints will take more severe damage. The mortise and tenon joint connecting the post and beam for instance will take damage when the construction can shake freely. The same applies to the beam to beam connection which has only a limited depth using the half dovetail joint. The little amount of surface in this joint limits the possibility for friction and transfer of energy. This results in large embedment in the material and therefore increasing the displacement with every earthquake force.

Overall, the construction does not allow for much replacement when a large earthquake occurs. In case of a small earthquake while the fasteners stay in place they could be replaced afterwards without taking the construction apart. The construction will therefore only score points for replacement of fasteners.

The final criteria test the structure on the traditional embedment in the environment. Because this Dekbalk bent is the actual bent used in the barns in Groningen this criteria can be answered shortly. The bent is built with traditional joinery and fasteners as has been done in the province for over hundreds of years. Because of this the structure receives full points for these criteria.
The information above is filled in to the rubrics as can be seen in Figure 21.

Earthquake resistance and Safety	0	1	2	3	4
Ductility capacity	No ductility is possible in the joints	Low amount of ductility is possible in some joints	Low amount of ductility is possible in all joints	High amount of ductility is possible in some joints	High amount of ductility is possible in all joints
Displacement in x and y direction	Structure is not stable in any direction after displacement	Structure loses some stability in one direction after displacement, lost all stabilty in the other direction	Structure loses some stability in both directions after displacement	Structure loses some stability in one direction after displacement, remains stable in the other direction	Structure is stable in both directions after displacement
Ductility in fasteners	No fastener has possibility for ductility	Some fasteners have low possibility for ductility	All fasteners have low possibility for ductility	Some fasteners have low possibility for ductility and some have high possibility for ductility	All fasteners have high possibility for ductility
Possibility for repair	No elements can be replaced without breaking down the entire structure	Fasteners can be replaced by breaking down the structure	Fasteners can be replaced without breaking down the entire structure	Fasteners and minor elements can be replaced without breaking down the entire structure	All elements can be replaced without breaking down the entire structure
Traditional embedment in environment	0	1	2	3	4
Joinery used	No traditional joinery is applied in the construction	The construction contains a combination of tradional joinery and non traditional joints	All connections contain non European tradition joinery	All connections contain a combination of European and non European tradition joinery	All connections contain European traditional joinery
Fasteners used	No tradional fastener is used in the construction		The construction contains a combination of tradional fasteners and non traditional fastners		All fasteners used are tradional fasteners

Figure 21. Rubrics result Dekbalk bent

3.3.2. Shiratori inspired construction

The research of Shiratori (2009; 2010) showed that it is possible to use the isotropic behavior of wood to the designers advantage. His K-N joint is therefore applied to the bent structure visible in Figure 22. When translating the principles of the joint by Shiratori to a barn bent some differences need to be made as illustrated in Figure 23. Instead of using different smaller posts the bent will use a larger sized 250x250 mm post with two half lap cuts for the beams. Similar to the K-N joint, wedged beams are added in the void now present between the Nageshi beam and post. This Nageshi beam is the triangular shaped beam in the center. The wedged beams will be made out of oak, like the entire structure. This oak material has a high density which makes it ideal for the embedment the wedges have to endure (Pirinen, 2014). The Nageshi beams will be put in pre stress using a M20 bolt and nut with washers. Because the structure is based on Asian joinery there will be no braces or any other diagonal in the structure. Japanese constructions rely on complex geometry of their joints to establish stability (Zwerger, 2015).

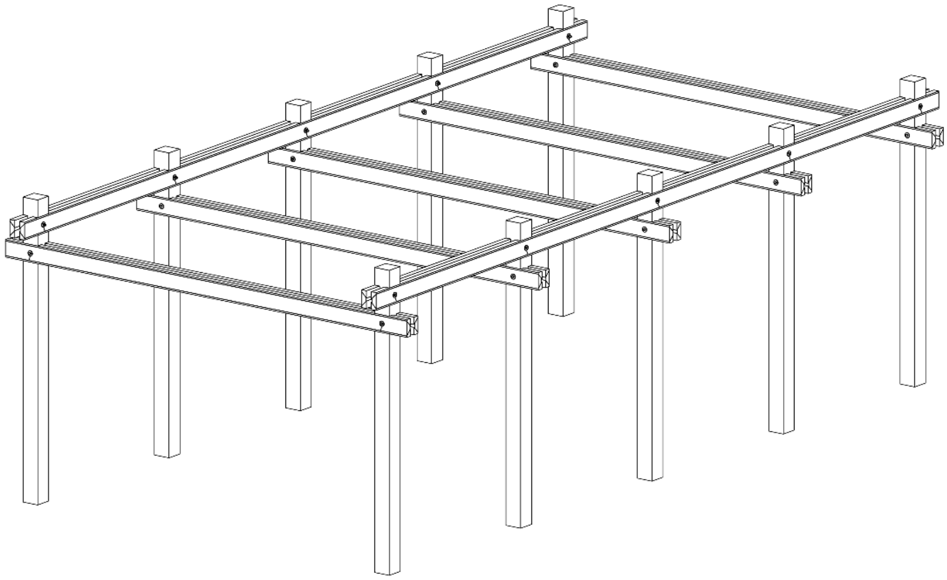

Figure 22. Shiratori inspired construction

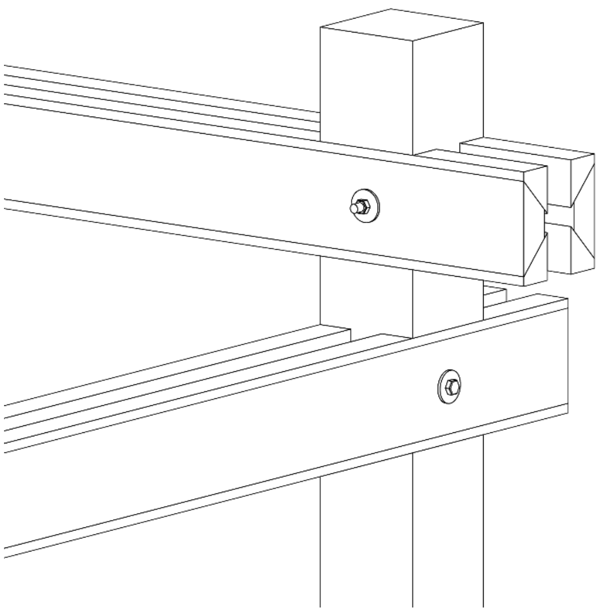

Figure 23. Shiratori inspired detail

Figure 24 shows the schematic displacement in the x direction caused by an earthquake force from the left side. An earthquake shakes the building from both sides meaning the Figure can be used in mirror to show the displacement caused by a force from the right side. The figure is used to analyze where the displacement will occur but does not show the exact displacement. For this exact displacement it would be necessary to perform (scale) tests which are not covered in this research.

Ductility for timber structures is possible in compression parallel to the grain and in some lower amounts in compression perpendicular to the grain (Jorissen & Fragiacomo, 2011). Figure 24 shows the force caused by the earthquake on the Nageshi beam, this beam will displace both posts in its movement. The rotation caused by the force makes the post embed in the wedge. This is due to the lower strength perpendicular to the grain in the wedge over the larger strength parallel to the grain in the post. The embedment of the post into the grain lets the wedge react ductile and with that dissipate some energy. More important is the behavior which occurs in the post itself. Due to the prestressed Nageshi beam the wedged beams are forced out into the half lap cut of the post. This creates a compression force in the direction parallel to the grain of the post and triggers the ductile behavior or the wood. This connection makes it possible to redirect horizontal forces into grain direction of the post and dissipating energy while doing this.

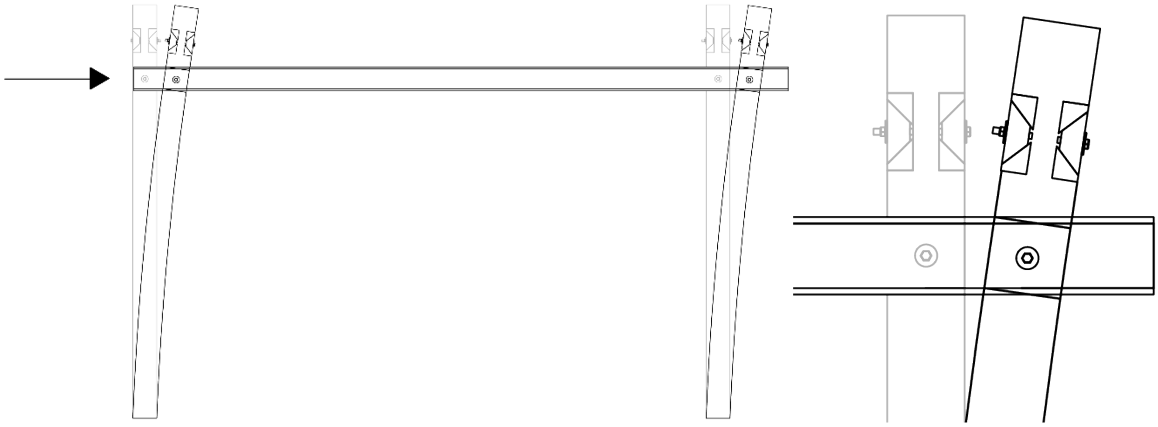

Figure 24. Shiratori inspired construction in x direction

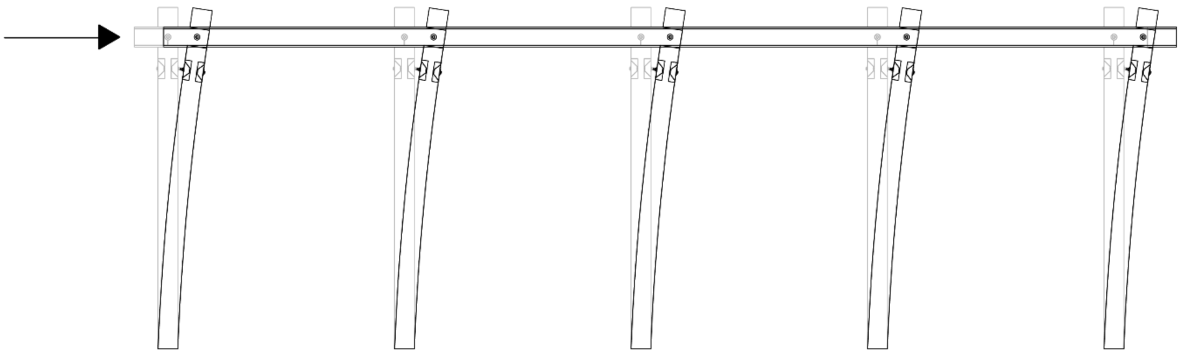

Figure 25. Shiratori inspired construction in y direction

The Shiratori inspired construction reaches its stability by using Japanese joinery instead of braces. By creating a complex joint the forces are redirected into the posts and therefore highly efficient in creating ductility (Jorissen & Fragiacomo, 2011). However, by focusing on one complex connection this connection becomes critical for the entire structure when failing.

This joint heavily relies on prestress put into the connection using a steel bolt fastener and in case this prestress can remain the joint can dissipate energy. However, when the connection gets loosened, either by embedment of the wedges or overtime shrinkage of the wood, the joint falls back in its ability to dissipate energy. When this happens and an earthquake occurs the rotations will be bigger and the structure will become instable. Assuming the steel bolt fasteners are tightened frequently to ensure the prestress in the construction, the stability of the structure should not be at risk. However, as mentioned the prestress will be lost in case the wedges get too embedded into the post. This can be resolved by changing the wedges after severe damage by earthquakes. The steel bolt fasteners allow the joint to be taken apart and reassembled with new materials without taking apart the entire structure.

Lastly, the embedment in the environment is reviewed. The type of joint used is based on Asian traditional joinery, using clever tight fitting beams to transfer forces. Because the joint is a combination of traditional joinery and modern steel fasteners the necessary prestress in the connection can be created. However, the usage of these kind of fasteners is not known to traditional European joinery and therefore will be granted less points. The joint does use traditional joinery at its basics but not joinery known to the environment of Groningen.
The analysis of the Shiratori inspired bent is filled in to the rubrics as can be seen in Figure 26.

Earthquake resistance and Safety	0	1	2	3	4
Ductility capacity	No ductility is possible in the joints	Low amount of ductility is possible in some joints	Low amount of ductility is possible in all joints	High amount of ductility is possible in some joints	High amount of ductility is possible in all joints
Displacement in x and y direction	Structure is not stable in any direction after displacement	Structure loses some stability in one direction after displacement, lost all stabilty in the other direction	Structure loses some stability in both directions after displacement	Structure loses some stability in one direction after displacement, remains stable in the other direction	Structure is stable in both directions after displacement
Ductility in fasteners	No fastener has possibility for ductility	Some fasteners have low possibility for ductility	All fasteners have low possibility for ductility	Some fasteners have low possibility for ductility and some have high possibility for ductility	All fasteners have high possibility for ductility
Possibility for repair	No elements can be replaced without breaking down the entire structure	Fasteners can be replaced by breaking down the structure	Fasteners can be replaced without breaking down the entire structure	Fasteners and minor elements can be replaced without breaking down the entire structure	All elements can be replaced without breaking down the entire structure
Traditional embedment in environment	**0**	**1**	**2**	**3**	**4**
Joinery used	No traditional joinery is applied in the construction	The construction contains a combination of tradional joinery and non traditional joints	All connections contain non European tradition joinery	All connections contain a combination of European and non European tradition joinery	All connections contain European traditional joinery
Fasteners used	No tradional fastener is used in the construction		The construction contains a combination of tradional fasteners and non traditional fastners		All fasteners used are tradional fasteners

Figure 26. Rubrics result Shiratori bent

3.3.3. Ankerbalkgebint construction

Bent structures come in different shapes and sizes within The Netherlands. The most commonly used is the "Ankerbalkgebint" (van Cruyningen et al., 2003) this type of bent is formed by two posts connected by a beam which goes through the post with a through tenon locked by wedges and pegs as can be seen in detail in Figure 27. The braces are connected using an oblique tenon joint to the column and beam. To connect multiple bents the horizontal beam is connected by a mortise and tenon connection fastened by pegs. This type of bent is found in most areas around the Netherlands, except for large areas in Friesland, Noord-Holland and Groningen (van Cruyningen et al., 2003).

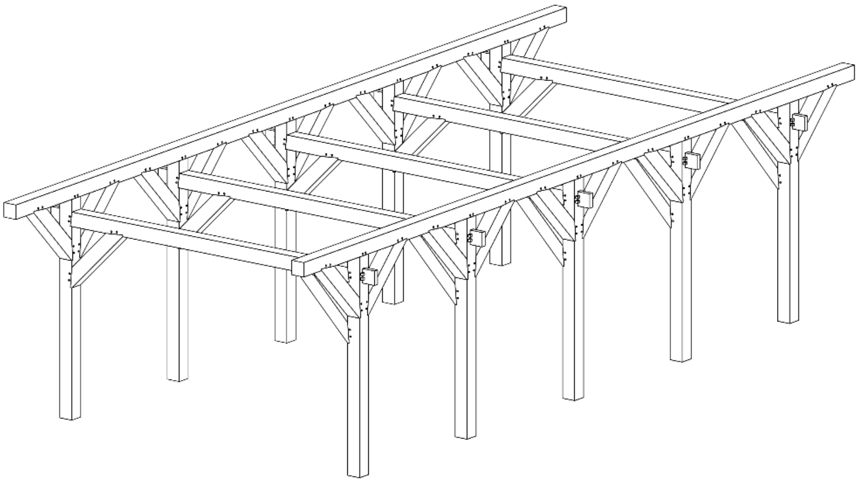

Figure 27. Ankerbalkgebint

The "Ankerbalkgebint" is formed by a horizontal bent beam which is connected to the post by a notched through mortise and tenon joint. This tenon is locked by two oak pegs through the post as can be seen in Figure 28. The tenon will go through the post and will be locked there with two additional wedges. These wedges make sure the joint is a tight fit. On top of the post a beam is added to connect the different bents. This beam is connected using a mortise and tenon joint running in the length of the beam. The mortise and tenon joint is additionally locked by oak pegs. In this structure the stability is provided by braces connected to both of the beams. These braces use an oblique tenon joint for connecting the beams to the post. The fasteners used in locking the braces in place are oak pegs running through the post and beam.

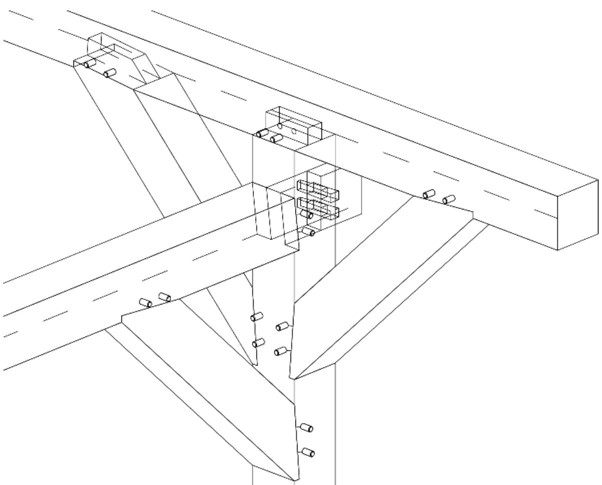

Figure 28. Ankerbalkgebint detail

When an earthquake occurs the forces can be placed on the construction in x and y direction as mentioned before. Figure 29 shows the schematic displacement in the x direction caused by a force from the left side. An earthquake shakes the building from both sides meaning the figure can be used in mirror to show the displacement caused by a force from the right side. The figure is used to analyze where the displacement will occur but does not show the exact displacement. For this exact displacement it would be necessary to perform (scale) tests which are not covered in this research.

The ductility for timber in this bent structure is similar to that of the Dekbalk bent. Figure 29 shows the force caused by the earthquake on the bent beam, the force creates a displacement in the brace on the right side of the bent. This displacement forces the lower part of the brace in the post creating a compression force to the post. This compression makes a low amount of ductility possible whereas the force is not purely in the direction parallel to the grain. This ductility implies a dissipation of energy resulting in a lower force the structure has to endure. The energy dissipation works in both the x and y direction of the construction using the braces, however this ability of dissipating energy is limited to the displacement of the construction. With every shake of an earthquake the fasteners which hold the braces in place get weaker, until brittle failure. When this brittle failure occurs the braces which are exposed to tension will come lose from their post and cause instability. Losing the braces means the construction will not only lose its stability but the possibility of dissipating energy in this way as well. This effect on the braces will be visible the most in the x direction whereas only two braces hold the construction stable. The multiple braces in the length direction will hold the structure stable for a longer time whereas more braces can counter the earthquake forces.

Additional to the ductility due to the braces a small amount of ductility can be reached in the connection between the beam and post. Because the beam is forced into the post a compression force perpendicular to the grain occurs. Although the ductility in this direction is limited it can result in some dissipation of energy.

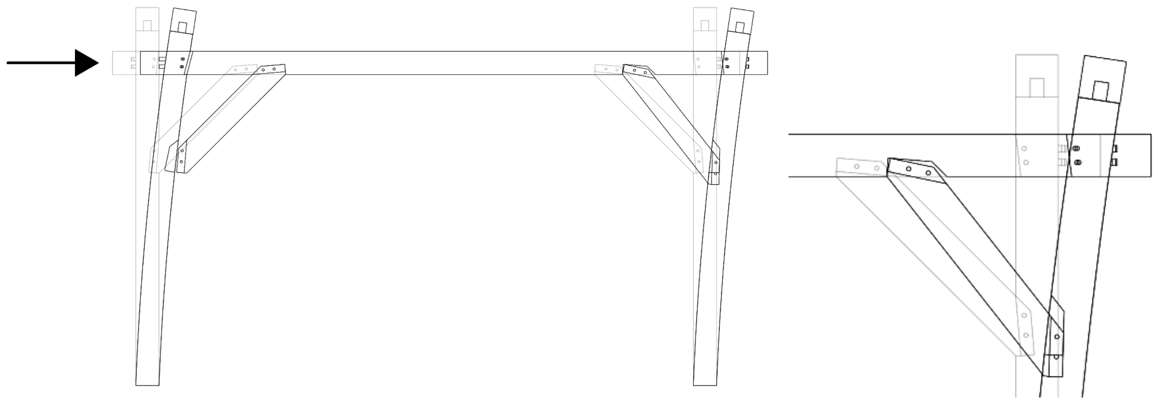

Figure 29. Ankerbalkgebint in x direction

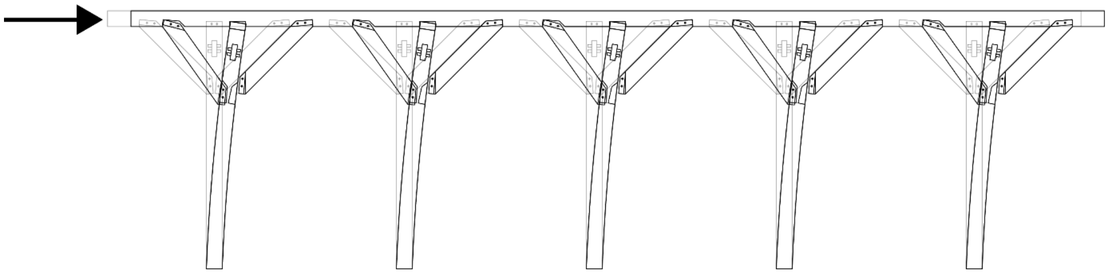

Figure 30. Ankerbalkgebint in y direction

The construction of the Ankerbalk bent relies on oak pegs to hold the braces in place. These pegs are loaded in tension perpendicular to the grain of the peg and therefore do no hold a possibility for ductile behavior (Jorissen & Fragiacomo, 2011). When the tensile strength of the peg is reached it will fail brittle.

The braces of the Ankerbalk bent rely on oak pegs for locking. In case of a heavy earthquake resulting in the collapse of the building it is likely the following will happen. The pegs will fail brittle before the earthquake damages the construction elements. This failure will make the braces come lose and therefore the braces will stay relatively unharmed after the earthquake. However, because the structure will lose its stability the other joints will take more severe damage. The bent beam running between the two posts in x direction has two locking mechanisms which hold it in place. The wedges at the end of the tenon will be prone to a compression force when the beam is receiving a tensile force. As long as the tensile force is not too big the wedges will hold and dissipate some energy perpendicular to the grain of the wedge. Because the wooden wedge cannot hold a large loading in this direction it will break. After the wedges have given in, the pegs are vulnerable to the tensile force which will make them break in a brittle way.

With all the bracing gone, the mortise and tenon joint connecting the post and beam will take damage when the construction can shake freely. This results in large embedment in the material and therefore increasing the displacement with every earthquake force.

Overall, the construction does not allow for much replacement when a large earthquake occurs. In case of a small earthquake while the fasteners stay in place the pegs and wedges could be replaced afterwards without taking the construction apart. Similar to the Debalk bent the construction will therefore only score points for replacement of fasteners.

The final criteria test the structure on the traditional embedment in the environment. Because this Ankerbalk bent is used in different farmhouses all across the Netherlands it will receive the full points. The bent is built with traditional joinery and fasteners known to European carpentry.
The information above is filled in to the rubrics resulting in Figure 31.

Earthquake resistance and Safety	0	1	2	3	4
Ductility capacity	No ductility is possible in the joints	Low amount of ductility is possible in some joints	Low amount of ductility is possible in all joints	High amount of ductility is possible in some joints	High amount of ductility is possible in all joints
Displacement in x and y direction	Structure is not stable in any direction after displacement	Structure loses some stability in one direction after displacement, lost all stabilty in the other direction	Structure loses some stability in both directions after displacement	Structure loses some stability in one direction after displacement, remains stable in the other direction	Structure is stable in both directions after displacement
Ductility in fasteners	No fastener has possibility for ductility	Some fasteners have low possibility for ductility	All fasteners have low possibility for ductility	Some fasteners have low possibility for ductility and some have high possibility for ductility	All fasteners have high possibility for ductility
Possibility for repair	No elements can be replaced without breaking down the entire structure	Fasteners can be replaced by breaking down the structure	Fasteners can be replaced without breaking down the entire structure	Fasteners and minor elements can be replaced without breaking down the entire structure	All elements can be replaced without breaking down the entire structure
Traditional embedment in environment	**0**	**1**	**2**	**3**	**4**
Joinery used	No traditional joinery is applied in the construction	The construction contains a combination of tradional joinery and non traditional joints	All connections contain non European tradition joinery	All connections contain a combination of European and non European tradition joinery	All connections contain European traditional joinery
Fasteners used	No tradional fastener is used in the construction		The construction contains a combination of tradional fasteners and non traditional fastners		All fasteners used are tradional fasteners

Figure 31. Rubrics result Ankerbalk bent

3.3.4. Analytical Hierarchy Process

This chapter describes the outcome of the AHP as explained in the methodology. The rubrics matrices of the three alternatives were used to score the options individually. This information is the input for the AHP pairwise comparison matrices.

The first step in the analytical hierarchy process is to set the weights for the criteria. The most important function of the structure is that it has to provide safety for the users of the building (Gerrits, 2018; Vlek, 2018). Because of this the first two criteria score the highest value in this comparison. The ductility capacity and displacement of the construction add the most to the safety of the users. The ability for the construction to behave ductile and dissipate energy lowers the earthquake forces (Jorissen & Fragiacomo, 2011; SKH, 2017), and with that the risk of collapse or damage. Evenly important is the displacement of the construction. This displacement can lead to instability of the construction and because of that jeopardize the safety of the users. Furthermore, the displacement of the construction can lead to additional damage to other building parts. Both these criteria will get the highest values in the pairwise comparison. The next criterium is the ductility in the fasteners. These fasteners can provide a certain amount of ductility and energy dissipation to the overall construction. However, this amount is lower than the construction and connections can provide. This is why this criteria is regarded less important than the previous ones. The last criterium in this category is the possibility for repair in the construction. When a construction has permanent joints or is difficult to repair without breaking down the entire structure it becomes difficult to repair damages. Without this possibility to repair, the next earthquake can cause bigger damages to the structure (Sarhosis et al., 2019). The possibility to repair does not have an immediate influence on the safety of the users of the building during an earthquake. Because of this, the criteria is regarded less important than the first two.

The last two criteria cover the embedment in the traditional landscape of Groningen. These criteria do not contribute to the safety of the users or the limitation of damage to the building. The criteria merely test the esthetics of the joinery, which in some researches are valued important (Rumlová & Fojtík, 2015). However, in this research the earthquake resistant qualities are regarded of higher importance because the residents should feel safe in their houses. Because of this, the criteria receive the lowest values of the pairwise comparison.
Table 3 shows the pairwise comparison filled in according to the importance of the different criteria. The values used in this matrix are in line with the table of relative scores as proposed by Saaty (1980) and illustrated in Table 1.

	Ductility capacity	Displacement in x and y direction	Ductility in fasteners	Possibility for repair	Joinery used	Fasteners used
Ductility capacity	1	1	5	5	9	9
Displacement in x and y direction	1	1	5	5	9	9
Ductility in fasteners	1/5	1/5	1	5	7	7
Possibility for repair	1/5	1/5	1/5	1	3	3
Joinery used	1/9	1/9	1/7	1/3	1	1
Fasteners used	1/9	1/9	1/7	1/3	1	1

Table 3. Pairwise comparison criteria

3.4. Results and discussion

3.4.1. Results

This chapter contains the results of the pairwise comparison of the three proposed alternatives. The pairwise comparison scores from Table 3 are used in matrix *B* in accordance with equation (5). Matrix B is then normalized using equation (6) and turned into the criteria weight vector *w* using equation (7).

Matrix *B*:

$$\begin{bmatrix} 1 & 1 & 5 & 5 & 9 & 9 \\ 1 & 1 & 5 & 5 & 9 & 9 \\ \frac{1}{5} & \frac{1}{5} & 1 & 5 & 7 & 7 \\ \frac{1}{5} & \frac{1}{5} & \frac{1}{5} & 1 & 3 & 3 \\ \frac{1}{9} & \frac{1}{9} & \frac{1}{7} & \frac{1}{3} & 1 & 1 \\ \frac{1}{9} & \frac{1}{9} & \frac{1}{7} & \frac{1}{3} & 1 & 1 \end{bmatrix}$$

Normalized matrix *B*:

$$\begin{bmatrix} 0.38136 & 0.38136 & 0.435323 & 0.30000 & 0.30000 & 0.30000 \\ 0.38136 & 0.38136 & 0.435323 & 0.30000 & 0.30000 & 0.30000 \\ 0.07627 & 0.07627 & 0.087065 & 0.30000 & 0.23330 & 0.23330 \\ 0.07627 & 0.07627 & 0.017413 & 0.06000 & 0.10000 & 0.10000 \\ 0.04237 & 0.04237 & 0.012438 & 0.02000 & 0.03333 & 0.03333 \\ 0.04237 & 0.04237 & 0.012438 & 0.02000 & 0.03333 & 0.03333 \end{bmatrix}$$

Criteria weight vector *w* :

$$\begin{bmatrix} 0.34967 \\ 0.34967 \\ 0.16771 \\ 0.07166 \\ 0.03064 \\ 0.03064 \end{bmatrix}$$

In the next step the rubric matrices with the results of the analysis are used to create pairwise comparisons of the three alternatives per criteria. The scores granted to the alternatives are consistent with the table of relative scores as proposed by Saaty (1980) and illustrated in Table 1. In appendix B these separate matrices are shown. To make sure the matrices are filled in consistently, equation (9) is used. All the matrices were to be found completely consistent or either with a small acceptable inconsistency. The matrices are then normalized using equation (6) and turned into vectors using equation (7). The separate criteria vectors are then combined into matrix *S*. The scores of the alternatives can be read in the matrix by finding the six criteria in the columns and the three alternatives in the rows. The order is the same for all the matrices, the top row holds the results for the “dekbalk” bent, the second row the Shiratori inspired bent structure and the third row the “ankerbalk” bent.

Matrix *S*:

$$\begin{bmatrix} 0.05556 & 0.05556 & 0.03426 & 0.07143 & 0.22727 & 0.23684 \\ 0.38889 & 0.38889 & 0.38830 & 0.35714 & 0.04545 & 0.02632 \\ 0.05556 & 0.05556 & 0.07745 & 0.07143 & 0.22727 & 0.23684 \end{bmatrix}$$

The global scores of the pairwise comparison are given by multiplying matrix *S* with the criteria weight vector *w* using equation (8). This global score vector consists of one column with three rows. Again, these three rows represent the alternatives. As mentioned before, these values should be read decreasingly to find the overall weighted ranking of the alternatives.

Global scores:

$$\begin{bmatrix} 0.064 \\ 0.365 \\ 0.071 \end{bmatrix}$$

These results are found by conducting the analysis with the above mentioned scores. To see whether there is a difference in the outcome when different weight factors are used three different situations are tested. These three alternative situations are influencing the criteria weight vector. The first option is to test the results with no weights at all, this means that all the pairwise comparison scores in matrix *S* directly result in the global scores. A different approach is to make the scores more subtitle. This is done because the initial pairwise comparison of the criteria uses big difference on the proposed scale by Saaty (1980). The last alternative weighting is by reversing the importance. This means the higher importance is no longer with the earthquake resistance but with the traditional embedment. The overview of the results from these tests can be seen in Figure 32. On the left hand side he global scores are shown, which are used to calculate the percentage scores on the right hand side. The color coding of the alternatives indicate the highest value in green to the lowest value in red. In the next chapter these results will be discussed.

Omschrijving	Dekbalk	Shiratori	Ankerbalk		Dekbalk	Shiratori	Ankerbalk
Base situation	0.063937294	0.364881287	0.071181419		12.79%	72.98%	14.24%
No weights	0.113484938	0.265831163	0.120683899		22.70%	53.17%	24.14%
Subtle weights	0.067394569	0.357630115	0.074975316		13.48%	71.53%	15.00%
Tradional important	0.183029647	0.132141515	0.184828838		36.61%	26.43%	36.97%

Figure 32. Analysis on different weights

3.4.2. Discussion

The previous chapter showed the results from the timber construction analysis. It becomes clear from the information in Figure 32 that the Shiratori inspired structure is the most favorable within the set criteria and weights. In the base situation of the pairwise comparison this type of joinery receives a score of almost 73% over the roughly 13% and 14% of the other alternatives. This does not come as a surprise whereas this type of joint was specially designed for applications in earthquake areas (T. Shiratori et al., 2009; Takeshi Shiratori, 2010). The only two criteria this joint does not score high on in the assessment is the embedment in the environment. This becomes clear when the weights are left aside in the "no weights" situation in Figures 32. In this situation the score of the Shiratori inspired joint drops to 53% and the other two rise. This is because the two traditional embedment criteria are now relatively more important than in the base situation. The Shiratori joint does not score high on these criteria in the pairwise comparison whereas the other joints can be found in the Netherlands and the Shiratori joint is based on a combination of modern fasteners and Japanese geometry (Zwerger, 2015). Because the traditional European joints scored relatively higher in the "no weights" situation it was to be expected the scores would be better in case the weights were to be made more subtle. This is the case, as can be seen in the figure. However, the difference is not big. In both the "no weights" and the "subtle weights" situation the Shiratori joint stays the most favorable alternative. This changes when the importance of the criteria is switched around. The last alternative situation shows a situation in which the traditional embedment is regarded the most important. Only in this situation do the scores shift in favor of the European joints. However, the difference is not as big as can be seen in the other situations. Both the European joints receive a score of about 37% over the 26% of the Shiratori joint. This can be explained by the number of criteria (4) in favor of earthquake resistance over the criteria measuring the traditional embedment (2). Nevertheless, this difference in importance was chosen because the literature showed that the safety of the inhabitants is generally more important (Gerrits, 2018; Sucuoğlu & Akkar, 2014). Some studies argue that the esthetics play a role, but only when the overall safety is protected (Rumlová & Fojtík, 2015).

The overall result of the analysis shows that the Shiratori inspired joint is the most favorable to be applied in the earthquake area of Groningen. The joint allows for important earthquake resistant qualities such as ductility, energy dissipation and is able to be repaired fairly easily (Jorissen & Fragiacomo, 2011; T. Shiratori et al., 2009). The application of this type of structure in a residential building can give the inhabitants a sense of safety and prevent big damage to the house. The timber structure alone will not solve all the problems for building in an earthquake area but can help as a part of the solution.

3.5. Case study

The previous chapters described the use of different earthquake resilient methods. Ranging from CLT floors which aim to keep the mass low, to timber structures and brick wall systems which are specifically designed to dissipate the earthquake energy. The methods on their own promise to reduce the damage done by earthquake forces. However, this does not mean the separate methods can be combined into a building. This case study is used to merge these earthquake resilient methods into a residential building which suits the needs of the earthquake area in Groningen.

The residential building in figure 33 is an example of what can be found in the earthquake area in Groningen. This building will be used to model a new residential building with the mentioned earthquake resilient methods. The floor plans are used to make sure the house is of an appropriate size and livable for a family (Appendix C). In the upcoming chapter the different parts and connections of the building will be elaborated on using selected details and visualizations of the building process. (The complete overview of the details and building processes can be found in Appendix D and E)

Figure 33. Semidetached house in the earthquake area of Groningen and adaptation for case study (Makelaardij Huis, 2019)

3.5.1. Groundworks

The first step in the construction of the new building is the foundation (Figure 34). In this case the foundation is a traditional foundation as can be found in areas where the soil type is sand or clay. These soil types can be found in large parts of the Netherland and in Groningen. This type of foundation reacts stiff and will move with the earth when an earthquake occurs. Because of this stiff characteristic of the foundation the seismic forces are going to be absorbed by the upper construction. This is a welcome effect by the foundation because the energy dissipating function will be provided by the upper construction.

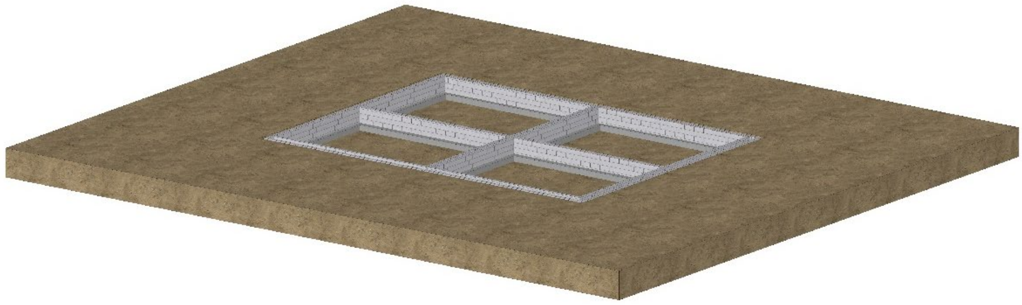

Figure 34. Building step: Foundation

The foundation consists of a concrete beam which is poured at a depth which reaches solid ground and which is below the frost line. On top of these concrete beams, low brick walls will be created. These will form a support for the floor and walls as highlighted in Figure 35.

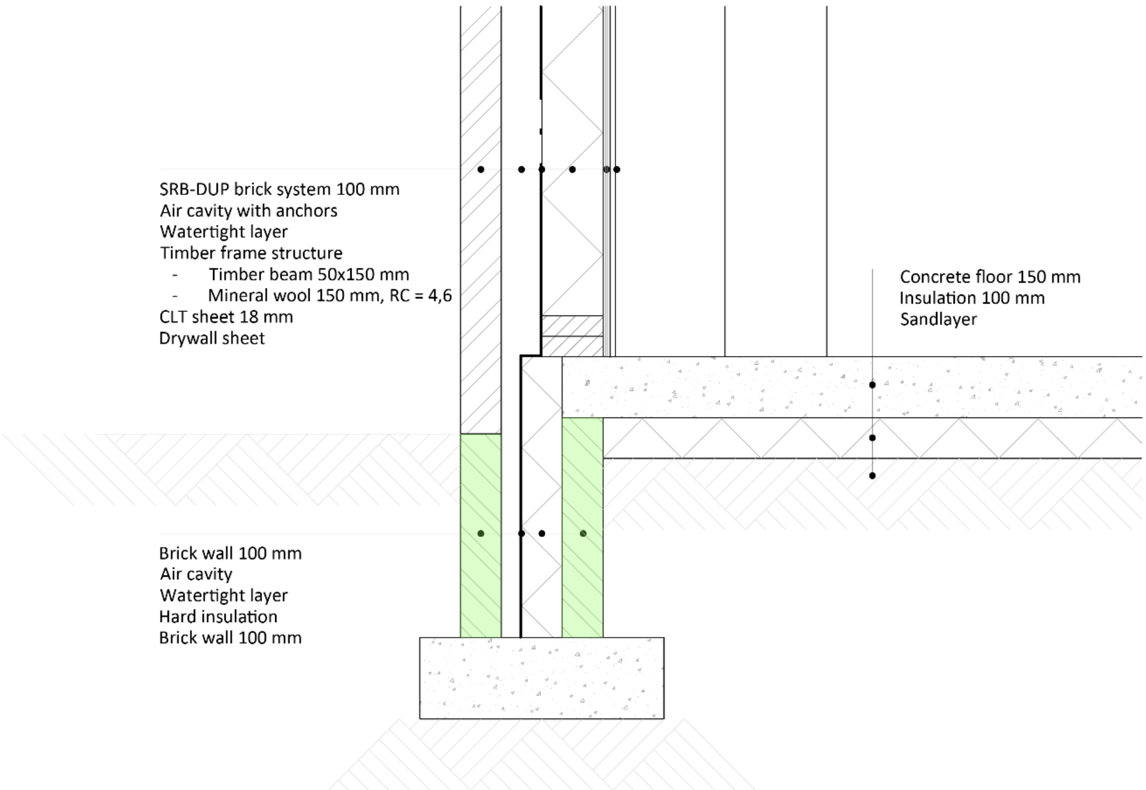

Figure 35. Foundation detail with highlighted brick walls

This case study analyses a semidetached residential building. Because of this it is important to keep the adjacent buildings separate in order to prevent cold bridges and noise transfers. This means each building will have a separate foundation and upper construction. This separation can be seen in Figure 36. In this figure the red highlighted floors show the separation of the two houses using an air cavity or insulation where necessary. This concrete floor will be poured on top of an insulation layer and will be surrounded by insulation to prevent cold bridges. This layer closes the ground works for the building. Up till this point the construction is traditional and does not allow for the earthquakes energy to be dissipated. The next phase will introduce the energy dissipating methods to the building.

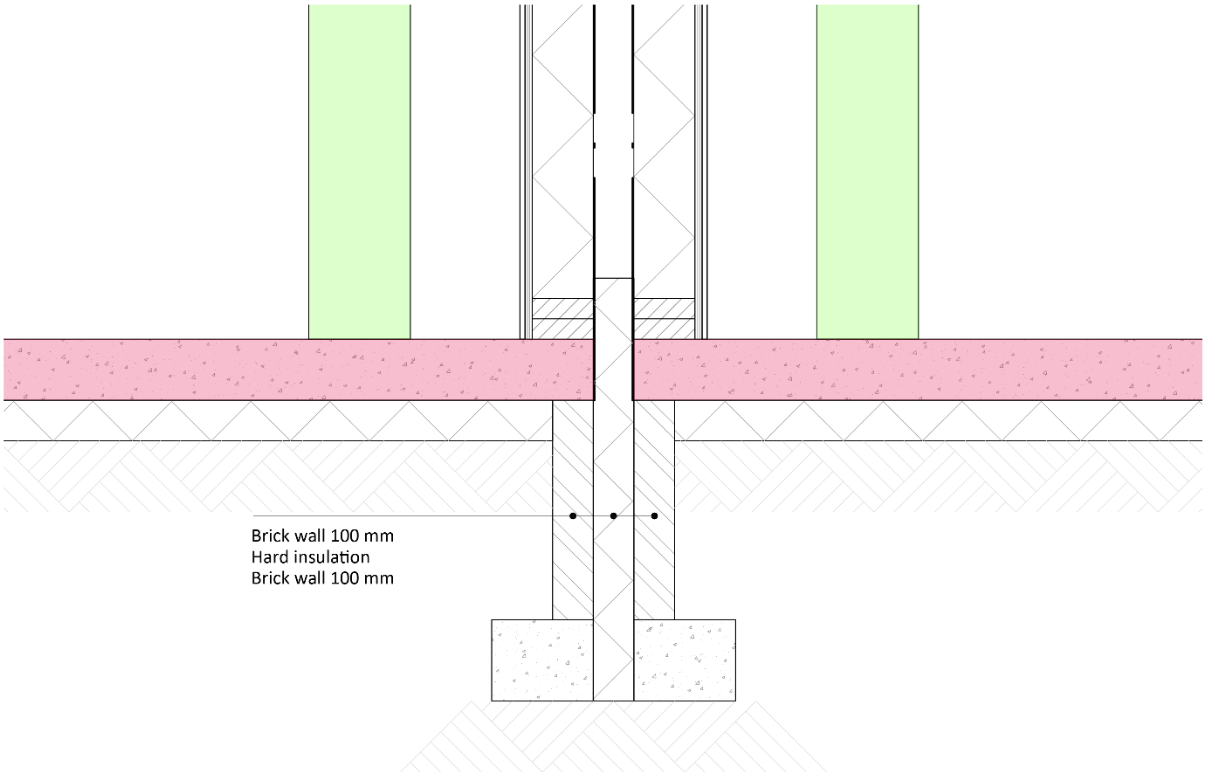

Figure 36. Foundation detail building separation

3.5.2. Upper construction

When the groundworks are finished the next step in creating the building is the upper construction. This is started by the timber structure (Figure 36 highlighted in green) which forms the core of the building and will dissipate the earthquake energy. The timber structure will be placed on top of the floor and will lead the non-earthquake forces into the foundation in this manner. This placement can be seen in Figure 37. The figure again shows that the adjacent buildings have a separate structure and are not connected.

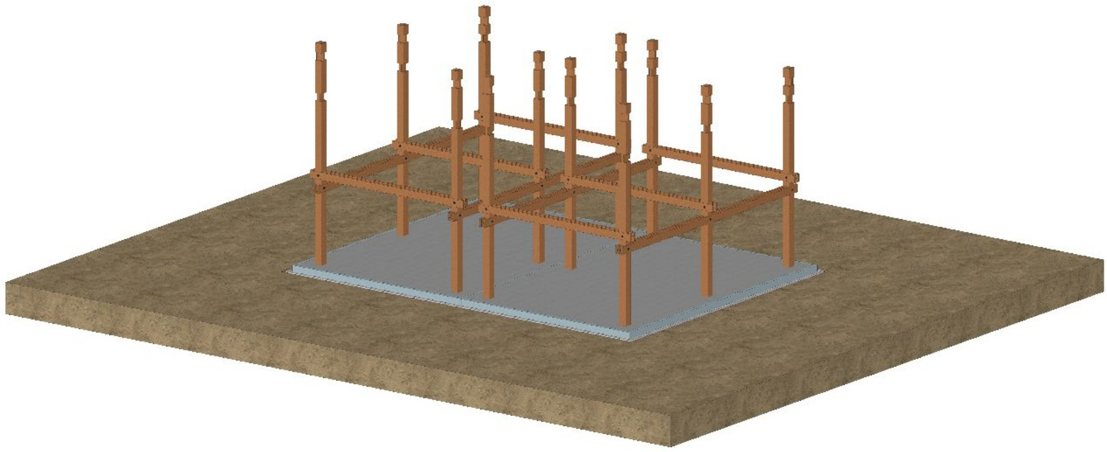

Figure 37. Load bearing timber structure

The timber structure forms the core earthquake energy dissipating element of the building. Other than dissipating the seismic energy, the timber structure works as the central load bearing structure carrying the roof and floor as can be seen in Figure 38. The detail as shown in the figure illustrates the timber structure inspired by the Shiratori K-N joint. For this case study the dimensions for the separate joint elements are assumed. Before the method can be applied in the earthquake area it will need structural calculations on these connections to define the required dimensions. Another important aspect of the connection is the required prestress in the joint. It became clear from the research done by Shiratori et al. (2009) that the prestress in the connection is important for the energy dissipating function of the construction. This prestress is provided by the steel bolt which needs to be tightly fitted. As mentioned earlier, the joint can become looser over time due to shrinkage of the wood or because of embedment by earthquakes. Because this prestress is so important to the overall structure it is necessary that the joint is accessible and can be tightened when necessary. Both the connection of roof and floor show that the bolts are left visible and accessible. This is done to make the inhabitants aware of the safety of their home. It will be necessary to check the connections after an earthquake and make sure that the bolts are tightly fitting. When this is the case or the bolts are tightened, the inhabitant will know the structure is ready and safe again for an upcoming seismic event.

The next stage in the construction of the building is the placement of the elevation floor. The Kerto-Ripa floor elements are placed on the beams of the timber structure and connected together with diagonal screws at the interface of two elements to guaranties a homogeneous displacement of the floor elements (Metsä Wood, 2016). The floor has a considerable lower mass than a commonly used concrete floor but will still create a force on the timber structure due to an earthquake. Because the floor lies on top the load bearing timber structure, both will move simultaneously when an earthquake occurs. This movement will cause energy dissipation in the joint of the timber structure and with that lower the earthquake force. However, even though the timber structure dissipates energy this does not mean that the timber structure and floor will not move at all. To make sure that the timber structure and floor have the ability to move without influencing other building elements such as the walls, measures are taken. In Figure 38. a highlighted red area is shown, this illustrates a dampening insulation which is placed between the wall and the floor. This measure is applied all around the floor and will provide a sealing layer between the floor and wall. The layer assures the necessary space for the core construction to move, along with a heat and sound insulation for the different building levels.

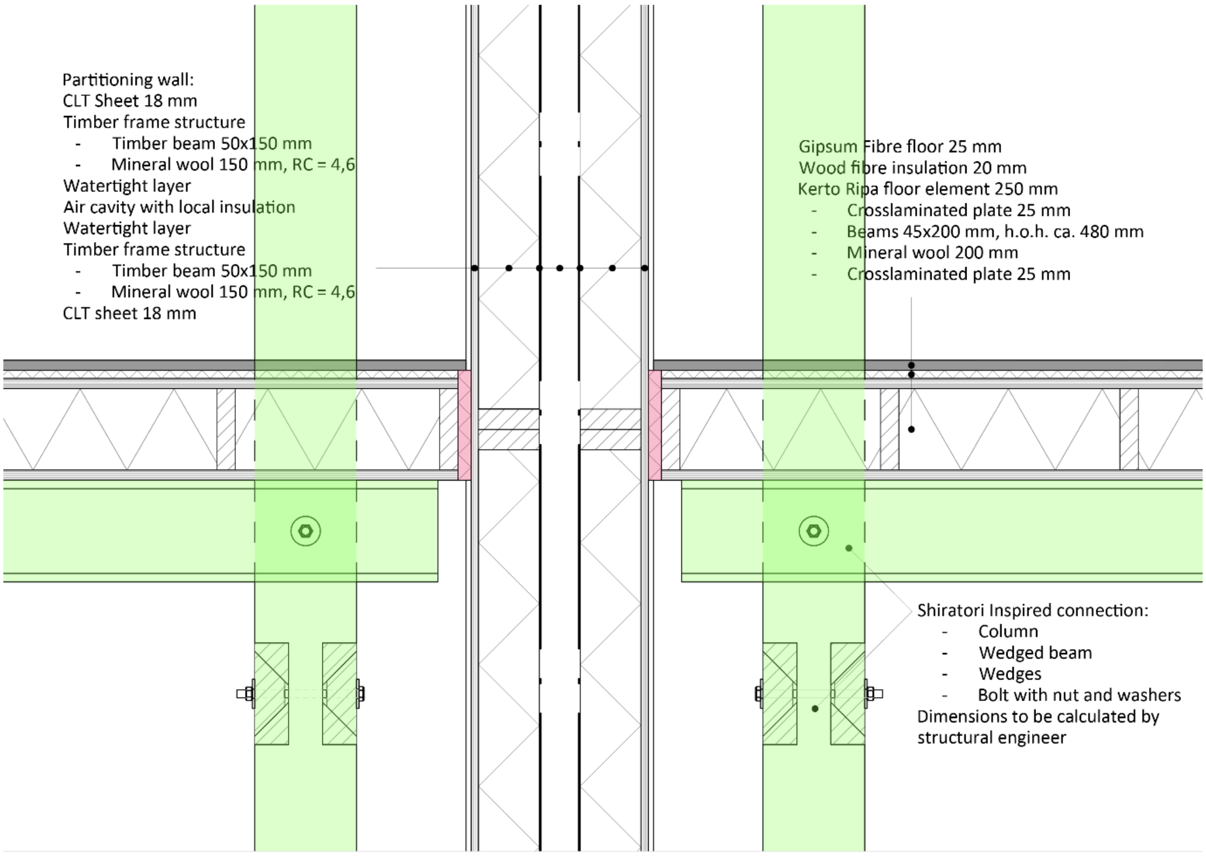

Figure 38. Detail connection timber structure and elevation floor

When the timber structure and floor are in place, the timber frame wall will be added as can be seen in Figure 38. This wall provides the house with a light weight thermal insulating layer which meets the minimum requirements set by the Dutch building decree. The timber frame is internally cladded with a CLT sheet to make the wall stiff. The advantage of a timber frame wall over traditional masonry work or the SRB-DUP system apart from the mass is the insulating qualities which can be given while keeping the wall thin.

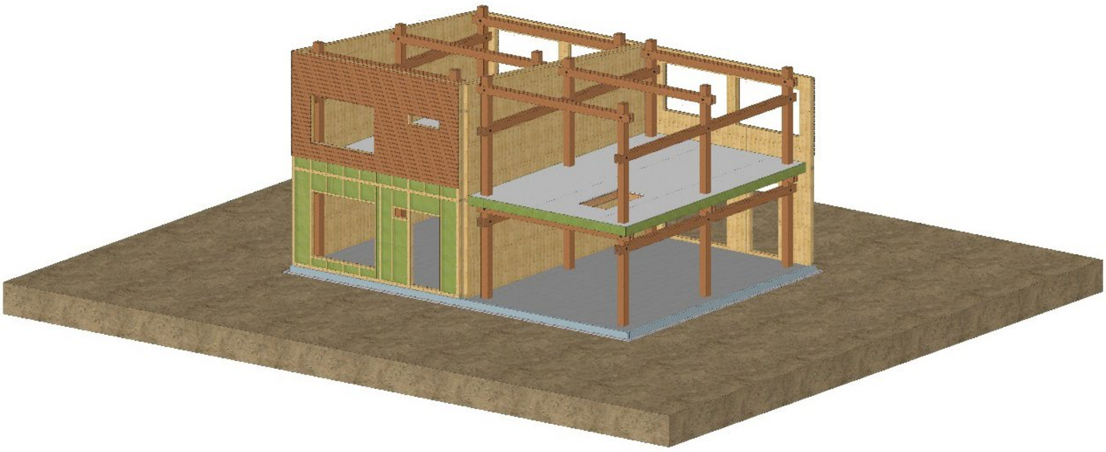

Figure 39. Placement of the walls

In the next phase of the built the roof will be added to the construction. This roof is formed with Kerto-Ripa elements similar to the floor and will also be placed on the load bearing structure. Similar to the floor, the roof will make the construction move in case of earthquake. This displacement will allow for energy dissipation in the load bearing timber structure and with that lower the effects of the earthquake on the building. The connection between the core structure and the walls is evenly important in this case, where it is necessary to keep the elements structurally separated. This is done in Figure 40. with the dampening insulating layer, in red, which separates the walls and the roof structurally. In the same image, the green highlighted insulation separates the two buildings structurally and will prevent the transferal of noise and heat.

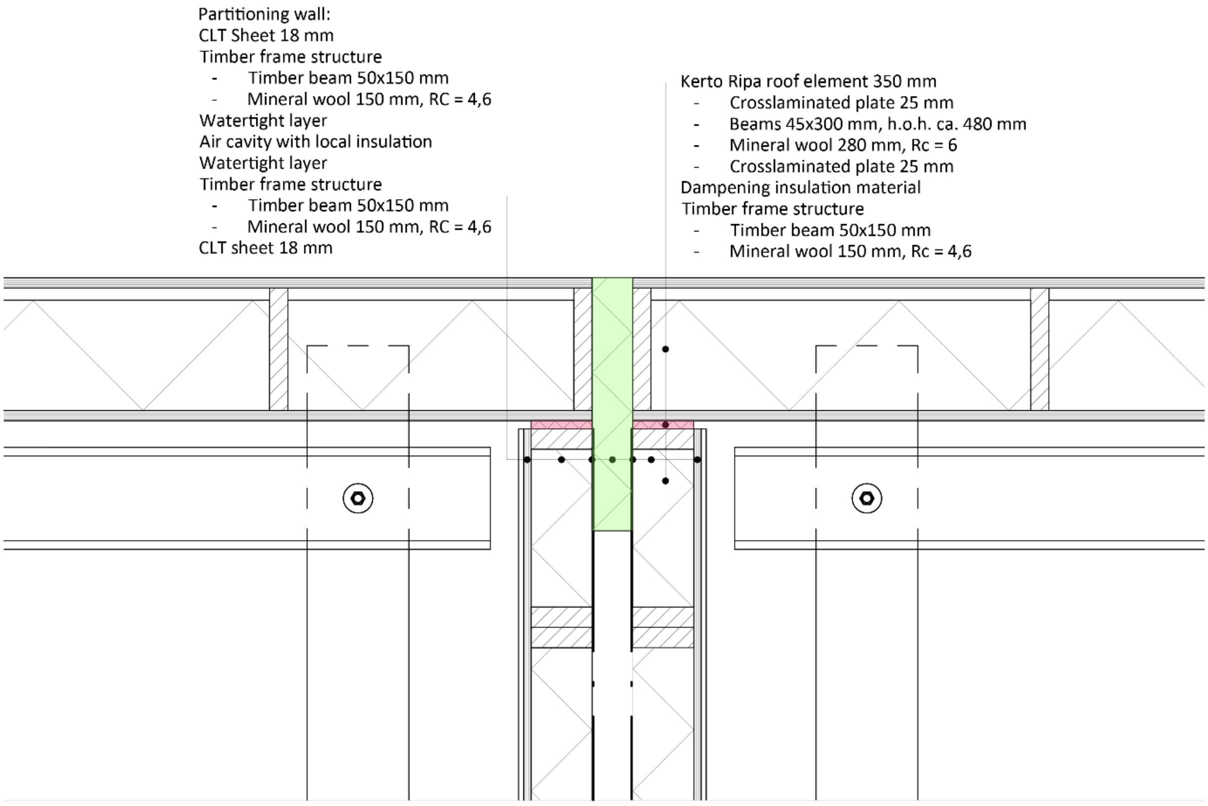

Figure 40. Detail roof connection

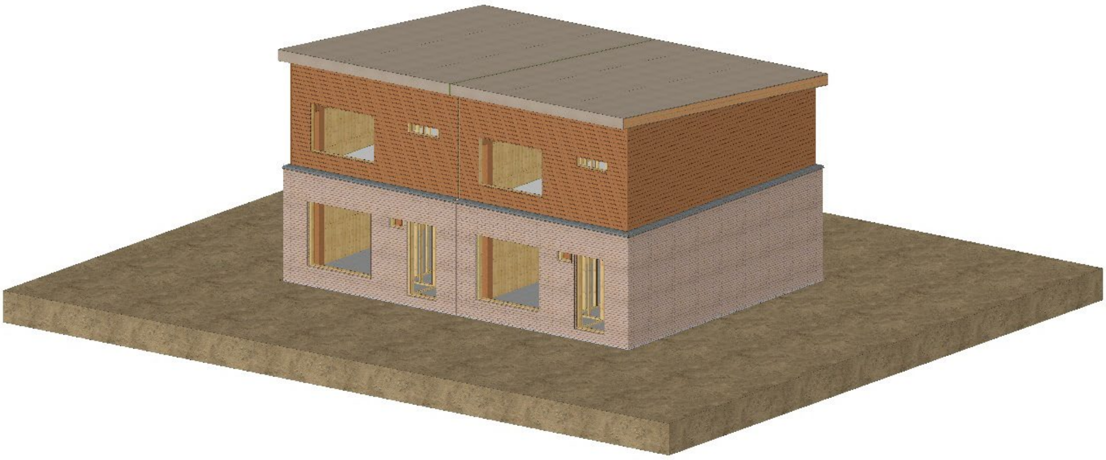

Figure 41. Placement of brick system and finishes

In an earlier stage the timber frame wall was placed to ensure a light weight insulating wall solution. In addition to this wall system a brick wall will be added at the ground floor level. This brick wall has a higher protecting value over softer wooden cladding and with that protects the first floor against forms of vandalism. Additionally, this brick exterior makes the building fit in with the surrounding built environment whereas masonry is the most applied finishing layer in the area. The specific system called SRB-DUP, which is applied here, provides good earthquake resilient qualities. The system was first applied in Japan, where both the inner and outer sheet of the wall were created with this material (Yamaguchi et al., 2007). Between the layers a thin sheet was added for thermal insulation. This detailing would not fit the Dutch insulating standards and therefore the SRB-DUP system is combined with the timber frame to comply with the building decree. The mineral wool insulation in the timber frame on itself has a Rd value of 4.6 $m^2 \cdot K/W$ which is the minimum according to the Dutch building decree. Additionally, the air cavity, CLT sheet and the brick wall make the Rc value reach a total of 4.92 $m^2 \cdot K/W$ (as calculated in Appendix F). The SRB-DUP wall is connected with the timber frame through anchors which allow for wind force to be translated to the inner wall. This connection with the inner wall makes it possible for the SRB-DUP system to dissipate energy for the entire wall construction through friction as it was designed to (Yamaguchi et al., 2007).

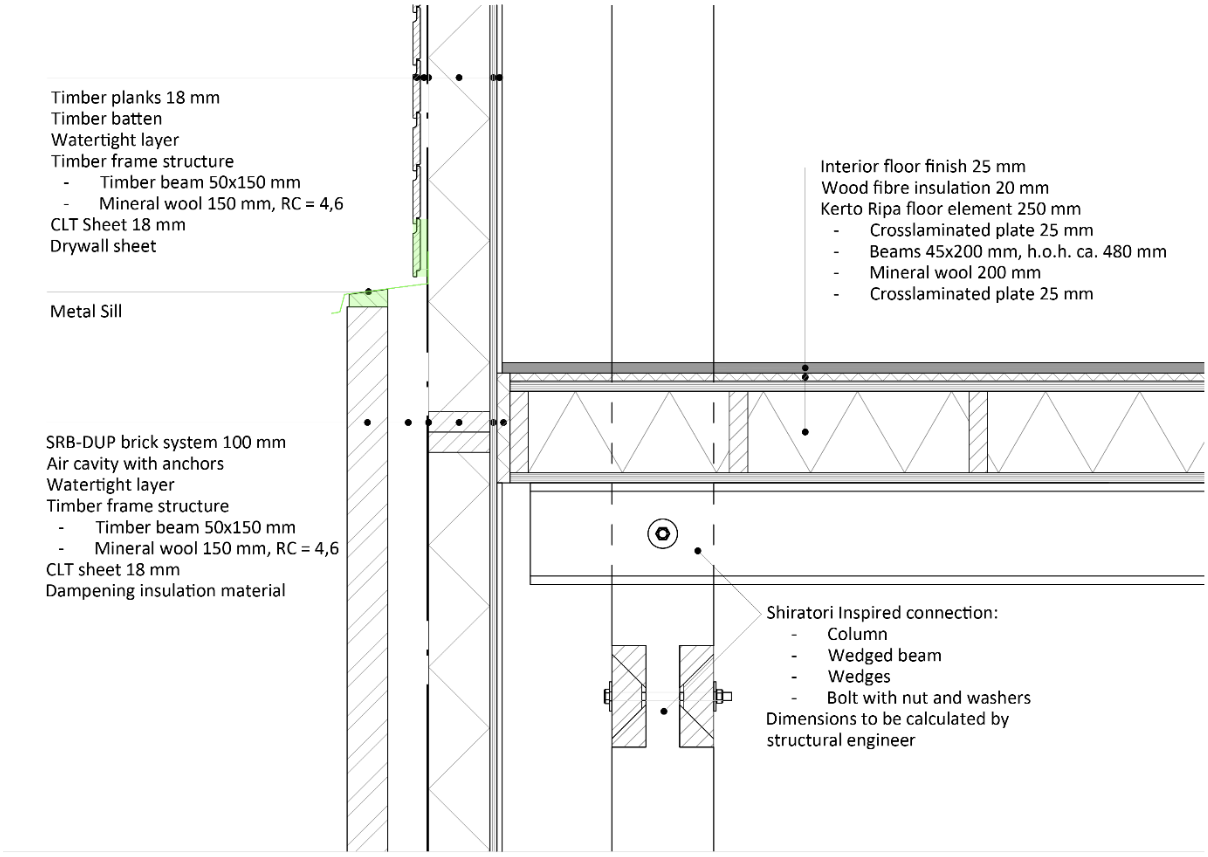

Figure 42. Detail connection brick wall system and timber frame

The brick system is only applied to the first floor as can be seen in the detail in Figure 42. The top floor is finished with timber cladding. This is done to keep the mass of the overall structure low. The connection between the both wall systems is the last step of this case study. In Figure 42 the connection using a metal sill is highlighted in green. This metal sill prevents unwanted water from entering the air cavity and closes the connection between the inner and outer wall sheet. As a last step the final wooden cladding element will be added now the sill has been placed.

This case study shows that it is possible to build new residential buildings in the earthquake area of Groningen as long as the detailing and material choices are done properly. Combining new technologies with established traditional knowledge gives this result which should react resilient to an earthquake. Whereas the end of the earthquakes in Groningen is not yet reached, this way of building gives the citizens of the area a possibility to build new and safe houses.

4. Conclusion

This graduation project is an exploratory research, aimed to find a solution for the citizens of Groningen who perceive a feeling of unsafety and whose houses are damaged by the induced earthquakes. In order to answer to this, the sub questions are answered followed by the main research question.

> *"What causes the earthquakes in Groningen and how does it cause damage to the built environment?"*

The literature showed that the earthquakes in Groningen were caused by human activity. The production of natural gas in the area creates a pressure difference in the soil layers which make the layers move. A sudden movement then causes an earthquake. When the earthquake waves reach a building it will put a force on the building in accordance with Newton's second law. This means the mass of the building has a big influence on the size of the earthquake force. The current built environment of Groningen is mostly built with heavy and brittle materials such as concrete and brickwork which are prone to damage by the earthquake.

> "What traditional timber structures can be found in the earthquake area of Groningen and are these earthquake resilient?"

The area in Groningen which is struck by the earthquakes contains large amounts of traditional farmhouses and accompanying barns. These barns are built with traditional timber bent structures which form the load bearing construction of the building. In the area the "Dekbalk" bent is the most common. Even though this type can be found in Groningen, the "Ankerbalk" bent is general the most commonly used in the Netherlands. The evaluation done for the two most common bent structures in the Netherlands showed that there is a possibility for energy dissipation, however small. The structures are relatively light weight and can show some ductility. Using the evaluation it was shown that there is some earthquake resilience possible with these structures, limited though.

> "How can international earthquake resistant traditional timber structures be used in Groningen?"

The research introduced the K-N timber joint which was created by prof. Shiratori. This joinery type uses the ductility of wood in the right direction in order to dissipate earthquake energy. The K-N joint is used in Japan for wall constructions but was adapted to the usage in Groningen. Similar to the Dutch bent structures the joint was used to connect columns and beams. The functioning of the K-N joint stayed the same; horizontal movement is translated to compression in the longitudinal directing of the columns. By using the K-N joint in a bent structure the international earthquake resistant timber joint is adapted to Groningen.

> "What wall type can be used to build residential buildings in the earthquake area of Groningen?"

In order to build earthquake resilient it is necessary to use light and/or energy dissipating materials. In this research a light timber frame is used for the inner walls. This wall type allows for a high insulating value in combination with a low mass. Additionally, the SRB-DUP system was used. This prestressed brick system allows for energy dissipation and creates a protection against vandalism.

“What floor type can be used to build residential buildings in the earthquake area of Groningen?”

The floors in the current built environment of Groningen are mostly made with concrete. This material has a high mass and behaves brittle. Both are characteristics which are not desirable in earthquake design. As an alternative, the Kerto-Ripa floor elements are proposed. These CLT floor elements have a relatively low mass and can show ductility. Because of this, they are applicable in new residential buildings in the earthquake area of Groningen.

“How can a traditional timber structure be used to build new earthquake resilient residential buildings in Groningen?”

Traditional timber structures are light weight, can preform ductility and dissipate energy. These characteristics make traditional timber structures a possible building method in earthquake areas such as Groningen. However, not all researched timber structures in this study are expected to behave equally well. The Shiratori inspired bent structure is the best fitting solution for building earthquake resilient residential buildings in Groningen. The case study shows a way to build these residential buildings using the traditional timber structure and additional earthquake resilient building elements. This example shows that the timber structure can work as long as the connection with other applied building elements is detailed correctly.

4.1. Scientific relevance

This study focused on the application of traditional timber joinery in earthquake resilient buildings. By doing this, the study is limited to a smaller field of possibilities since concrete and steel structures were left out, for example. The topic of traditional structures has not been covered extensively in literature. When covered, promising outcomes were shown but this was mostly on the level of an individual element instead of the entire construction (Bulleit et al., 1999; Parisi & Piazza, 2008; Xue et al., 2018). The application of traditional joinery for the entire construction of a building, in order to improve the earthquake resistance, was not yet covered. This study used the lack of research as an opportunity to analyze the overall behavior in an application for the earthquake area in Groningen. For this purpose of this study, only the relevant Dutch and foreign structures have been evaluated in order to show that it is possible to use these old techniques in a new application. This selection implies that there are more traditional timber structures to be found but were not tested in this research. The analysis done on the three types of timber structures shows that there is a potential gain in using these types of constructions in earthquake areas. The ductility and energy dissipation, possible in the structure, have benefits for the resistance of earthquakes. The exact contribution however, could not be calculated in this research. The research can merely serve as an indication that these types of structure are applicable in new buildings when earthquakes are the problem. Nevertheless, further research into the exact behavior of the construction through experimental research and structural calculations will still be necessary before applying the structure in a real life situation. This further analysis can improve the MCDA as well. The analyses in this study were based on existing literature, which was limited.

The main research question explored whether new earthquake resilient residential building could be built in the earthquake area using a traditional timber structure. This question is answered through a case study example, in which the knowledge from the sub questions was used. This example shows that the separate building methods and materials can be combined in a building. Although the detailing is based on manufacturer drawings and standard details, it is not complete yet; the dimensions for the structural components were not calculated in this research. Nevertheless, the case study provides an answer to the research question in showing that the multiple earthquake resilient methods, from which the traditional timber structure is one, can be combined into a single earthquake resilient residential building.

4.2. Societal relevance

This research project is mainly aimed for the societal need. The built environment in the earthquake area of Groningen suffers from induced seismicity. These earthquakes cause damage to the residential buildings and make the population feel unsafe. The government and the NAM, proposed a short term solution for reinforcing existing buildings. The aim for this research was to find a long lasting solution to build new residential buildings in the earthquake area using a traditional timber structure. The study provides a possible answer to this by proposing a combination of earthquake resilient building methods applied to one case study. This creates the opportunity to apply the building methods on different building typologies to solve the earthquake damage to buildings in the earthquake area.

4.3. Recommendation

The study is an exploratory research into the possibility of using traditional timber structures in the new context of building earthquake resilient houses in Groningen. As mentioned before, the evaluation on the proposed timber structures was based on theories retrieved from literature. This evaluation was able to show that there is a possible gain in working with these type of structures for the earthquake area in Groningen, however more experimental research is required. As pointed out before, the dimensions and behavior of the timber structure need experimental and calculated research before the structure can be applied to a real life situation. This is a point of interest for further research which can point out the exact required dimensions and the behavior of the overall construction in case of an earthquake.

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Appendices

Appendix A. Tectonic earthquakes

As mentioned in the literature review it is possible to distinguish two types of earthquakes: tectonic and induced. The first type of earthquakes are the ones caused by the constant movement of the earth's crust. The earth's crust exists of multiple tectonic plates which are in constant movement. When these plates move alongside each other and get locked they built up friction stress. This stress builds up along the so called faults (Sucuoğlu & Akkar, 2014). The major faults can be found at the edges and smaller ones within the tectonic plates. When the stress hits a critical point a rapture in the fault occurs. This sudden failure releases the energy causing a seismic wave in the earth's crust. This phenomenon is known as an earthquake. The biggest and most frequent raptures occur at the edges of the tectonic plates and are known as intraplate earthquakes, less frequent are the interplate earthquakes taking place within the tectonic plates. These interplate earthquakes are less frequent but can be as strong.

Appendix B. Pairwise comparison of alternatives

Ductility capacity	D	S	A
D	1	1/7	1
S	7	1	7
A	1	1/7	1

Figure 1. Pairwise comparison matrix of the criteria Ductility capacity

Displacement in x and y direction	D	S	A
D	1	1/7	1
S	7	1	7
A	1	1/7	1

Figure 2. Pairwise comparison matrix of the criteria Displacement in x and y direction

Ductility in fasteners	D	S	A
D	1	1/9	1/3
S	9	1	7
A	3	1/7	1

Figure 3. Pairwise comparison matrix of the criteria Ductility in fasteners

Possibility for repair	D	S	A
D	1	1/5	1
S	5	1	5
A	1	1/5	1

Figure 4. Pairwise comparison matrix of the criteria Possibility for repair

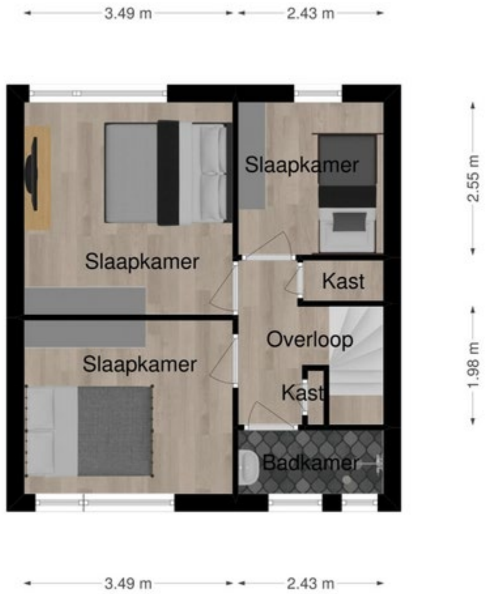
Joinery used	D	S	A
D	1	5	1
S	1/5	1	1/5
A	1	5	1

Figure 5. Pairwise comparison matrix of the criteria Joinery used

Fasteners used	D	S	A
D	1	9	1
S	1/9	1	1/9
A	1	9	1

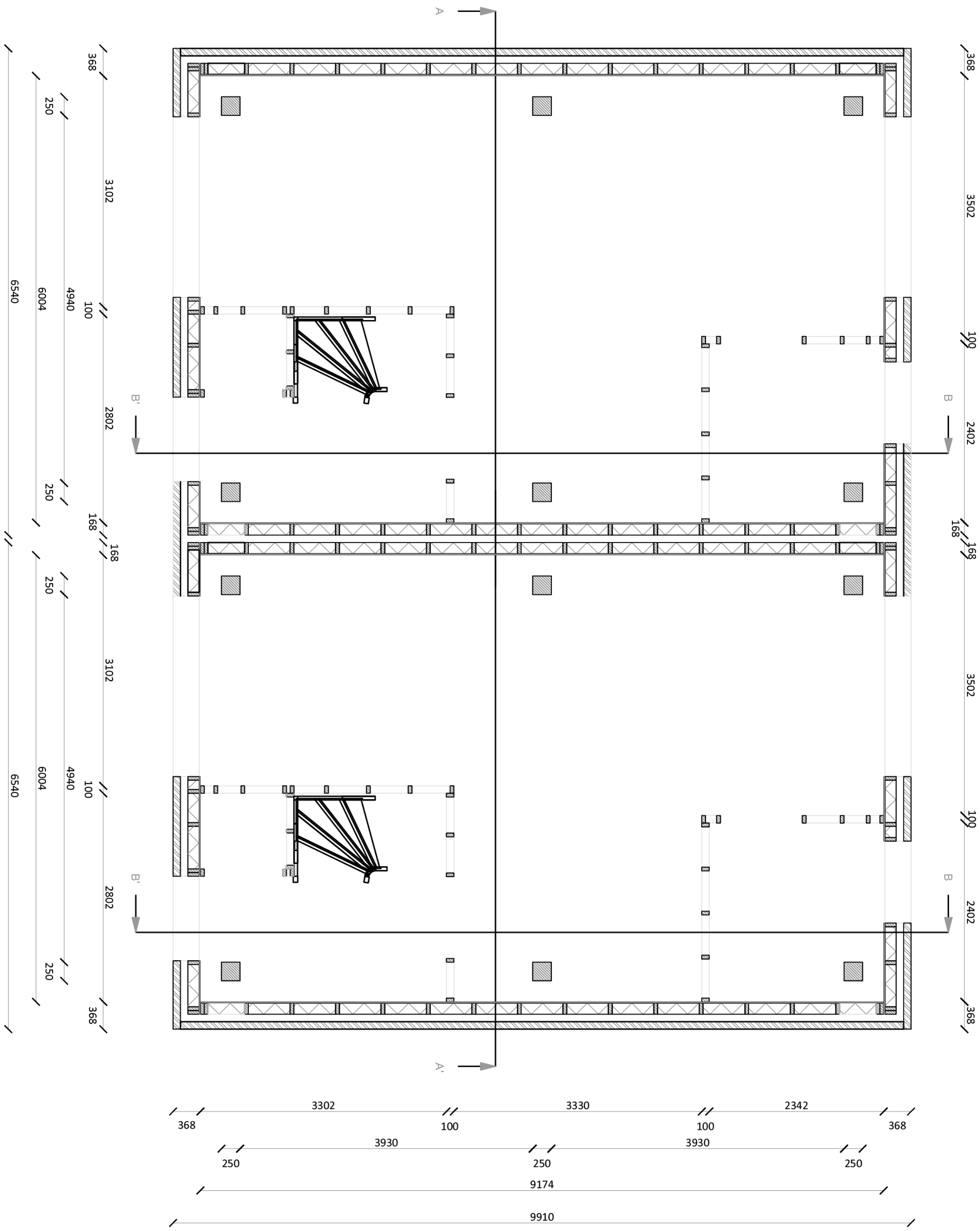
Figure 6. Pairwise comparison matrix of the criteria Fasteners used

Appendix C. Residential building original layout

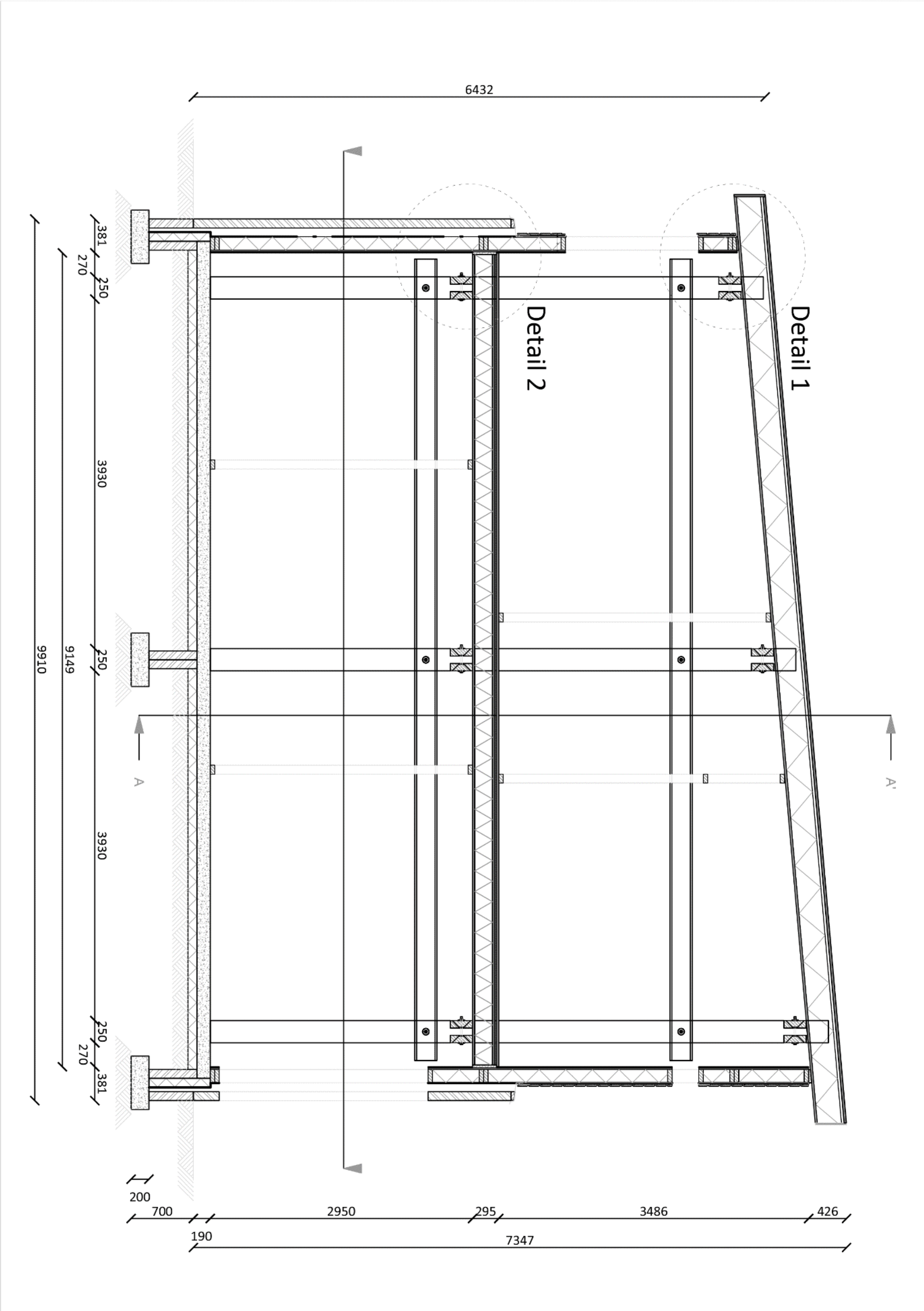


Appendix D. Detailing of the case example

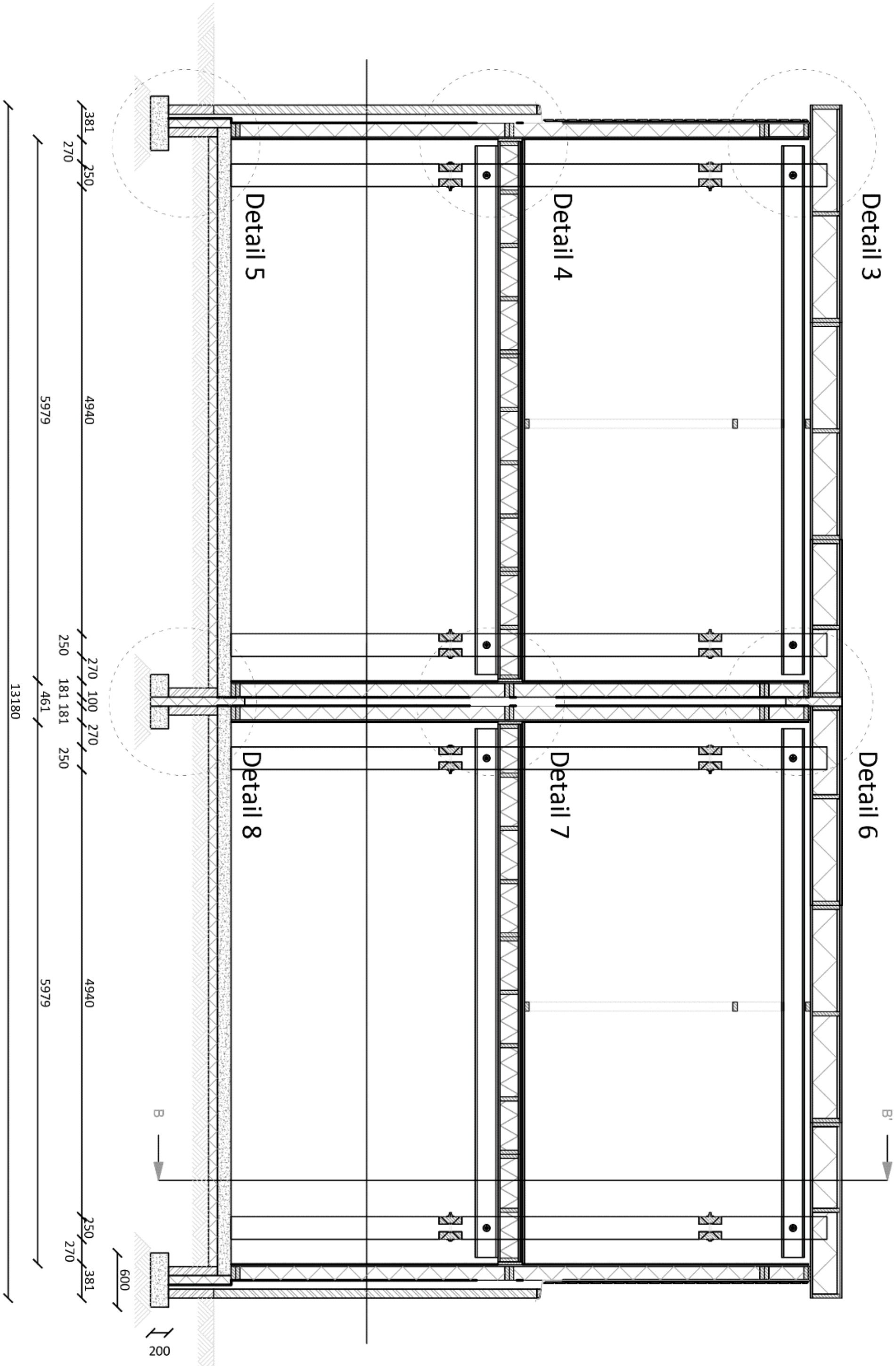
This appendix holds the drawings for the case example in which the earthquake systems are applied. The building shape and interior where retrieved from a building in the earthquake area.



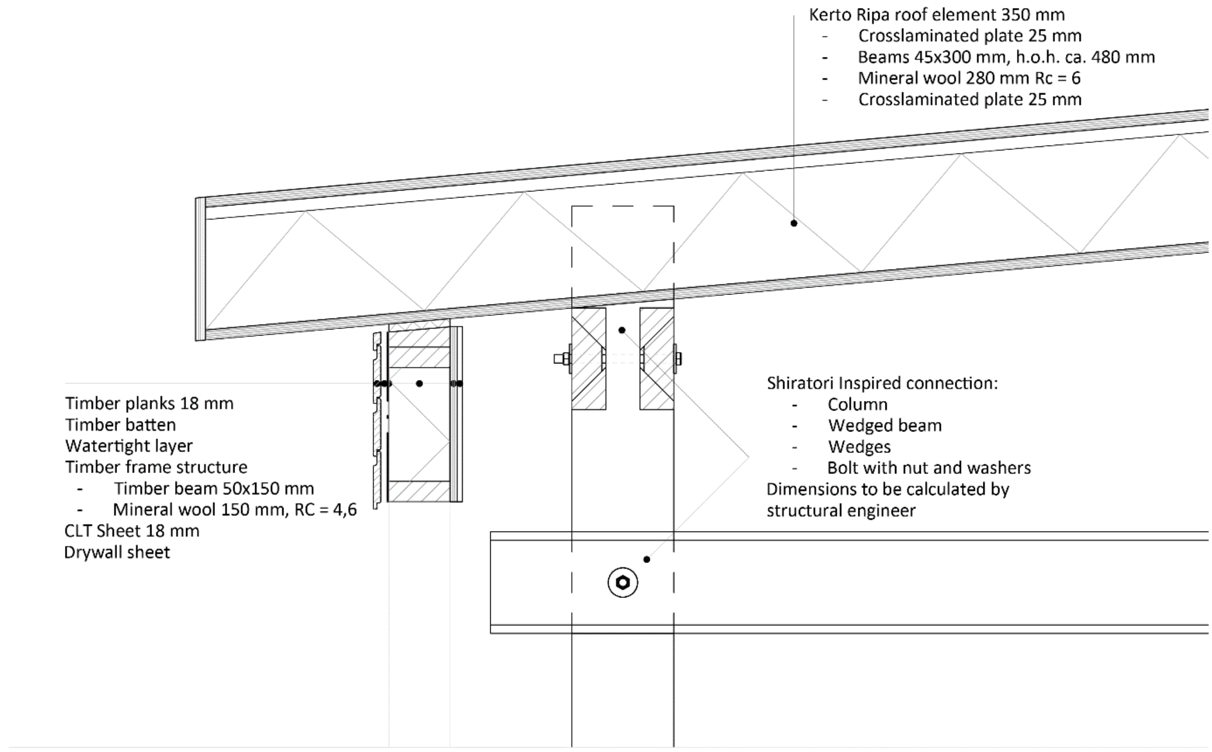
Floor plan of first floor


6432
Detail 2
Detail 1
381
270
250
3930
9910
9149
250
3930
250
270
381
A
A'
200
700
190
2950
295
3486
426
7347

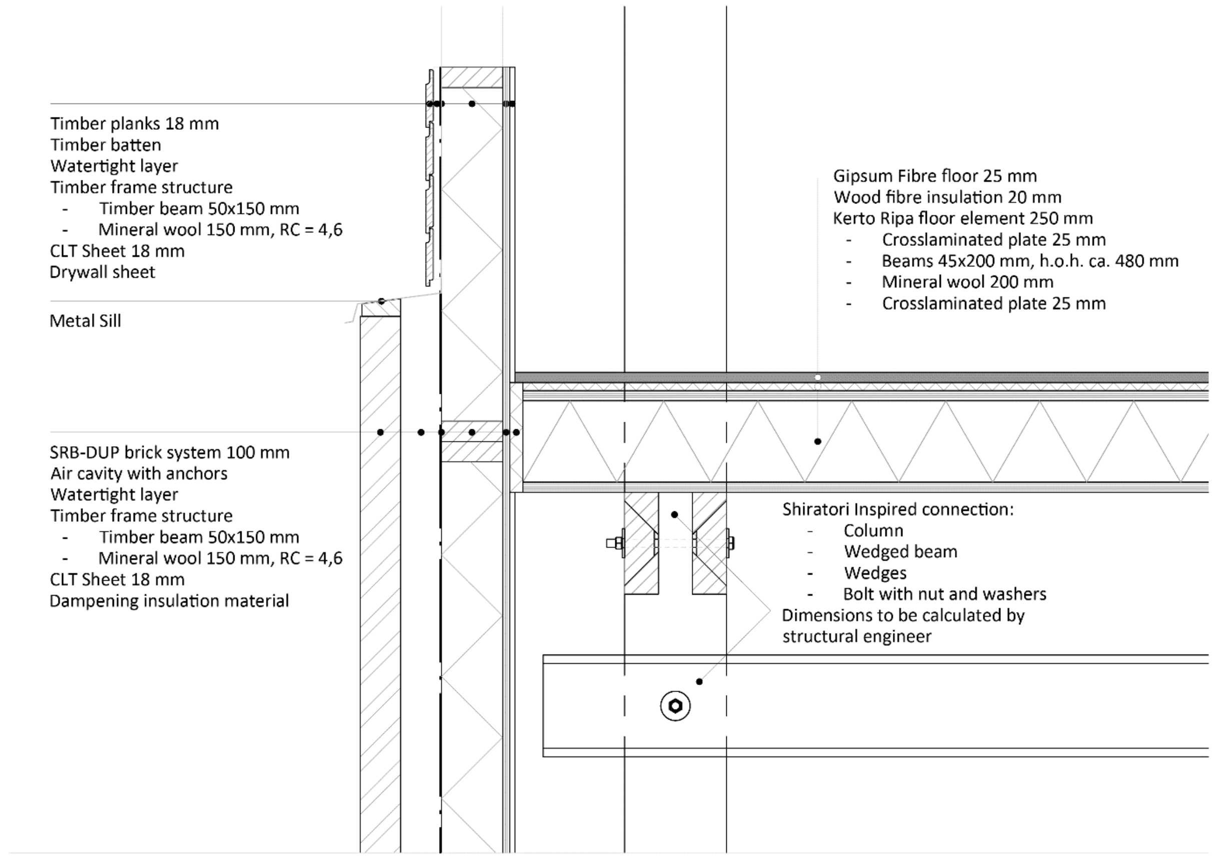
Section BB’


Detail 3
Detail 4
Detail 5
Detail 6
Detail 7
Detail 8
B
B'
13180
5979
4940
461
381
270
250
181 181
100
600
200
700
190
2950
295
3158
351
6944

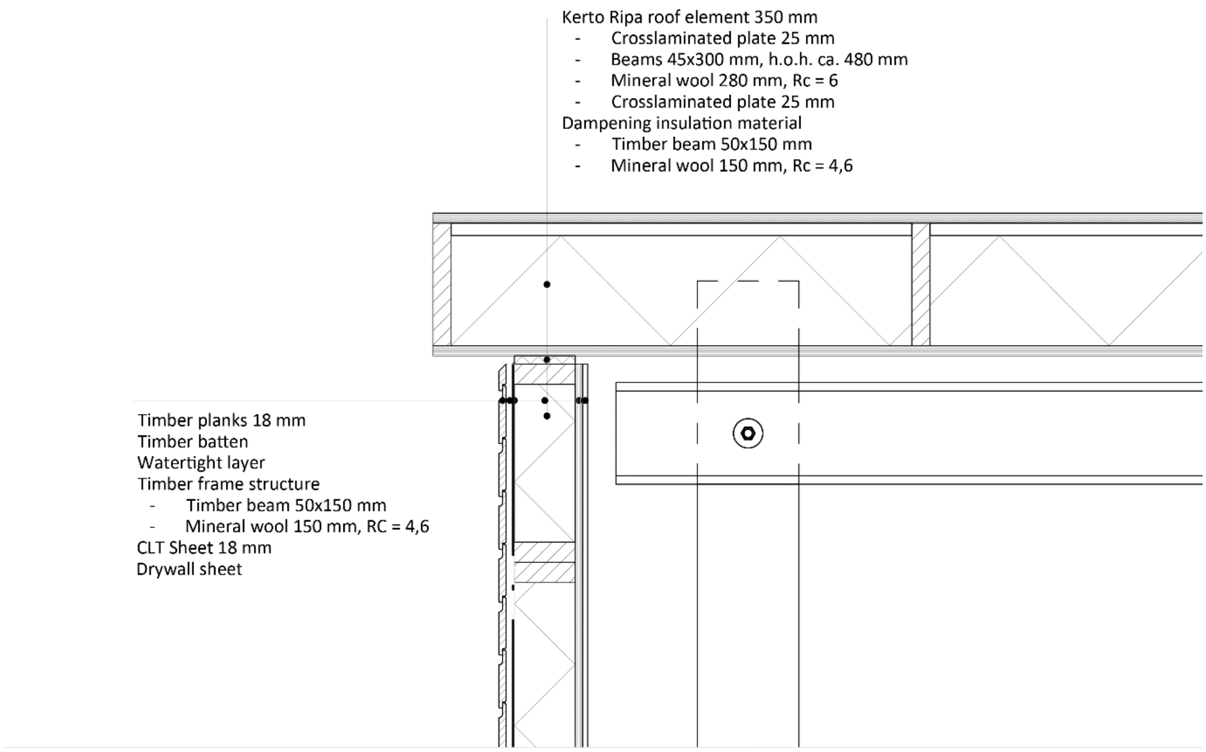
Section AA’



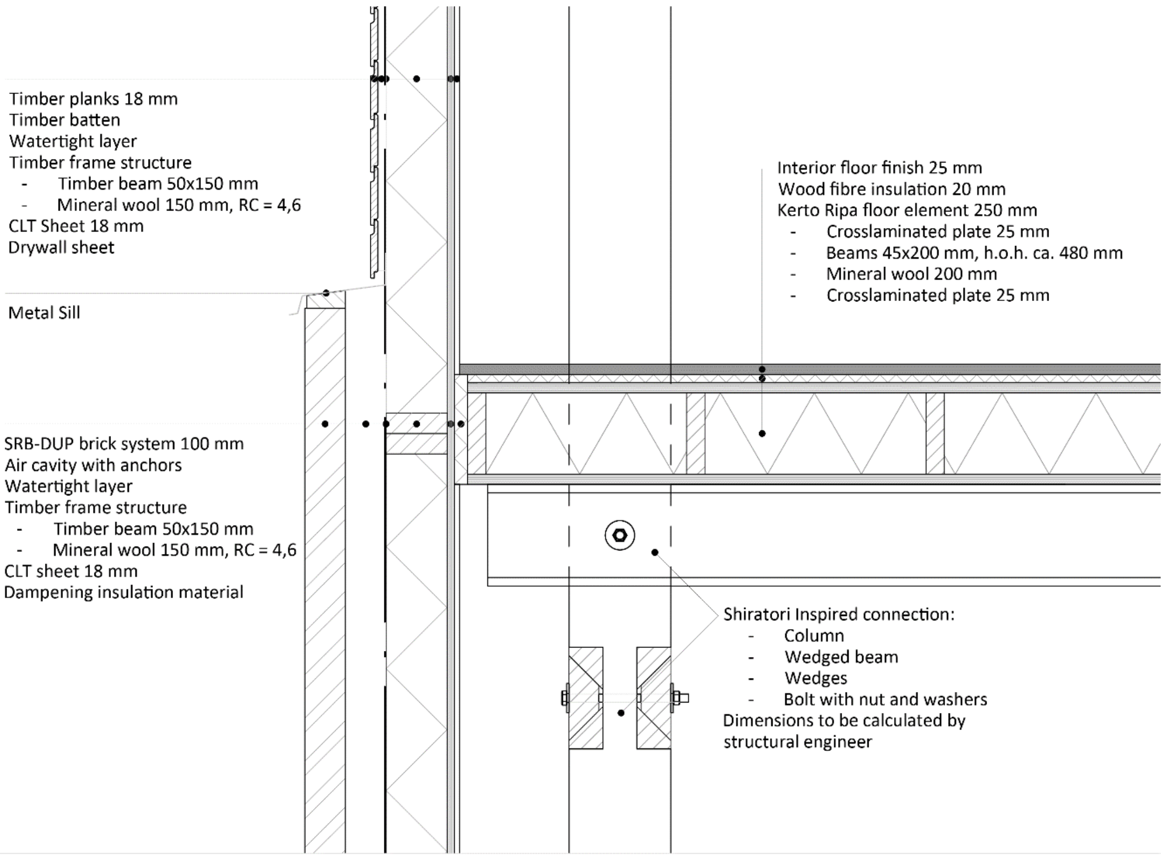
Detail 1 Roof connection



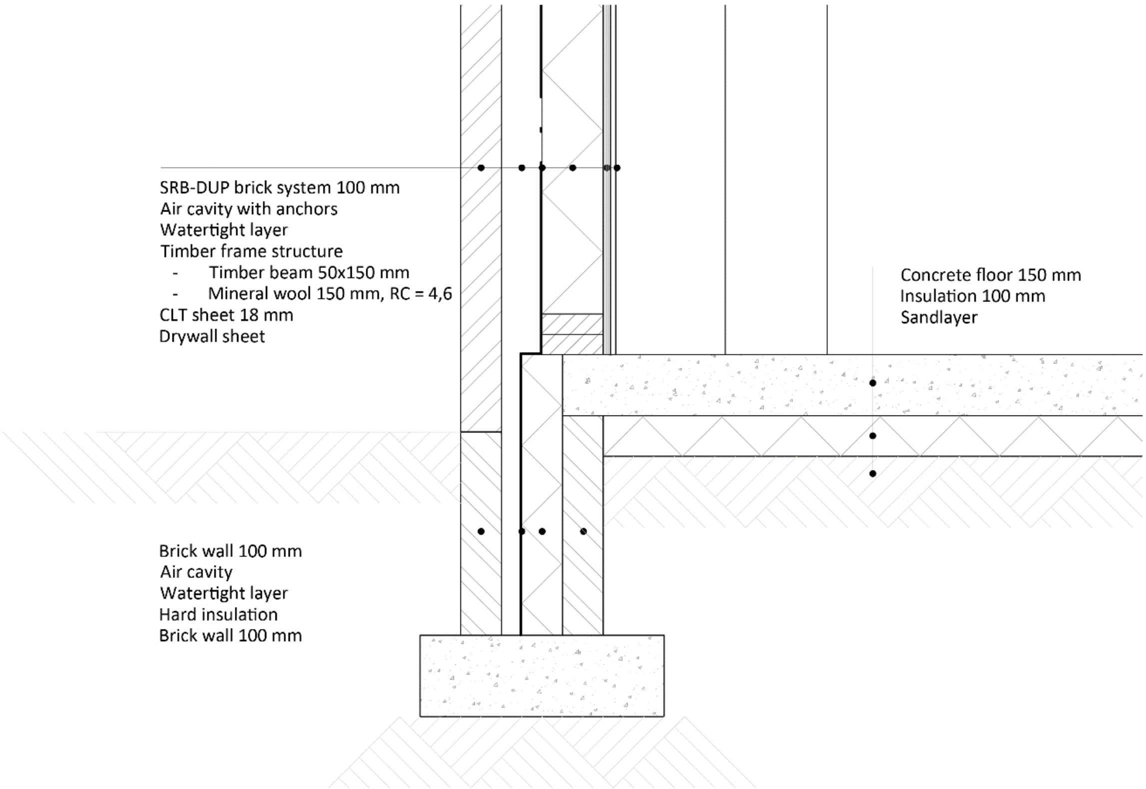
Detail 2 Elevation floor connection



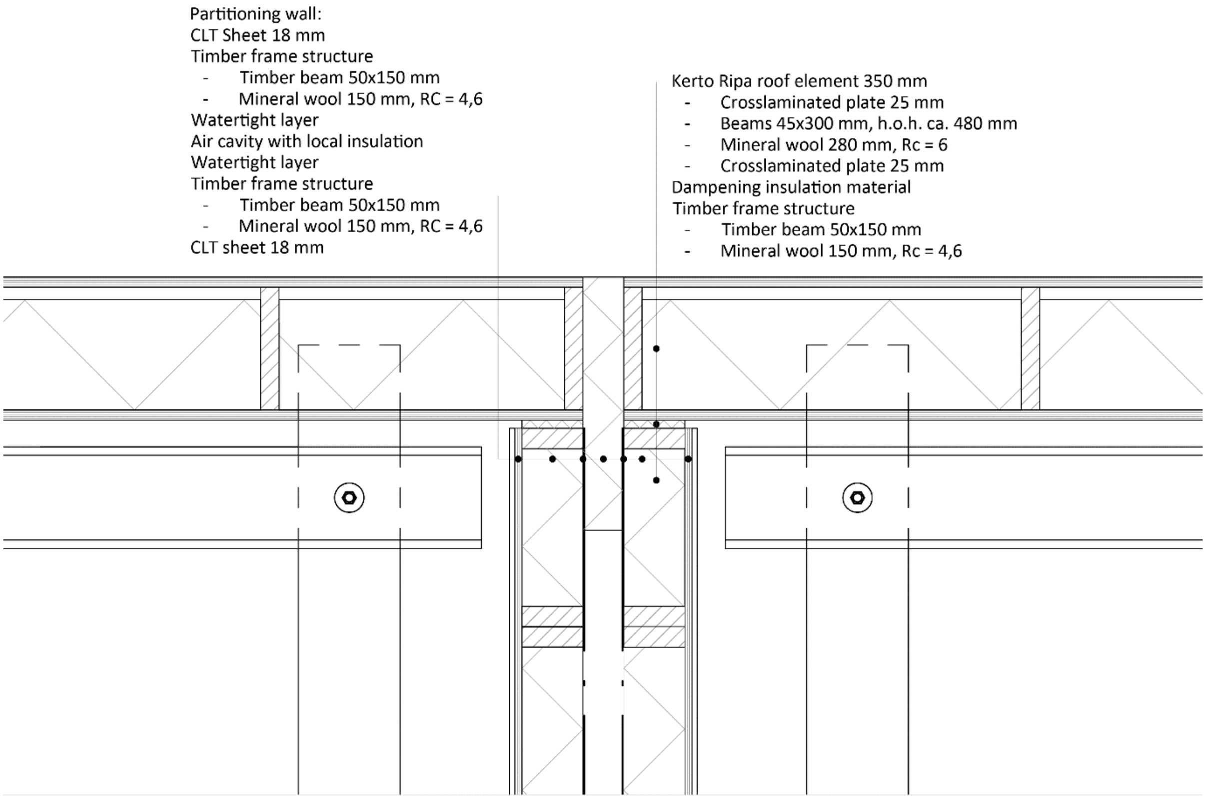
Detail 3 Roof connection



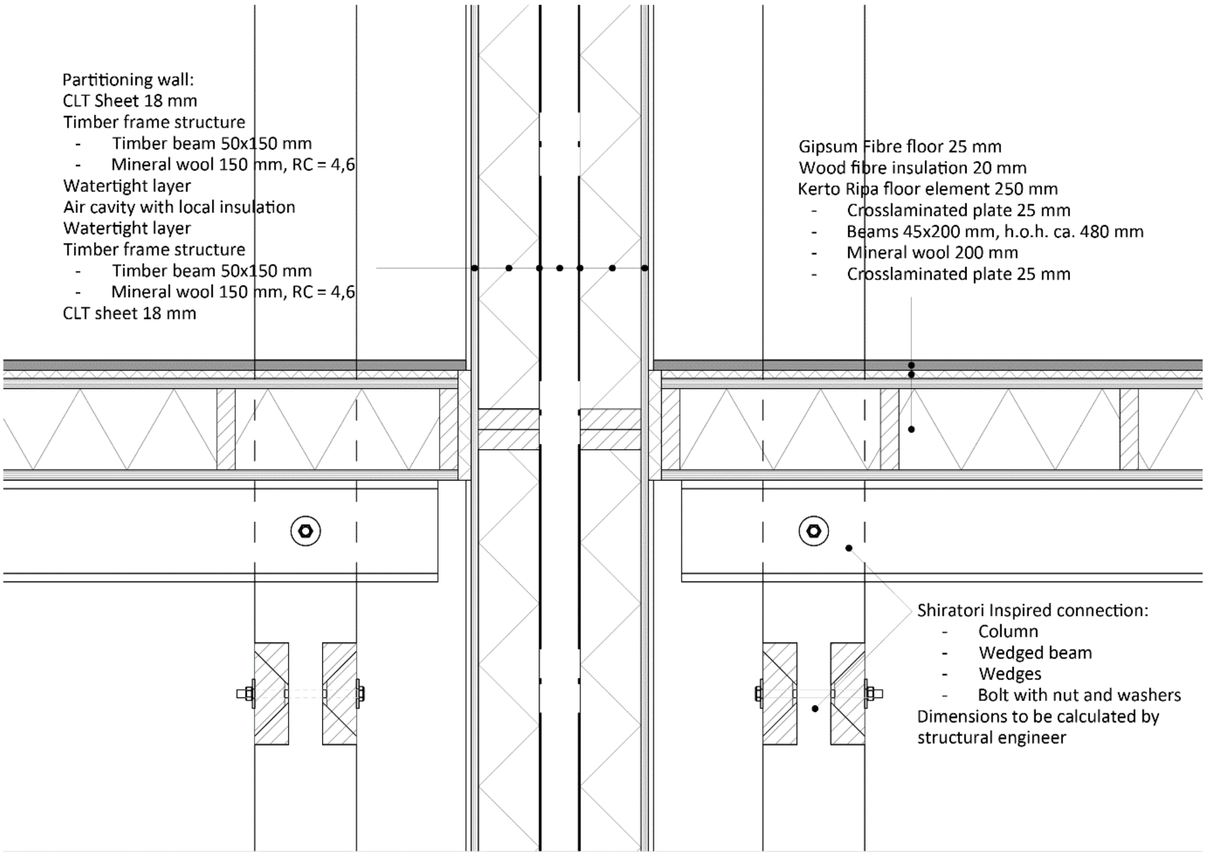
Detail 4 Elevation floor connection



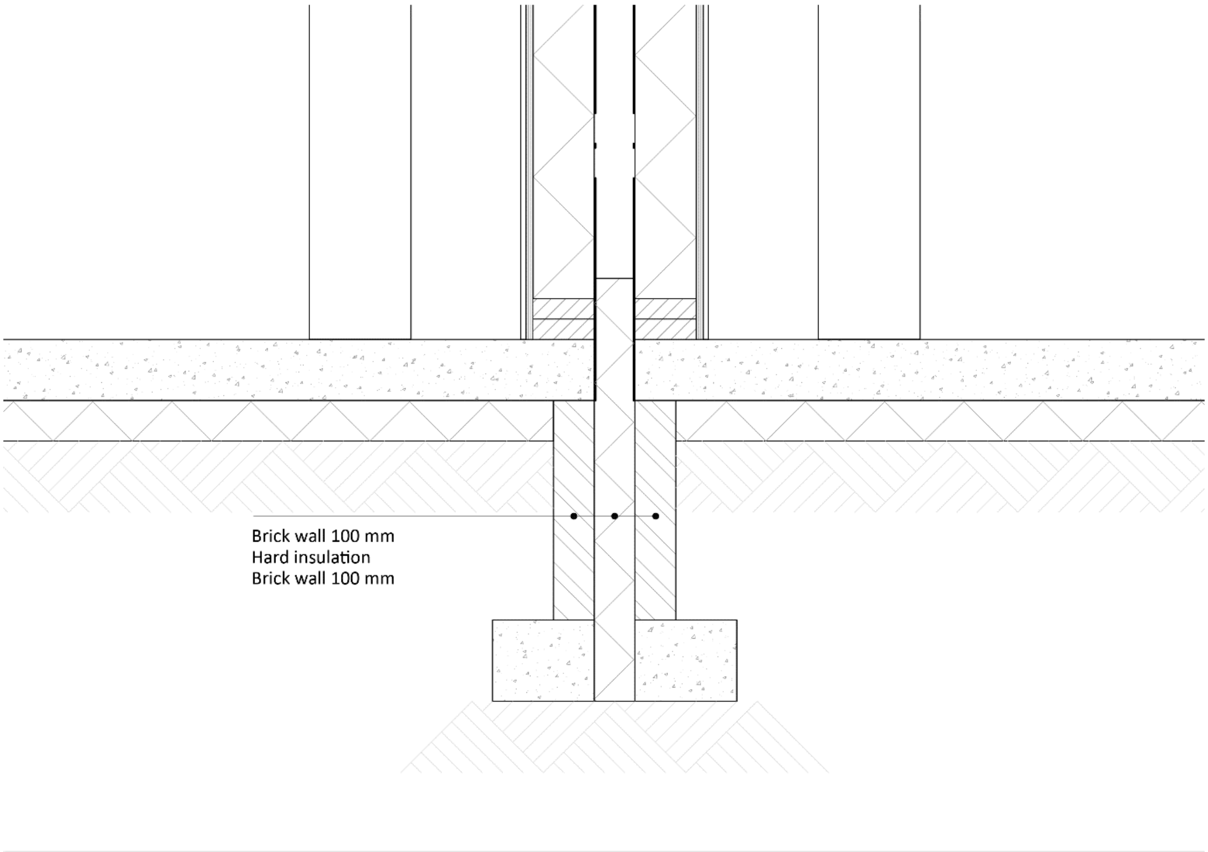
Detail 7 Foundation and connection to outer wall



Detail 6 Separation roof connection



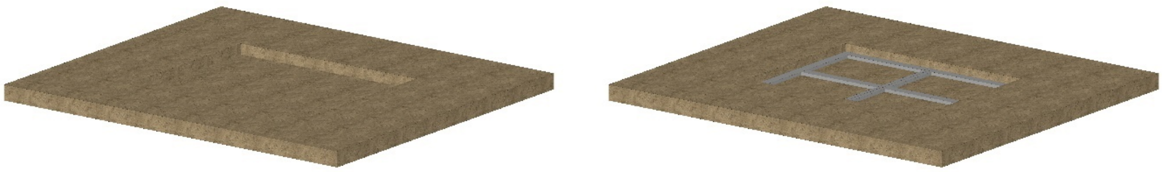
Detail 7 Elevation separation floor connection



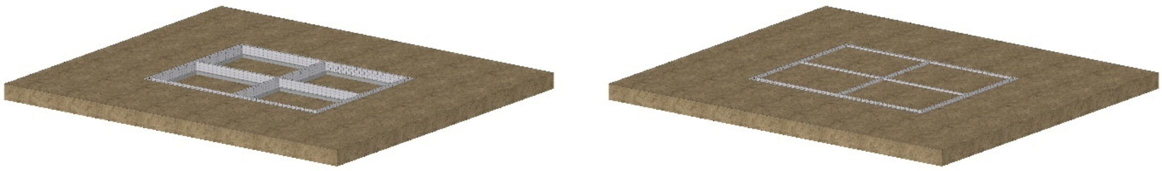
Detail 8 Separation foundation connection

Appendix E. Complete building process

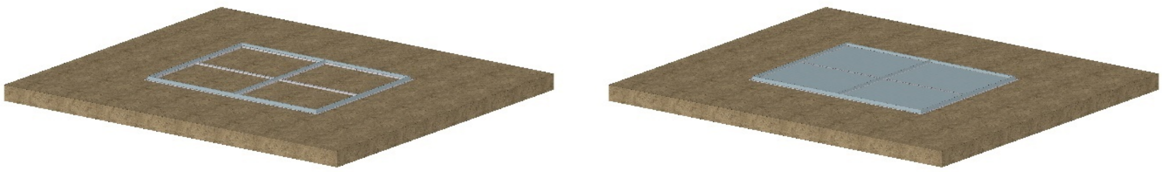
In this appendix the complete overview of the building process of the earthquake resilient residential building is illustrated. The following figures show the proposed steps for the creation of the building.



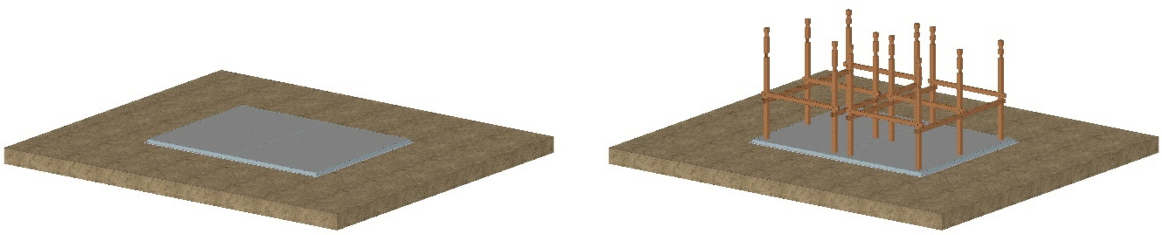
Digging of building site and pouring foundation beams.



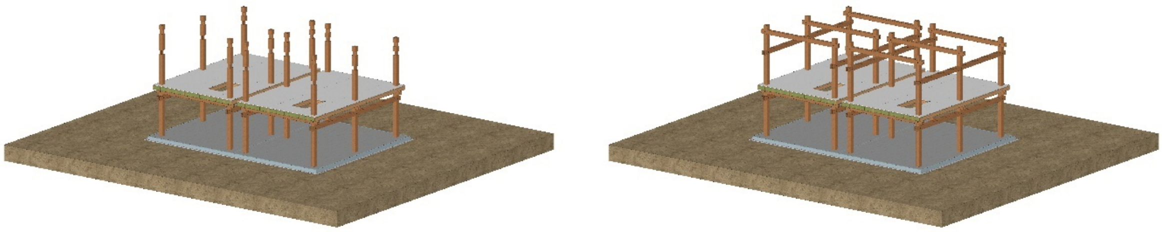
Adding foundation masonry and filling site with soil.



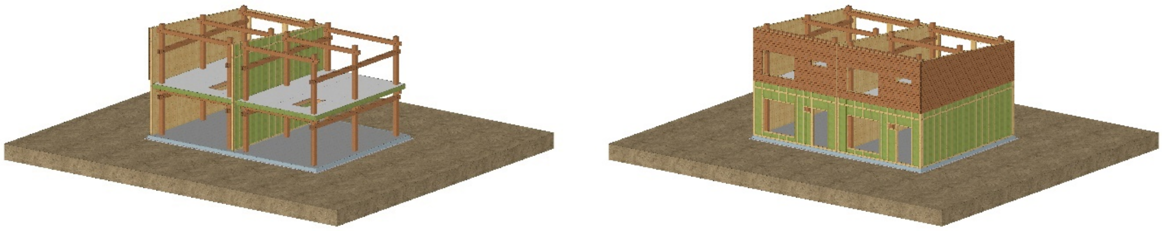
Adding insulation to the foundation masonry walls and on top the soil.



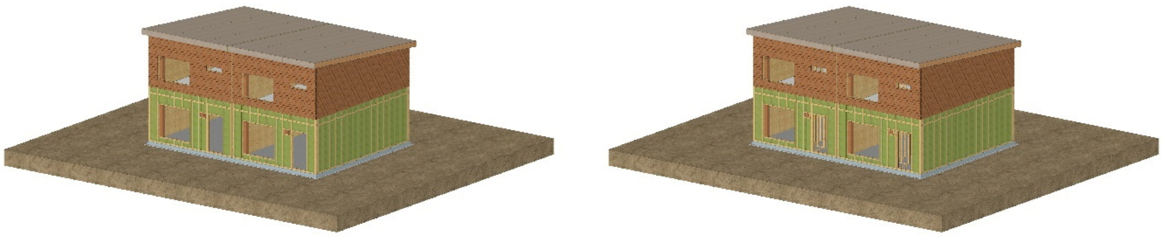
Pouring of concrete floors and placement of traditional timber structures.



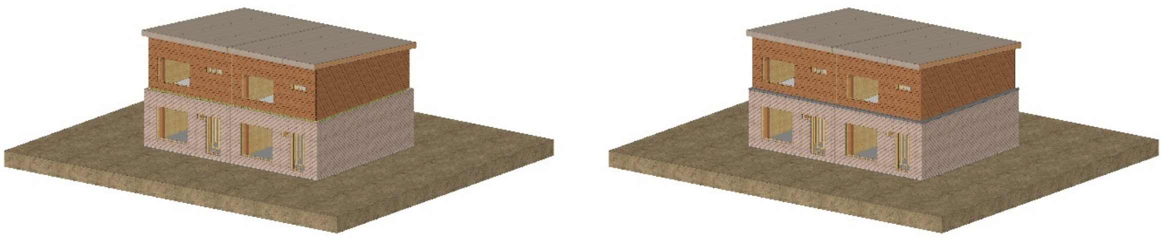
Placement of elevation floors and adding final traditional timber structure beams.



Adding timber frame walls.



Placement of roof elements and addition of interior walls.



Adding SRB-DUP brick walls system and finishing connection between timber and brick wall.

Appendix F. Building performance calculation

In this appendix a short calculation is made to show that the walls of the case study building meet the minimum set by the Dutch building decree. This minimum is set on a Rc value of 4.6 $m^2 \cdot K/W$ for façade walls. The Rc value is calculated using equation 1.

$$R_c = \frac{\sum R_m + R_{si} + R_{se}}{1+\alpha} - R_{si} - R_{se} \qquad (1)$$

The following values are used:

$R_{si} = 0.13$ Wall adjacent to outside conditions

$R_{se} = 0.04$ Wall adjacent to outside conditions

$\alpha = 0.02$ The wall element is prefabricated

The material Rd values are calculated using equation 2.

$$R_d = \frac{d}{\lambda} \qquad (2)$$

In equation 6 the *d* is the thickness of the material in meters and λ the thermal conductivity coefficient of a material.

$$R_{CLT\ sheet} = \frac{0.018}{0.17} = 0.11 \text{ m2·K/W}$$

$$R_{Mineral\ wool} = \frac{0.15}{0.033} = 4.55 \text{ m2·K/W}$$

$$R_{Air\ cavity} = 0.18 \text{ m2·K/W}$$

$$R_{Brick} = \frac{0.1}{0.55} = 0.18 \text{ m2·K/W}$$

$$R_c = \frac{(0.11 + 4.55 + 0.18 + 0.18) + 0.13 + 0.04}{1.02} - 0.13 - 0.04$$

$$R_c = 4.92$$

Because 4.92 > 4.6 the wall meets the requirements set by the Dutch building decree.