Exo-Skeleton for prevailing damage on existing monumental buildings using Japanese wood techniques

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Abstract

This paper contains the research on scaffolding structures that are used to reinforce monumental brick buildings against seismic events. This research is done in view of the current seismic events in Groningen. A church in Bedum will be used as an example and within this paper an analysis is made of this building with regard to seismic behaviour. At the start of the analysis Japanese wood techniques seem to be a promising solution for the scaffolding structures. This hypothesis is tested within this research. If Japanese wood techniques are not the right solution, another solution is proposed.

Masonry buildings in seimic areas, scaffolding structures, timber, japanese wood techniques.

I
Introduction

Seismic events in the province of Groningen, created through the drilling of oil, are causing damage to its buildings. Within these buildings are a lot of old monumental buildings. Now, these monuments are not protected in a way that they will last, but only to prevent people from getting harmed. Because of the contemporary character of this problem, the first reaction is making the buildings user-safe, so that no one is in danger. Unfortunately, this reaction comes áfter an earthquake already has done its damage. A proposed solution is for example a scaffolding structure that makes the - already damaged - building saver. This scaffolding structure has a purpose to make the damaged building safe for its users and this structure is meant to be temporary. Nowadays these temporary solutions are still there, because the buildings still aren't reinforced in a non-temporary way. So, the temporary solutions will stay for an unknown amount of time and until they are removed the visual quality of these monumental building are subjected to the ugly temporary solutions like the scaffolding structures.

So the graduation project for which this paper is written is answering the following question: What is the best structural addition to reinforce a monumental façade against earthquakes, that is quick and temporary, but adds new qualities to the appearance of the monumental building? This means that a structure should be designed that can be added to different kind of buildings, that will be able to withstand the forces caused by an earthquake. A modular system is proposed as a structure, because it should be applicable on multiple buildings, it should be easy to make and it shouldn't cost too much time to build it.

An uncountable number of solutions can be found to answer this research question, so the fascination of the architect is important as well. What fascinates him will be researched and this will reduce the total research to a manageable problem. Wood is chosen as a fascination, because of its appealing appearance and its interesting characteristics. So the research will unfold around wood as the main material for the structure. As said before the structure should be easy to make and the building time should be short, so a structure with standardized elements in proposed. Therefore the Japanese wood techniques is suggested as a solution for this problem, because they have shown that they have mastered wood techniques that withstand seismic events.

Research should tell whether this proposed technique can be used in an earthquake resistant structures onto monumental buildings in the north of the Netherlands. To show how this technic can be implemented with all the seismic demands, a church is used to give an example of the workings of these findings.

So, with this research a start is made to design a wooden scaffolding structure, with the use of Japanese wood techniques, that is not only preventing monumental buildings to get further damage, but it will also add new qualities to the existing building. The main research question that is answered in this technical paper is thus: **will the Japanese wood technique be a proper solution to gain a wooden scaffolding structure that is able to reinforce a building to earthquakes and add visual quality to it as well?**

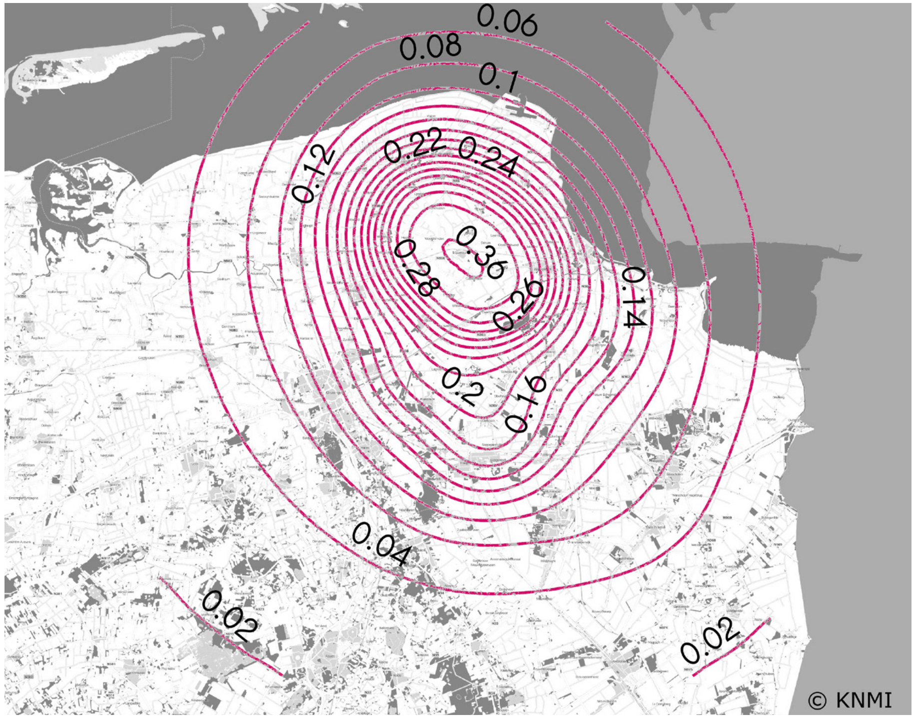


Figure 1: Illustration; Seismic events in Groningen (van den Brom, 2016)

II
Methodology

In this chapter the methods are discussed that are used to answer the main research question of this paper. This question is stated below:

Will the Japanese wood technique be a proper solution to gain a wooden scaffolding structure that is able to reinforce a building to earthquakes and add visual quality to it as well?

This is answered by formulating a number of subquestions that are answered with the use of an extensive literature research. For this literature research the following subjects are broached:

- How does masonry reacts to seismic events and how does a church react to this event.
- The existing scaffolding structures in Groningen that are reinforcing buildings against earthquakes, are analyzed, so the demands for a new structure onto churches are found.
- The characteristics of wood are checked and compared to the de mands for seismic design.
- The Japanese wood techniques are also checked and compared to the demands for seismic design.
- The techniques are checked for demands for visual quality as well.
- The subquestions that are part of the subjects stated above, are elaborated in the following paragraphs.

A . I
Analysis of the behavior of masonry structures in seismic events

To understand what the demands are for an additional structure, the behavior of the structure of the building itself should be analyed. What is the failure mechanism of the construction during the seismic events? To make this subject more relevant, this research is tested onto a church.

During this analysis the following subquestions are answered:
1. What is the structural behavior of masonry buildings?
2. What was the failure mechanism of masonry monuments during seismic events?
3. What is the most probable failure mechanism of the church?

A . II
Analysing how existing (scaffolding) reinforcing structures coop with seismic events, with a couple of examples

Scaffolding earthquake resistant structures
The method to gain information about the working of the existing scaffolding structures in Groningen for reinforcing (monumental) buildings,
is the following:
First a number of reference projects is gathered where monuments or other buildings are reinforced by an additional structures due to the seismic events in Groningen. These structures and buildings are analyzed structurally.

This is done to find the answers to the following subquestions:
1. What is the structural working of the additional structure? What parts of the structure are responsible for what purposes?
2. How is the scaffolding structure made and how is it fixed to the build ing?
3. On what parts of the building is the additional structure applied?
4. What is the problem of this structure with regard to visual appear ance?

A . III
What are the characteristics of timber that can be applied in to seismic design

Timber
The characteristics oft timber should be examined to know if this material could be used in seismic design. If the behavior of the material is known, it can be compared with the demands that come with seismic design and a conclusion can be drawn whether wood could be applicable in this field.

Subquestions that needs to be answered for this part are:
1. What are the properties of wood, taking into account the non-homo geneous and anisotropic behavior of wood?
2. What are the demands for wood properties with regard to seismic events?
3. What can be done to improve the performance of wood if it is not yet applicable for seismic events?

Japanese wood techniques
To learn more about how to deal with earthquake design I want to implement 'the traditional japanese techniques' on seismic design. This is very interesting because it is a combination of different qualities: Making a building earthquake resistant; Simplicity, only use the elements that are necessary; Building on site, labor-friendly; Working with just one material; Modular elements.
Because the new designed structure must have enough simplicity, it should have a modular character and the visual appearance is important, the Japanese wood techniques are proposed. Off course, research should be done to check if this technique is usable.

Research questions will be:
1. How does the characteristics of timber meet with these techniques?
2. What are the structural possibilities of this method and is this technique able to meet the demands of seismic design?
3. Does Japanese wooden structures improve the strength of a building against seismic events?

III
Results

R . I
Does japanese wood techniques fit to the demands on seismic design

1. Does Japanese wooden structures improve the strength of a building against seismic events?
2. Are Japanese wood techniques able to reinforce a church against seismic actions?

R . II
What could be a better solution than using Japanese wood techniques?

IV
Conclusion

V
Resources

A . I
Analysis of the behavior of masonry structures in seismic events

In the past we have learned a lot about how a masonry building acts in seismic areas, like in Italy. A literature analysis is done to find out the main characteristics of masonry with regard to seismic stresses. Here a summary is given of the main characteristics (weaknesses) in an unreinforced masonry construction and it is explained why this type of constructions behave so poorly against seismic stresses.

1. Heavy and stiff construction elements: these elements are fixed to the foundation by a pored concrete connection. Large cracks will occur in this type of connections due to tensile stresses. This is enhanced by the large weight of the masonry walls.

2. Very low tensile strength: the poor mortars and brittle masonry bricks behave very poorly against tensile stresses, so cracks will occur.

3. Low shear strength: the poor mortars and brittle bricks behave very poorly against shear stresses, so cracks will occur due to shear as well.

4. Brittle behavior: a masonry wall has low ductility and will give little warning before failure.

5. Weak connections between walls: the walls aren't able to transfer a moment from one wall to another, because of the tensile stresses that will occur due to the moment. So forces cannot be transferred from one wall to the other.
6. Crack concentration at corners of windows and doors: at these spots moments will occur, leading to tensile stresses. So cracks will occur at these places.

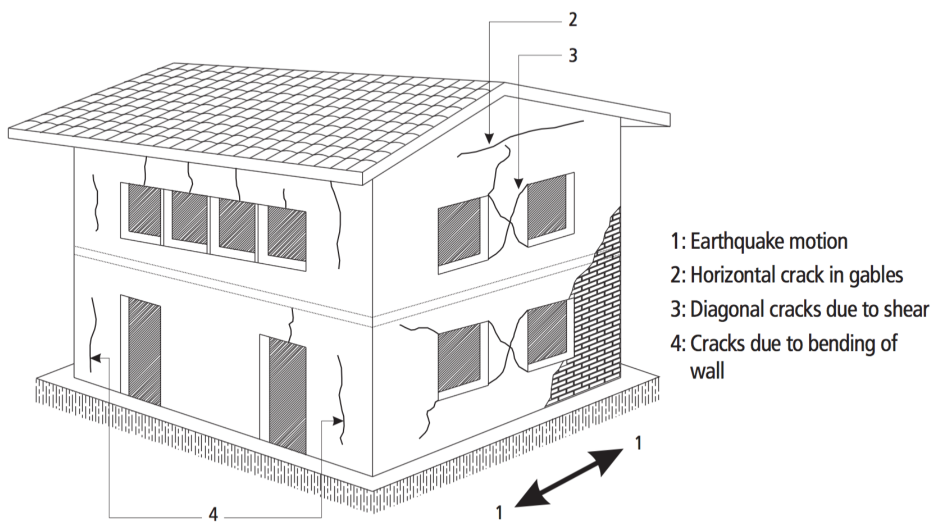


Figure 2: Illustration of earthquake damage onto a building (Kaikan, 2004, pp. Ch. 4, p.2)

Other important aspects with regard to seismic design are mentioned here as well.

1. Deviations in the symmetry in the plans and elevations of the build ing: the different parts of the building will deform differently, so extra stresses will occur.

2. Unsymmetrical behavior due to the imbalance in the sizes and posi tions of openings in the walls: extra stresses will occur due to this.

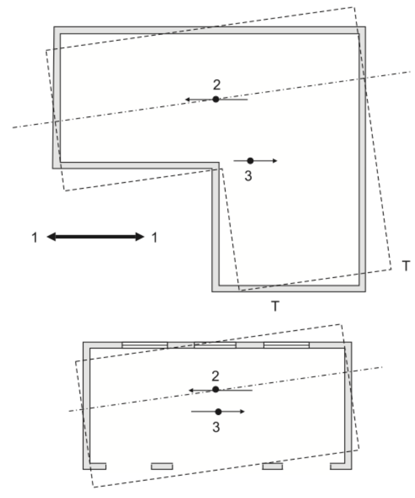
3. Defects in construction such as use of substandard materials, unfilled joints between bricks, walls that are not perpendicular, improper bonding between walls at corners and T junctions: will cause extra stresses in the elements.

Thus, when designing a masonry building, the following aspects will lead to a better design with regard to seismic behavior.

I Symmetry: The building as a whole or its various blocks should be kept symmetrical about both the axes. A-symmetry leads to torsion during earthquakes and is dangerous, see figure 3. Symmetry is also desirable in the placing and sizing of door and window openings, as far as possible.

II Regularity: Simple rectangular shapes, figure 4 (a) behave better in an earthquake than shapes with many projections figure 4 (b).Torsional effects of ground motion are pronounced in long narrow rectangular blocks.Therefore, it is desirable to restrict the length of a block to three times its width. If longer lengths are required two separate blocks with sufficient separation in between should be provided, figure 4 (c).

III Separation of Blocks: Separation of a large building into several blocks may be required so as to obtain symmetry and regularity of each block. For preventing hammering or pounding damage between blocks a physical separation of 3 to 4 cm throughout the height above the plinth level will be adequate as well as practical for up to 3 storied buildings, figure 4 (c).



1 - Earthquake force
2 - Centre of stiffness or resisting force
3 - Centre of gravity or the applied inertia force
T - Twisted building

Figure 3; Torsion of unsymmetrical plans (Kaikan, 2004, pp. Ch. 3, p.3)

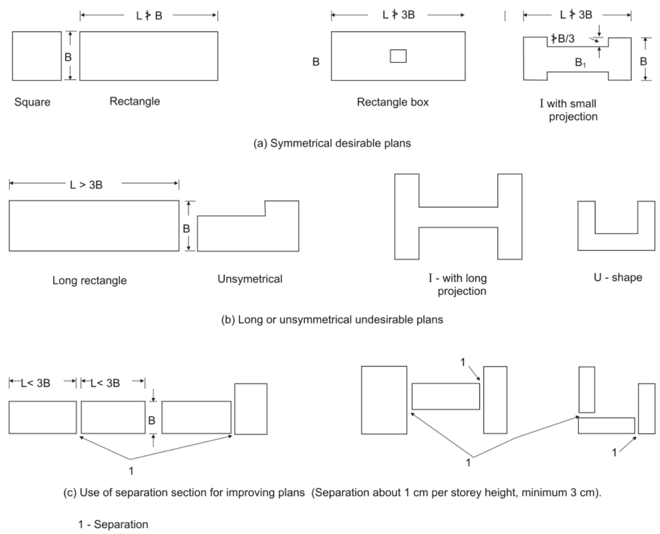


Figure 4; Plan of building blocks (Kaikan, 2004, pp. Ch. 3, p.4)

A . I.I
The church of Bedum

A goal for this paper is to find a solution to reinforce a monument with japanese wood techniques. To apply a reinforcing structure we need to understand the characteristics of the building itself. Every monument is different and acts differently to earthquakes, so to have a better idea about how it really reacts we need to choose a building to make the problem as visual as possible.

Not far from the epicenter of the earthquakes in Groningen I choose the Church of Bedum to attend.

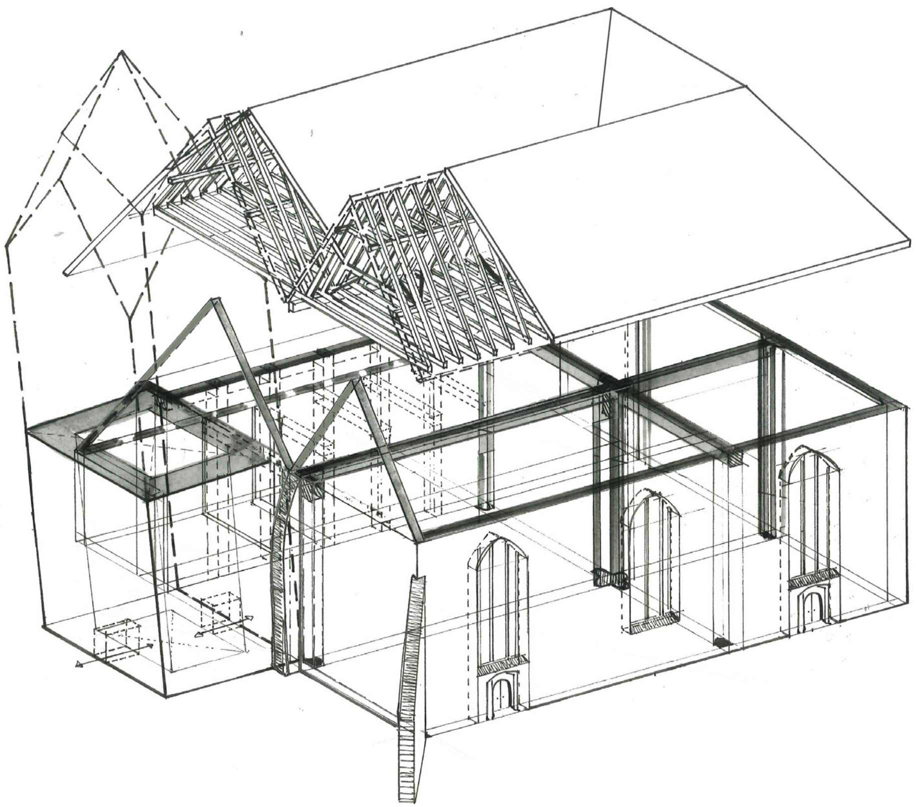


Figure 5: Illustration; Exploded view 'Walfridus' Church (van den Brom, 2016)

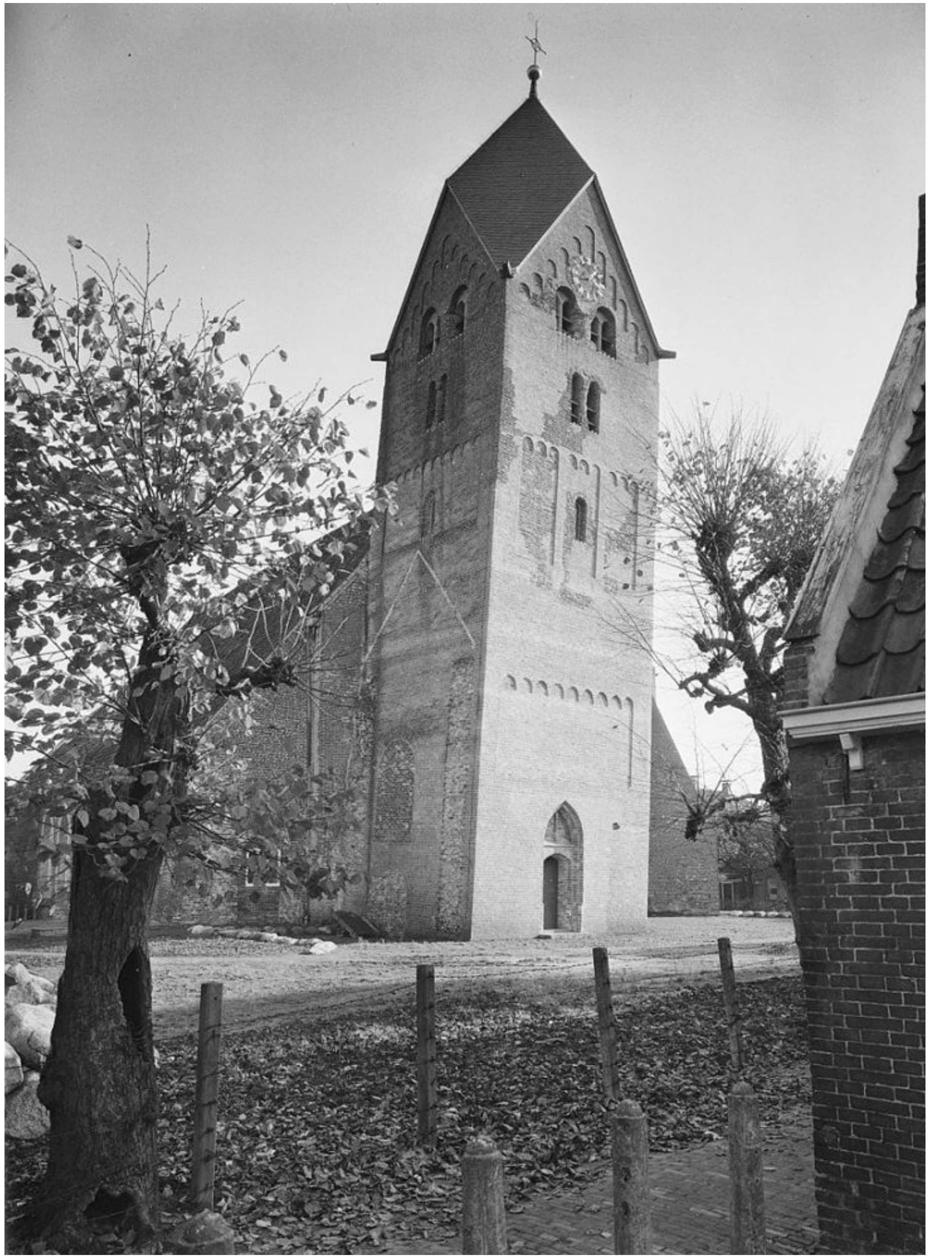


Figure 6: Photograph of the Walfridus Church in Bedum (Delemarre, 1958)

A . I.II
Analysis of the church onto earthquakes

Looking at the church as a whole you can divide it into 3 components, the tower, the roof and the ship (which is also devideable into a secundaire component, the aisle),see figure 7. The unsymmetrical compositions of these three components, its weight and having no deflections between the different components will cause every component to act differently on seismic actions. Heavier earthquakes than we have had in the past were not strong enough to do any critical damage. But looking at the predictions in seismic events we should be more critical to this problem. You can see in the right drawing that the tower will move differently than the rest. With its heavy body and long distance from the ground it will try to seperate itself from the ship. The walls are so heavy because they are a meter thick so one would think that this oversized building is stiff enough in all directions and against rotating. Seismic design needs a bit of flexibility, the stiffnes and weight of the wall ensures actually little flexibility so this type of structure is behaving poorly to seismic events.

The few next pages will be addressed to the reactions of the wall in seimic behaviour, the tower will be left aside. Figure 9 to 8 are analysis from the last reactions of the church onto seismic events.

In figure 6 is shown that the walls are tearing, with cracks through the stones. Cracks in the ceiling from the moving roof, because the roof is not really fixed onto the walls so that it moves by its own. The pink shade shows the biggest problem: The foundation is moment fixed onto the wall. This is a very stiff connection it will cause to cracks in the wall brick can not take tension stresses.

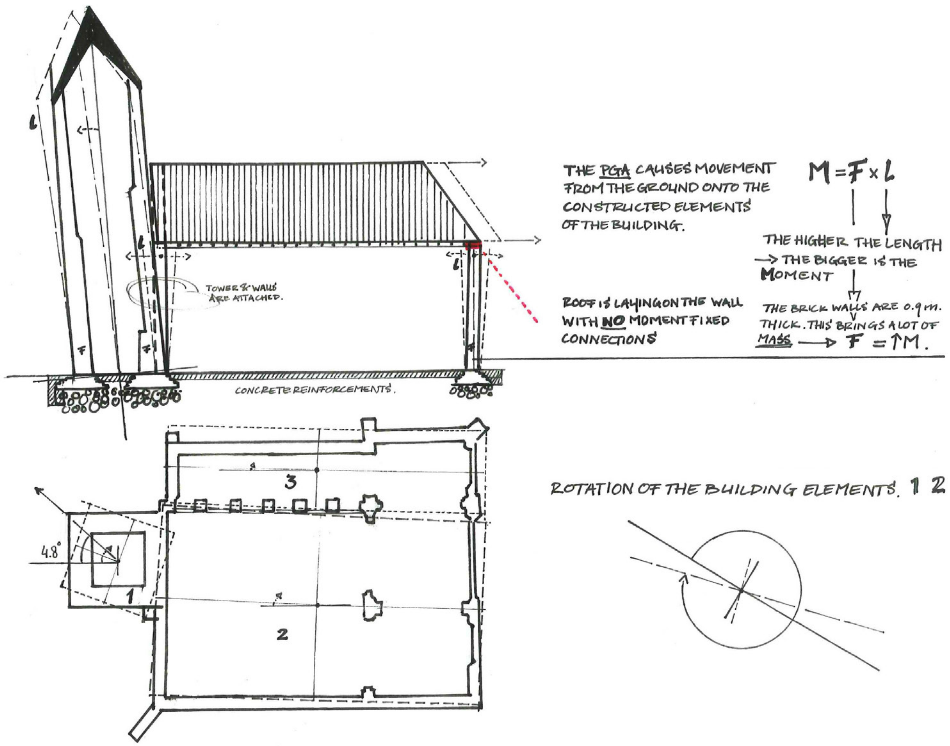


Figure 7: Illustration; reactions of the church onto seismic events (van den Brom, 2016)

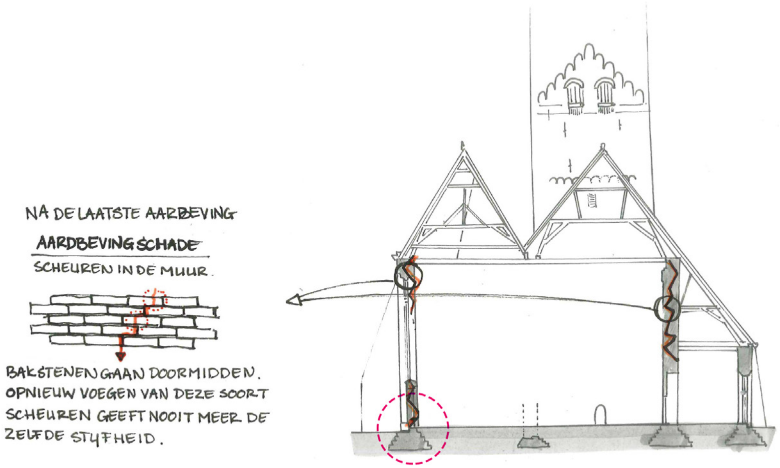


Figure 8: Illustration; rections of the chruch onto seismic events (van den Brom, 2016)

The connection of the roof onto the wall (figure 9) is an imposed connection and can not transfer momentum, maby very little. This means that the roof can move on its own, see figure 10. The only damage that the roof causes is little tensile stresses onto the wall due to the sliding.

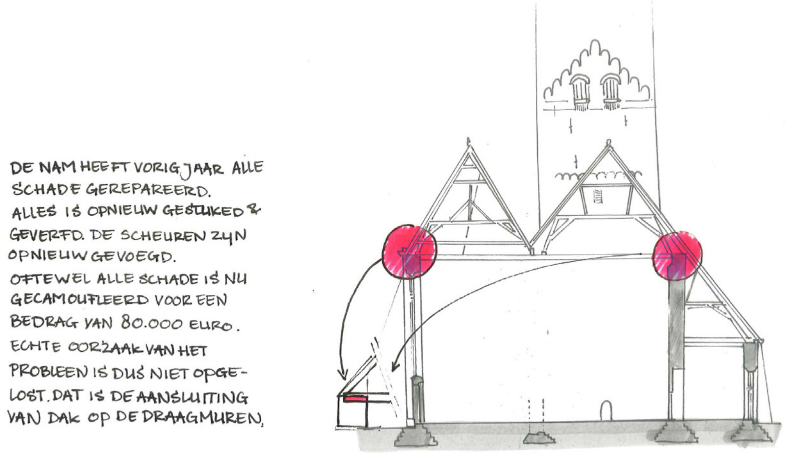


Figure 9: Illustration; reactions of the chruch onto seismic events (van den Brom, 2016)

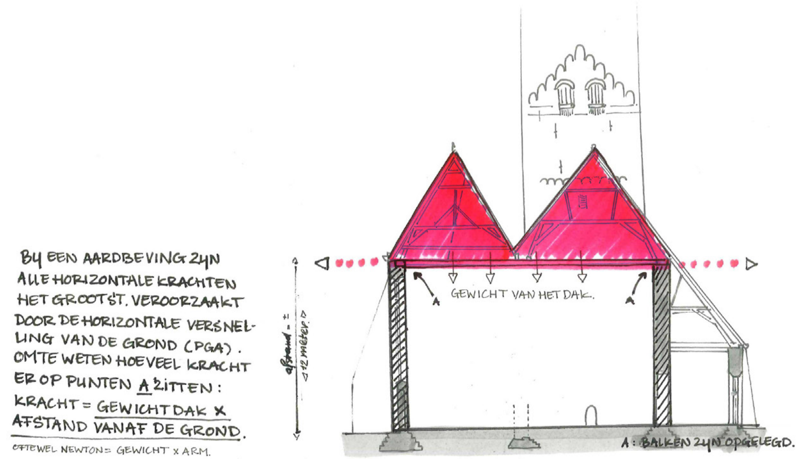


Figure 10: Illustration; reactions of the chruch onto seismic events (van den Brom, 2016)

The drawings in figure 11 show us how the church transfers horizontal loads to the foundation. This is done mostly trough moments. The walls longitudinal to the load are withstanding most of the load. This is due to the fact that the moment of inertia is much larger for walls in that direction than the walls perpendicular to the force. So they can withstand moments much better. So in the x- and y-direction other walls are used to withstand the horizontal forces. One can see that there are much more walls in the y-direction, than in the other direction. Also the gap between the walls in the x-direction is so large that horziontal forces in the middle of the churge will have difficulties to find their way to the foundation. Therefore we can assume that especially the x-direction needs extra attention to make it seismic proof. To improve the capacity of this structure we need to increase its moment capacity. This can be done by increasing the moment of Inertia or by adding material with a much larger E-modulus than the walls.

$$\mathbf{M}_{capacity} = \mathbf{E} \times \mathbf{I} \times \mathbf{K}$$

E-modulus

Moment of inertia

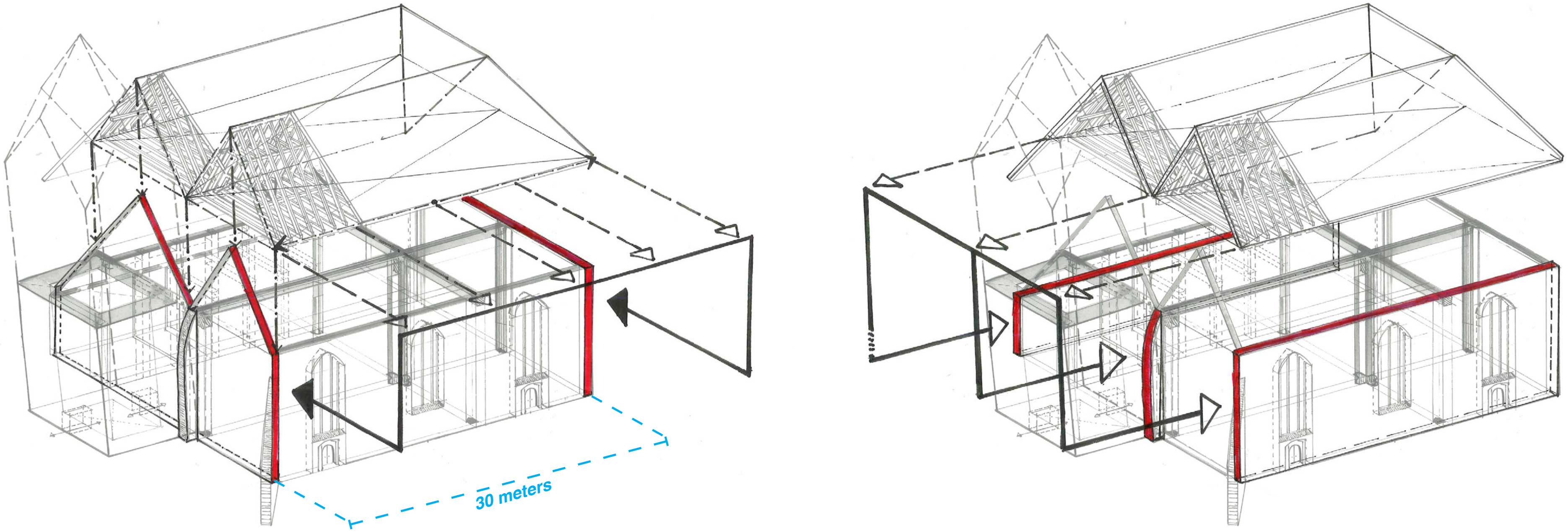


Figure 11: Illustration; reactions of the chruch onto seismic events (van den Brom, 2016)

A . II
Analysing how existing (scaffolding) reinforcing structures coop with seismic events, with a couple of examples

When an earthquake occurs and a building is in a critical state, engineers come up with quick actions to reinforce a building. These actions are engineered properly but add no architectural value tot the existing building. It actually lowers the visual quality as can be seen in the pictures below. It is clear that the structure is placed without considering the visual appearance, but only taking into account the safety of the building. In the following chapter is shown how the reinforcing structure works and how its meets the demands in earthquake design.

The structures that are made to reinforce the walls above are made very stiff through the triangle form of the structure in two directions to increase its moment capacity, see below in figure 13. This is necessary because masonry itself is a very stiff element/material. When an earthquakes acts in the direction that is shown in figure 13 and 14, the highlighted constructed elements are taking over forces brought onto the wall, because the have increased the inertia character of the wall. However, masonry cannot withstand tensile forces, so corners are critical shown in (figure 14). All the reinforcing elements are made of wood, which gives the construction a bit flexibility. This is good. Because having a ductile connection between the masonry and the reinforcing elements, will cause the masonry not to crack instantly. If the connection would be stiff, the masonry would crack easily.

Figure 12: Pictures of a farm in Groningen that is scaffolded against seimic actions (Groningen, 2015)

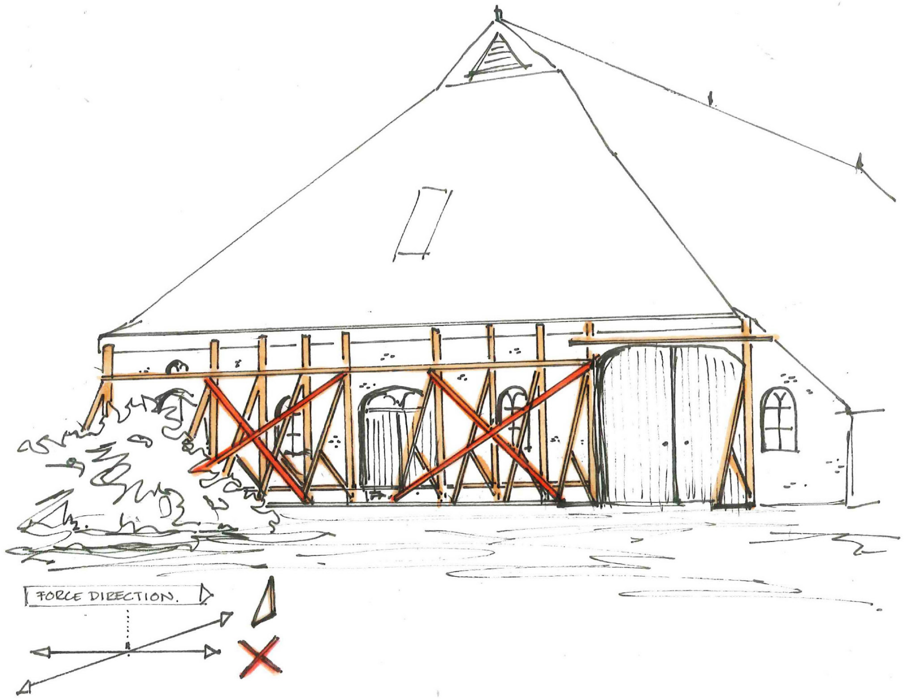


Figure 13: Illustration; Analysis low scaffolding structures (van den Brom, 2016)

In figure 14 below is shown how a little farm reacts to seismic events.
The drawing of the facade on the right, shows where cracks exists and through which forces and with what reinforcing elements you can solve these problems/cracks.

The tensile character of brick and mortar causes the connection in the corners weak. The walls aren't able to transfer a moment from one wall to another, because of the tensile stresses that will occur due to the moment. So forces cannot be transferred from one wall to the other, which causes cracks in the structure. This is shown when you follow the blue shaded arrow.

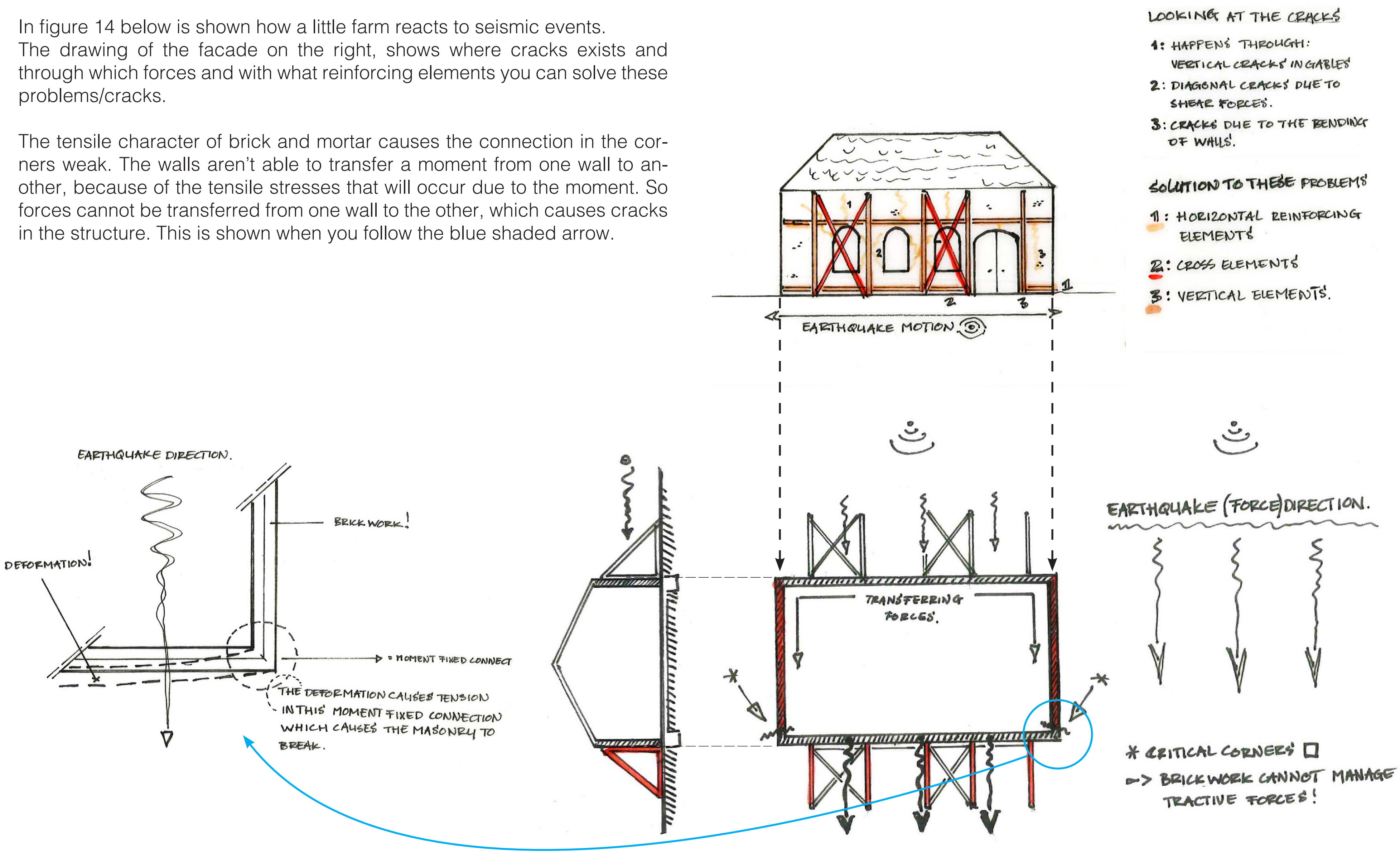


Figure 14: Illustration; Analysis low scaffolding structures (van den Brom, 2016)

The first example of the supporting scaffolding structure is made for small heights.

In the example below is shown that with higher walls, the scaffolding structure elements need to have bigger dimensions. Also, the structure is made out of more triangular shapes, to create more stiffness. One triangular is not possible anymore, due to local instability of the elements.

On the next page the two analysed examples are shown next to the churg, to show the scale of this project. The wall of the church is not only much higher, but also much thicker. Therefore, the church will need a much bigger scaffolding structure than the ones that were analysed. Unfortunately no example of this scale is already available (see figure 17).

Figure 15: Pictures of a farm in Groningen that is scaffolded against seimic actions (Groningen, 2015)

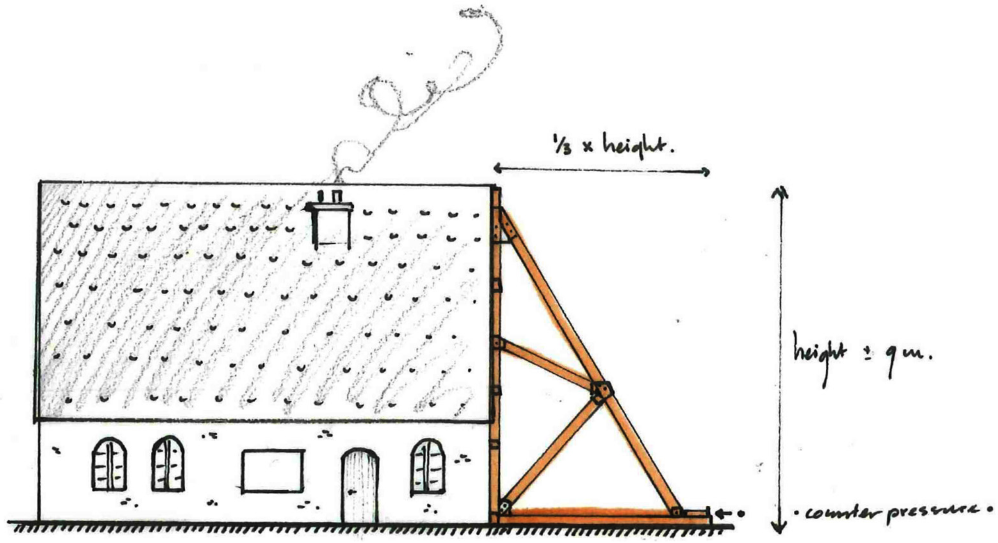


Figure 16: Illlustration; Analysis low scaffolding structures (van den Brom, 2016)

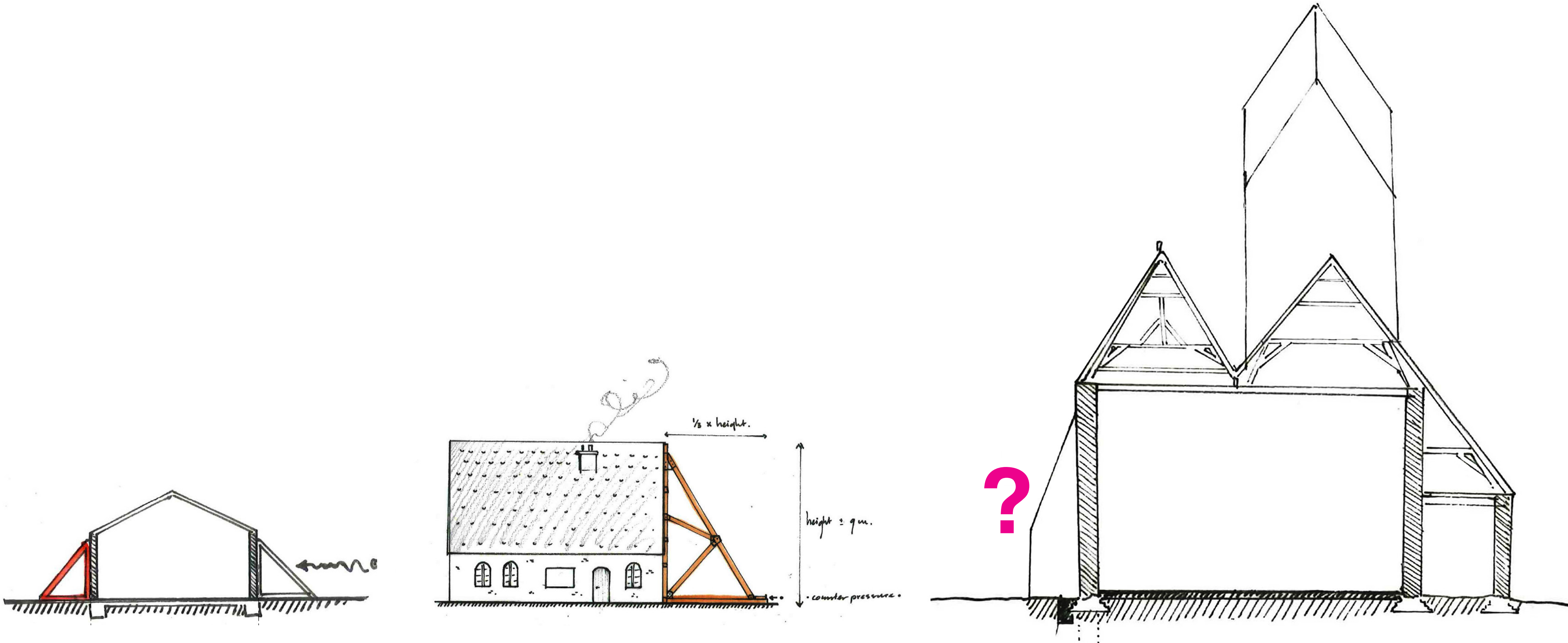


Figure 17: Illlustration; Analysis low scaffolding structures (van den Brom, 2016)

A . III
What are the characteristics of timber that can be applied in to seismic design

Monumental buildings have developed a certain character over the years. Applying a new construction onto a old brick building causes tension between the old and the new. Wood is an interesting material that can communicate well with old materials like brick. On one hand, this material is used for decades and therefor one is used to see these two materials together. On the other hand is wood is a modern material that has multiple new applications, since we've come to understand this material very well. Therefor it is the perfect material to add something new that is in line with the old.

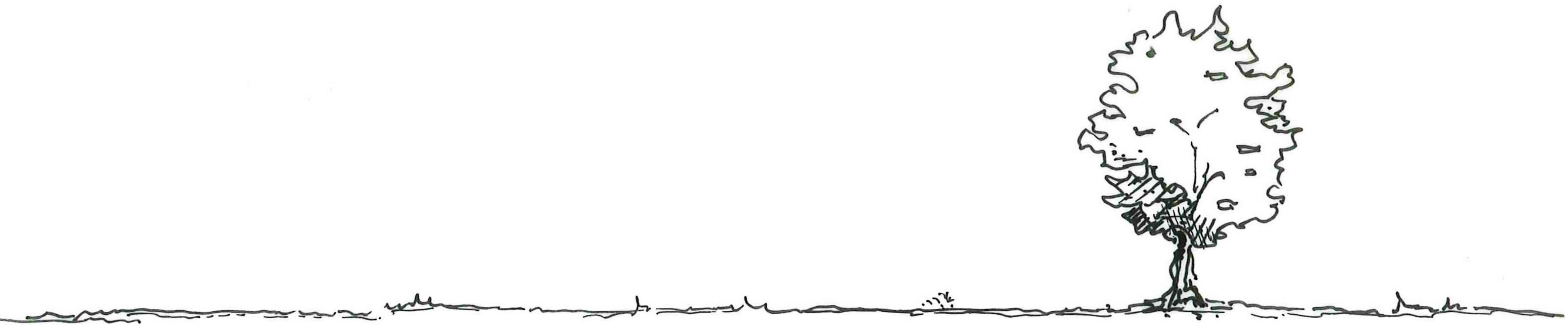
The scaffolding structures used in the previous chapters is made of timber. This paper is about turning the scaffolding technic into a Japanese technique. How this can be applied and how to understand the Japanese better in their techniques, we need to elaborate the material timber first.

Wood has already shown that it has great qualities for earthquake design. In Japan they got their traditional techniques and in California America they just made it a standard method to deal with earthquake design.

The prominent advantages of wood is that this material can be very light in weight in comparison to its strength. The light weight combined with the high damping behavior of wood, is the reason why this material is chosen so often to help in earth quake design. In Earthquake design you want to avoid the failure with brittle behavior. Wood can not behave as ductile like steel can, because it shows little warning before it breaks. However ductile behaviour can be enhanced by adding steel members. Also the characteristics of wood can be enhanced, by cutting it in pieces and glewing it together. An example is CLT wood. Cross Laminated Timber.

An important notification in building with wood, is that its behavior is very sensitive to moisture content. Therefore, wood must be well protected from rain or pre-treated with an protection layer such as Ecoleum.

The following chapter will explain the characteristics of timber and how the Japanese techniques are designed to use the characteristics of timber into seismic design.



A . III
What are the characteristics of timber

Timber is an interesting material due to it complex characteristics. The complex behavior of the material is following from the fact that wood is not build as a construction material, but it is build to function as a tree. Therefore, the transport of water from root to crown is the main influence in the structure of wood fibers. By understanding the structure of timber, this material can be used in its most optimal way. Below is a picture of the structure of wood, from large to small scale. In the following paragraphs this picture is used to describe the characteristic structural behavior of timber.

A. Structural wood (see figure 18 and 19)
Timber elements are of trees and a tree has 3 main directions. The longitudinal directioin, going from root to crown. The radial direction going from the centre to the perimeter of the trunk And the tangential direction, which follows the direction of the rings. In these three directions the wood has different material and mechanical properties, because a tree uses these directions for different purposes. The strenght of the wood is the highest in the longitudinal direction and in that direction also the expansion is the smallest. In the following paragraphs is explained why this is.

The characteristics of a timber element is highly dependent on faults in the wood, like knots. These faults can cause huge local differences in the characteristics of the timber.

Two main types of wood can be distinguised: hardwood and softwood, for timber elements mainly softwood is used. This wood grows fast and is less expensive.

B. Clear wood (see figure 18)
The centre of a tree is different from the rest. When the tree is young the wood has different characteristics, so this part is called the juvenile part. After a few years the tree is 'volwassen' and the charachteristics of the new layers are changing. The new wood (rings) that is created is made of heartwood. This is the biggest part of an adult tree and also the strongest. Sapwood is the part close to the perimeter of the trunk and after a few years sapwood is turned into heartwood. In timber mostly heartwood is used.

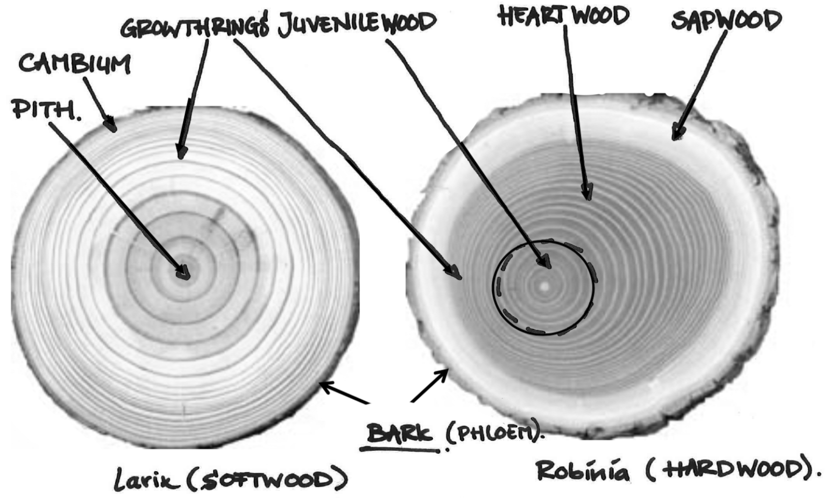


Figure 18: Illustration, Wood structures (van den Brom,2016)

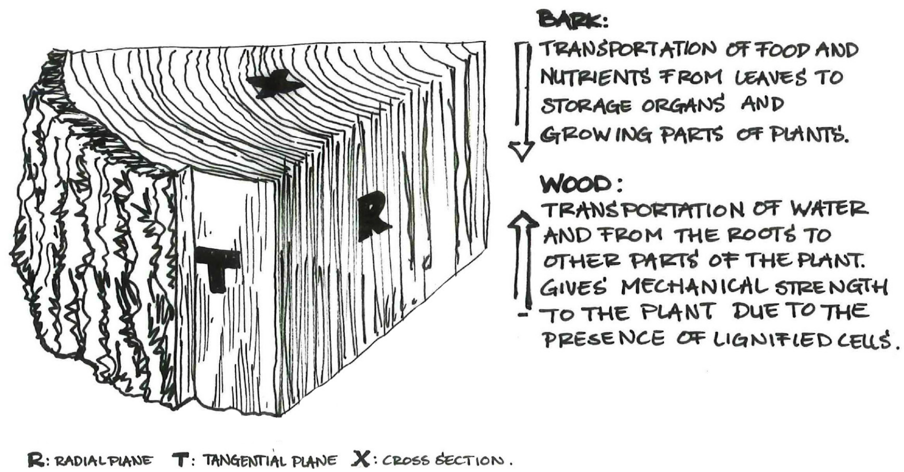


Figure 19: Illustration, Wood structures (van den Brom,2016)

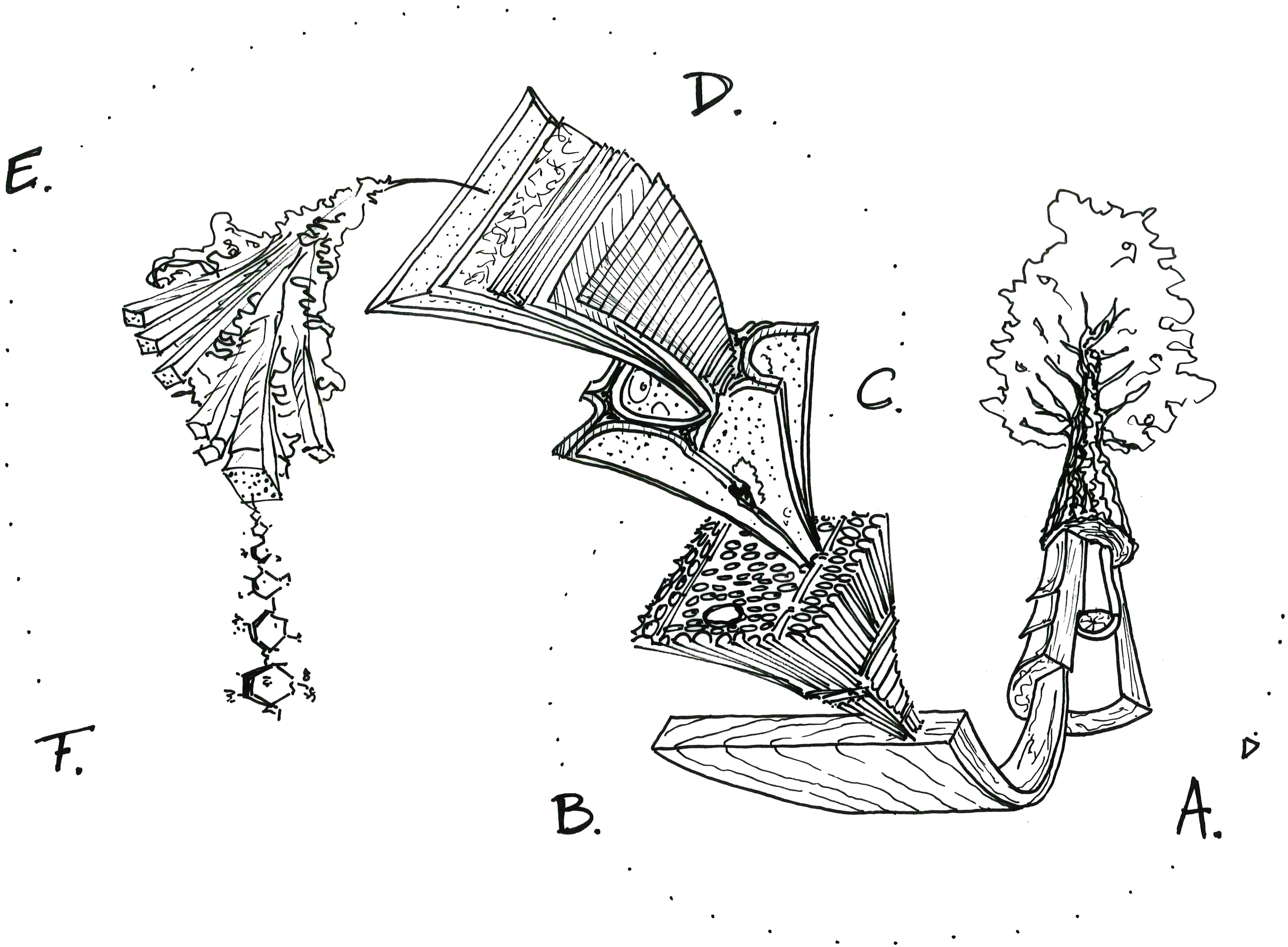


Figure 20: Chain of wood structures (van den Brom, 2016)

C. **Fibres** *(see figure 21)*

The stability is enhanced through the vains of the tree. In hardwood the vertical oriented vains are called vessels, they bring water from the roots to the crown. These vessels makes the tree strong in vertical direction. The stability perpendicular to the vessels are made by the rays, showed in figure 21. Resins is transported trough these vains to keep the tree healthy from any acid.

D. **Cell Walls** *(see figure 22)*

Cell walls found in the fibres of the tree also contributes to the strength of the tree. When the molecule transfers water through their vains, these molecules will expand. The direction of this expansion from these cell walls gives a certain stabilty factor. The biggest expansion finds its way into the x-axis. The y-axis is the strongest because the molecule finds strengt in the length direction showed in figure 22 .

E. **Fibrils**

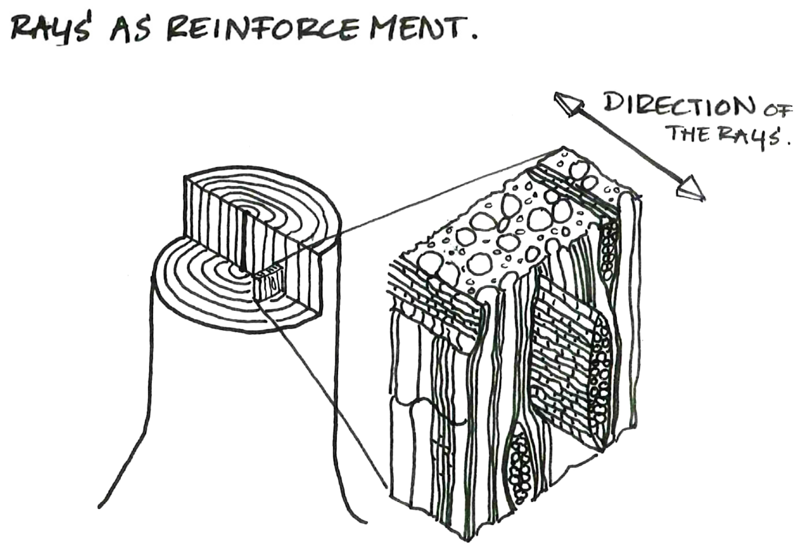


Figure 21: Illustration, Wood structures (van den Brom,2016)

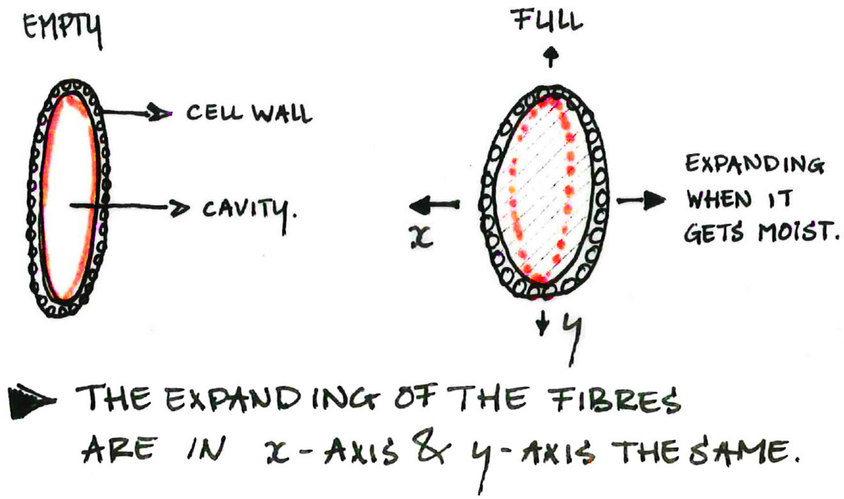


Figure 22: Ilustration; Analysis of timber cells (van den Brom, 2016)

F. Molecules

The chemical composition of the tree is reduceable into 3 different components: cellulose, hemicellulose and lignine. These componentes gives certain mechanical properties to the wood.

Cellulose: Characterised with a long chain of atoms (molecules) that can provide the material with tensile strength.

Lignine: A more complex molecule that gives timber a certain pressure strength and protects the tree from infestation like fungi.

Hemicellulose: Are also characterised with long chains but more ramified and shorter than cellulose

You can compare these aspects with reinforced concrete. Cellulose as steel, lignine as concrete and hemicellulose as concrete.

Lignine is darker of color than cellulose, so you can see which parts of the wood contains more lignine than cellulose. In the yearrings this is shown because the composition of wood is different through out the year.

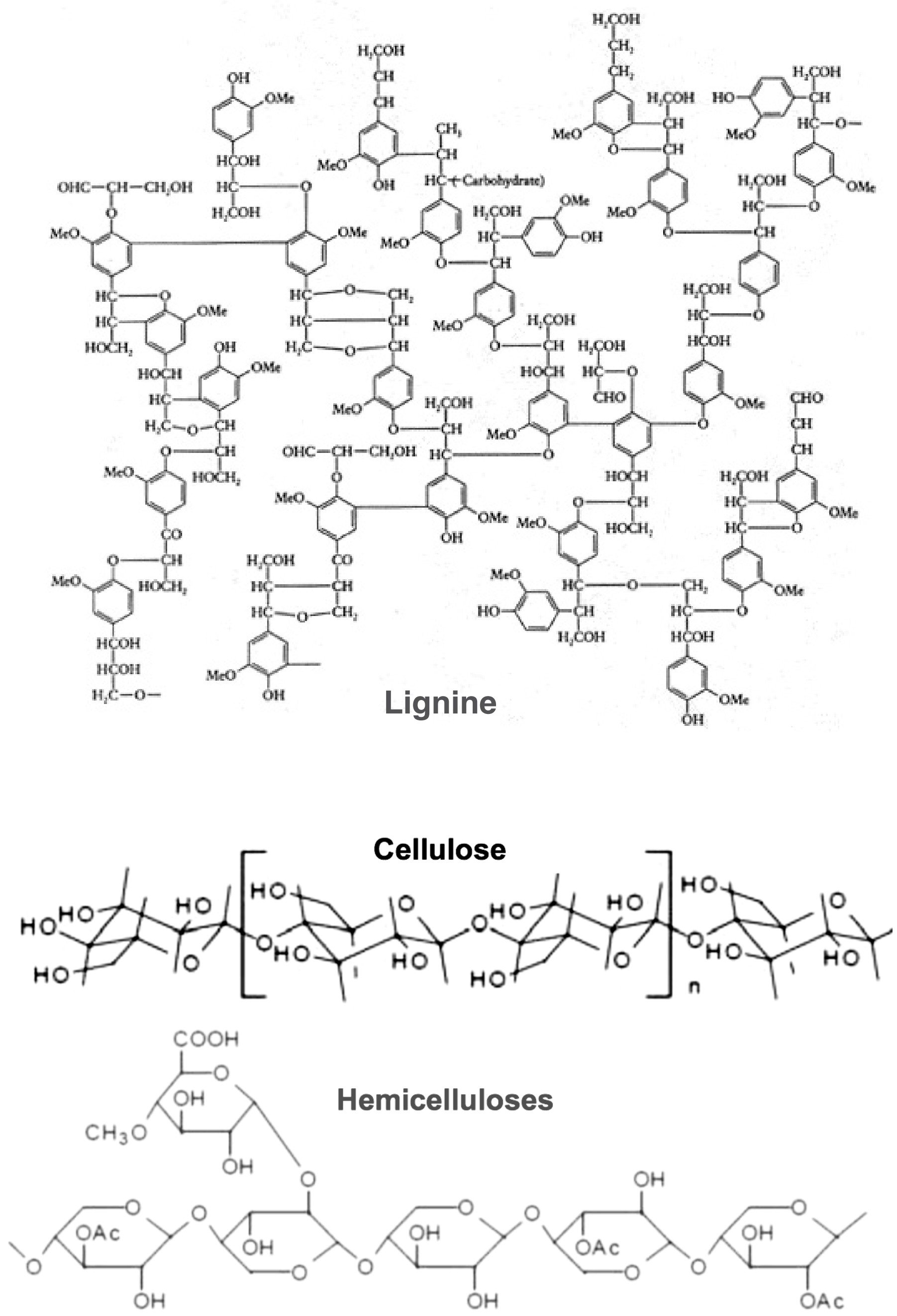


Figure 23: Ilustration; Cells structure of lignine, cellulose and hemicellulose (Gard, 2014)

Japanese wood techniques

The Japanese have mastered their struggles over the years dealing with earthquakes. Only using wood as a material they developed techniques that can withstand heavy seismic events. They are able to find strength and ductility by only designing the connections in wood. After doing analysis in seismic design in Japan, these technics became a fascination and will be further elaborated to find out if these techniques are able to use in seismic damage preventing structures. The Japanese use these techniques: to build very labor friendly; working with only one material, to build on site with elements that fits in each other and use connections that can be made with simple tools and no engine.

There are many different sorts of Japanese techniques but they all have the same character when it comes to earthquake design. The quality lays in the material itself. Wood. As told previous in this paper, timber has a flexible behavior. During earthquakes timber connections will push into each other. In figure 16 below is shown how embedment arises. The explanation about timber in the previous chapter shows us that embedment is created by pussing into the x direction of the timber cells, perpendicular to the grain direction. This embedment causes little space between these connections which make it more flexible to any ground-acceleration, wind etc. so it withstands high peak stresses vs strain (tension). The more embedment you create in a connection the stronger and stiffer its connection can be.

Will this be enough to strengthen a masonry wall?

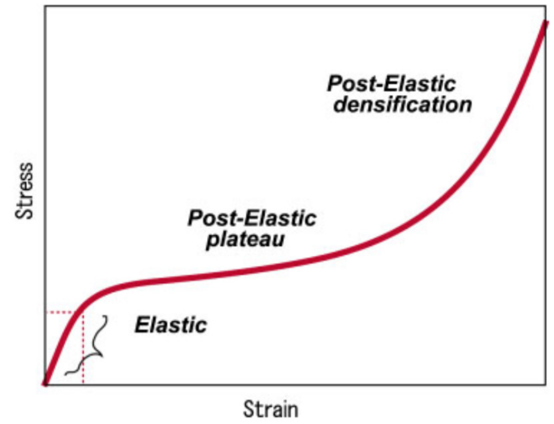


Figure 24: Stress-strain curve of timber subjected to compression (Takhesi, 2008)

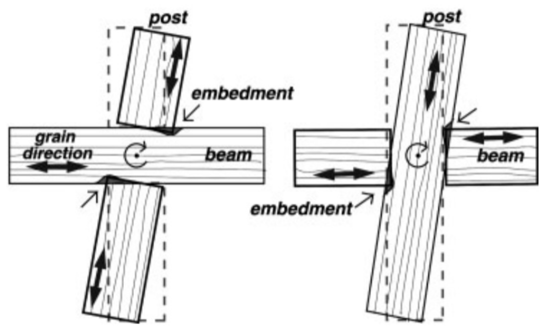


Figure 25: Grain direction of timber and embedment (Takhesi, 2008)

Two different joints shown in figure 26 the 'Stepped Dovetailed splice' (A) and the 'Stepped Gooseneck splice' (B) are elaborated to understand how a joint works and how it works while transfering loads. In figure 27 the differences are shown between two joints when it comes to the amount of embedment that is created. Joint A has just 4 angles in its connection and it can only put pressure perpendicular to the grain-direction on 4 places (creating embedment), this is caused by forces onto these joints, showed in figure 27. Joint B shows more angles, this means that this joint will be stiffer because of the better embedment. Figure 28 tells us how many shear forces a joint can handle. The bigger the blue shaded volume the more shearforce it can take, the more momentums it can handle.

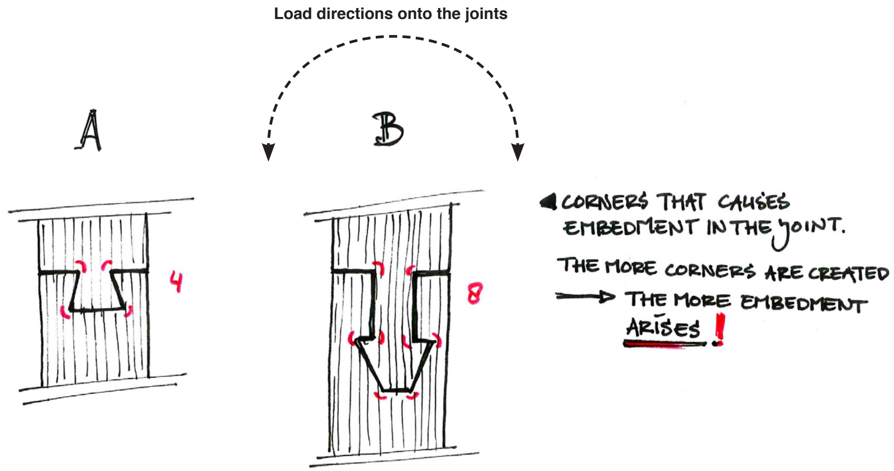


Figure 27: Illustration; Embedment of the joint A and B (van den Brom, 2016)

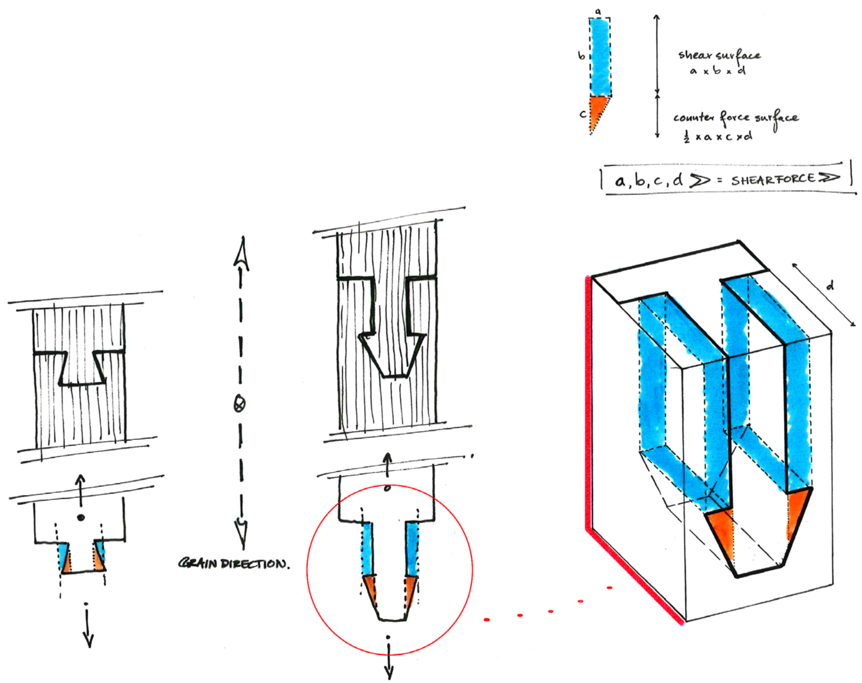


Figure 28: Illustration; Technical character of the joint A and B (van den Brom, 2016)

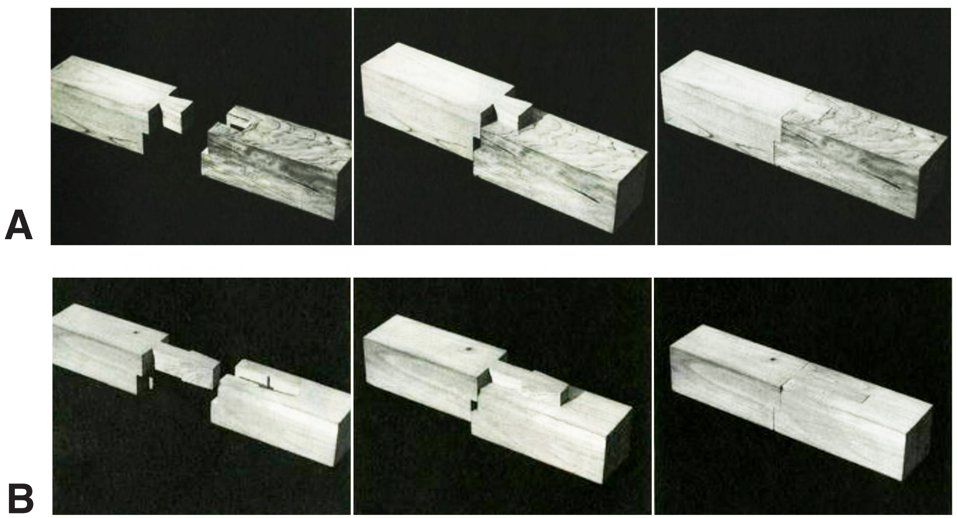


Figure 26: Japanses timber joints: A = ***Stepped Dovetailed splice*** **B =** ***Stepped Gooseneck splice*** **(T. Sumiyoshi, 1989)**

III
Results

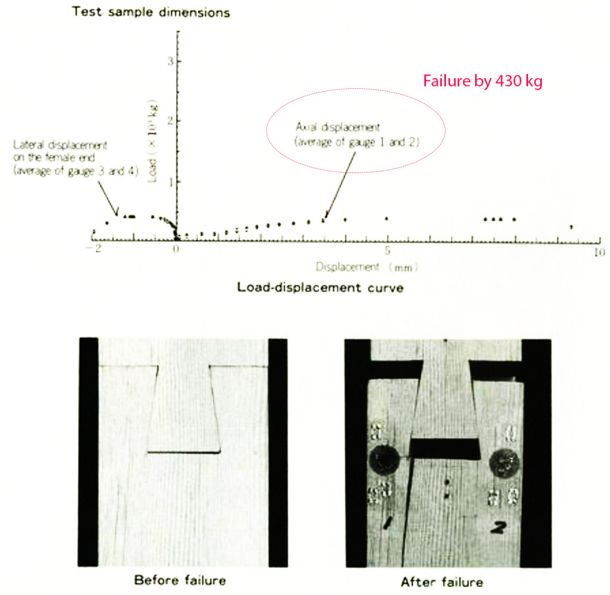
R . I
Results of the different Japanese joints

The elaborated joints are tested for the amount of bearing (1) and shearing (2) loads. Both have the same perimeter, material properties and the same amount volume.

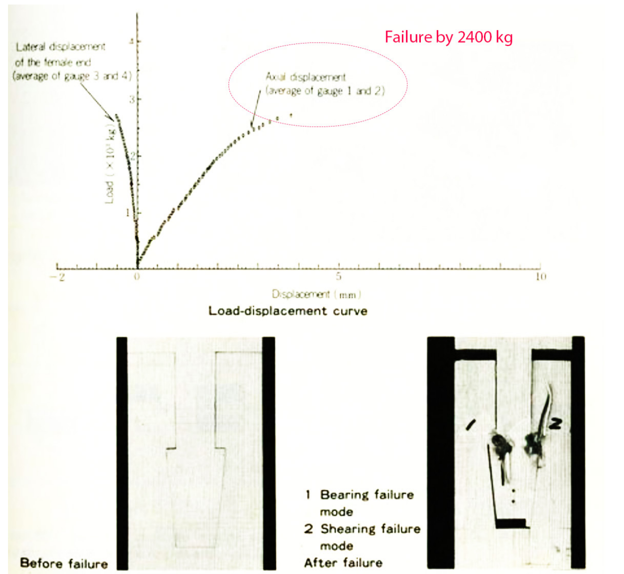
Joint A was not able to coop with more than 430 kg and Joint B failed with 2400 kg. That is a big difference by only changing the way of the connection form. But will it be enough to coop with seimic behaviour of a building like a church. Joint B is till not able to transfer th forces of such a heavy element like the walls of the church. So Japanese wood techniques are not the right choice for reinforcing brick structures

The height and amount of weight in a wall of any church of this era is just to big and to heavy. The timber will not be stiff enough to coop with seimic events in the church, this will be elaborated in the next chapter. As mentioned, brick buildings are stiff structures that show brittle behaviour. Adding wood on such great scale used with japanese joints will not improve its moment capacity unless the timber will be oversized aswell. Timber as material is to flexible to take over the loads of a stiff structure. To improve the timber elements one can add a material like steel to improve the E-modulus and stiffness.

If you would make a whole new building, chosing japanese wood techniques would be a good idea, but adding this technique onto something that already exists, a different material would be more adviseable.



A



B

Figure 29: Results in load bearing the Japanses timber joints:
A = *Stepped Dovetailed splice* **B =** *Stepped Gooseneck splice* **(T. Sumiyoshi, 1989)**

Which technique with wood can be applied to be a scaffolding structure?

R . II
Applying wood in this type of scaffolding structure

A scaffolding structure with such great height and with such amount of weight to withstand, will need a lot of wood. Supporting these walls with heavy timber elements in a triangle construction will not prevent the masonry from cracking. Looking at the characteristics, masonry is a lot more stiff than wood itself. So can wood by applied on such a heavy building that is a lot stiffer than itself? When a load goes through a construction, it always takes the shortest route through the stiffest connection. A timber construction can be stiff enough for small masonry buildings but not for bigger buildings like churches. Choosing a stiffer material like steel, will not prevent the cracking of the walls. Because steel is less flexible than timber, the cracks will occur around the connection of the steel and the masonry.

In the following drawing is shown how to deal with it using the existing approach on earthquake design.

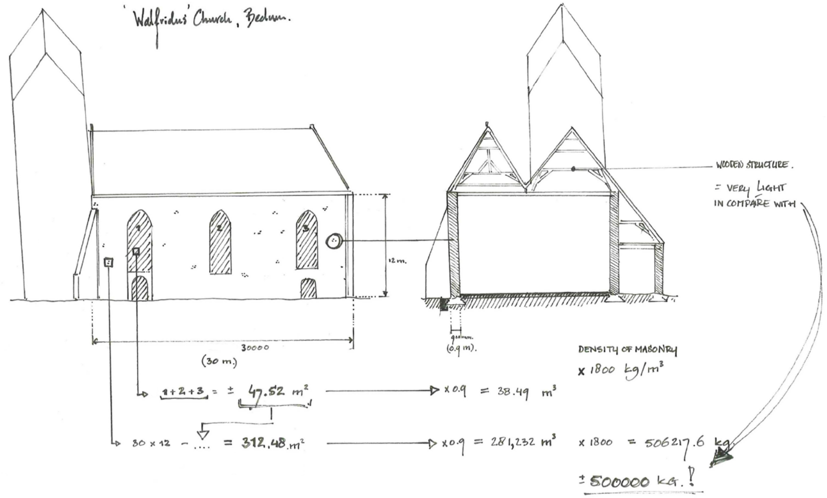


Figure 30: Own illustration; Anaysis weight of the wall (van den Brom, 2016)

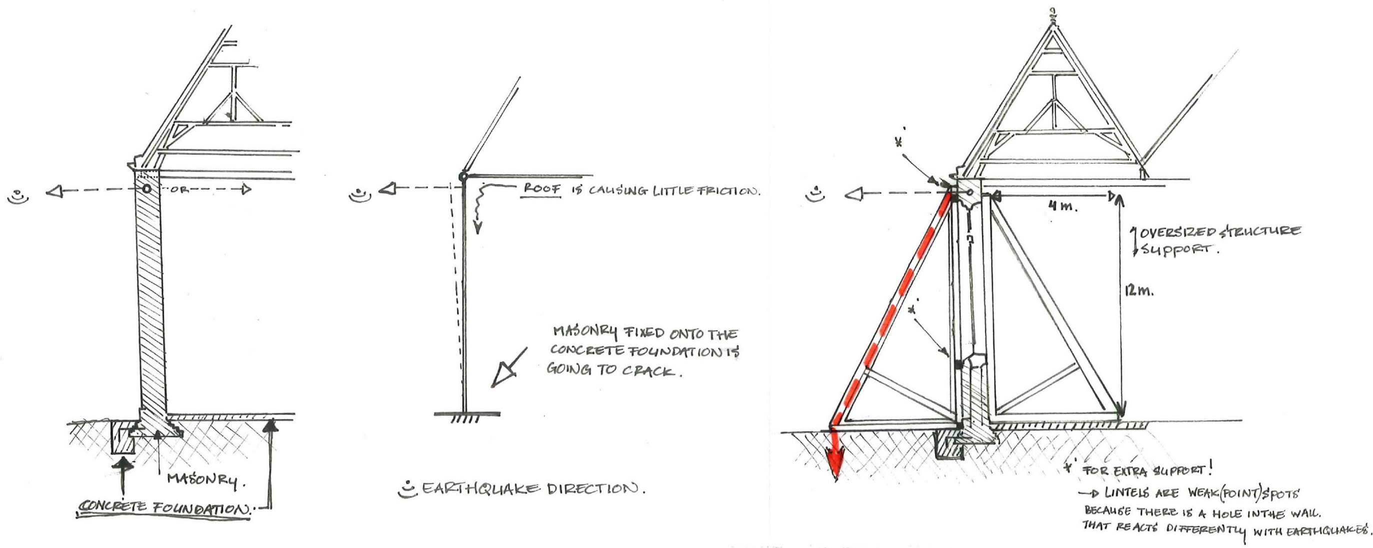


Figure 31: Illustration; Anaysis scaffolding structure onto the wall (van den Brom, 2016)

Knowing that these walls are going to crack anyway, why putting so much effort to prevent it. By adding vertical timber elements on both sides of the brick wall that clamp the masonry, this will keep the wall save from collapsing. Like bracing your leg while its broken.

The idea is to simplify a structure as far as possible, that will make the building save and still to try to obtain lesser cracks in the masonry, which can be done by using wood. By simplify is meant that the structure does not have to be as robuust as on the drawing in figure 32 on the right. This is explained on the right drawing with an analysis on how to react to seismic events in this type of structure.

The wooden flexibilty as a main character of this intervention could be enough to make the building save from collapsing. Arup explained that this addition of wooden elements every 3 meter will hold the walls together but will not prevent damage in cracking.

So this design will try to keep the building save from structural damage. This will be further researched by finding the right timber composition with additional steel.

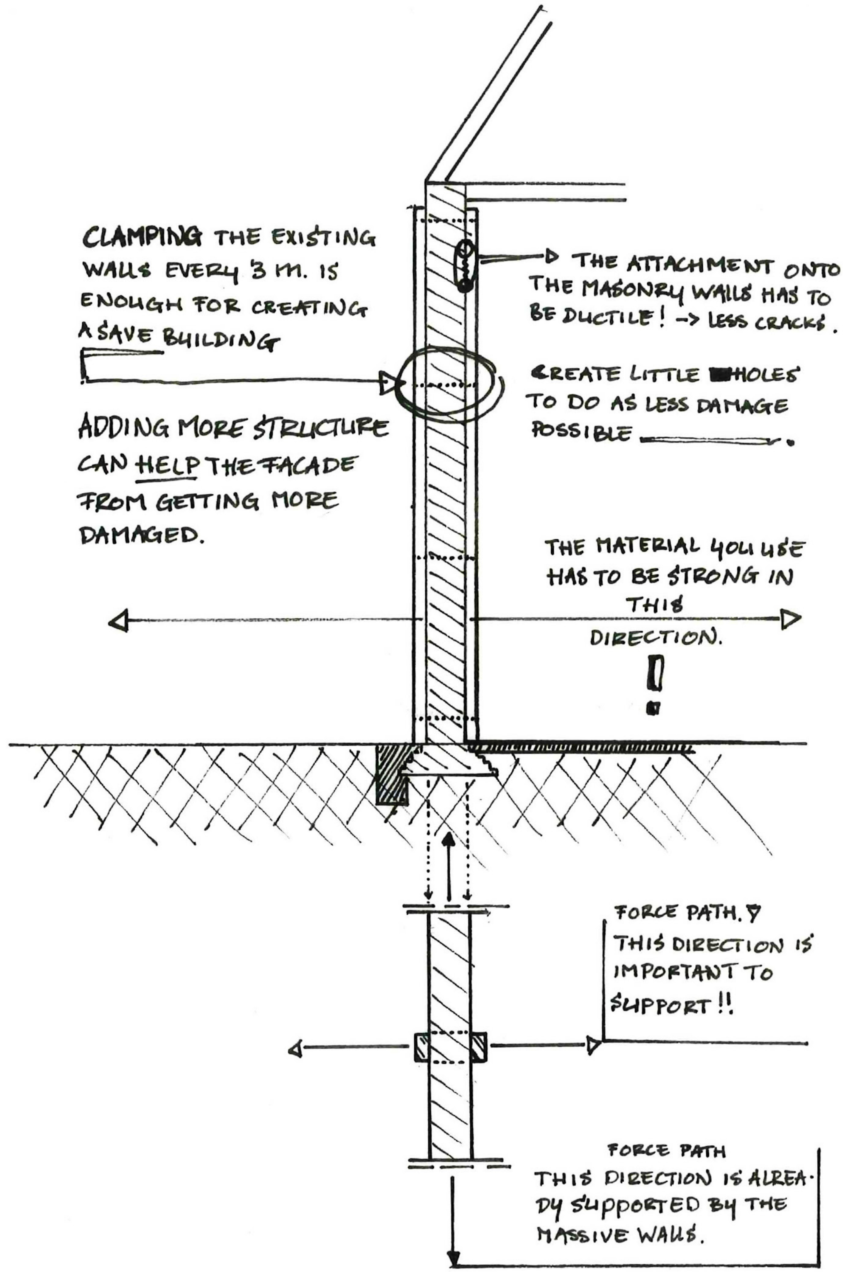


Figure 32: Illustration; Design idea structuring the wall(van den Brom, 2016)

Applying the right composition of wood in this type of structure, we need to understand how the forces flow through the existing structures.
You can see in the analyses in chapter A . I.II that the main forces are transfered in 2 directions, but has a certain weakness in one direction (see figure 11). This is shown in figure 33. So you need timber that has a strong character in one direction. After reading a lot in the *'Guidelines for earthquake resistant non-engineered construction'* they recommended cross laminated timber that is strong in 2 directions. Just laminated timber can be very strong in one direction. Laminated wood gets its strength and stability from the direction of the grain structure (vessels). When wood is cut and glued together with different layers on top of each other, the biggest strengt comes from the force direction perpendicular to the glued surfaces, plus timber finds also strength from the rays that are horizontal oriented. The strength of an laminated element is made stronger because the cut and glue of timber together removes most of the trees imperfections like knots.

As a result, this element is still very light in contrast to the load that it bears.

Wood that can be used in laminating, are most of the time just deal-wood (vuren) in class B or C or a combination of both. If it has to bear heavier weights deal-wood (grenen) is also just good enough. These wood types are very easy to work with and complies to the demands of sustainability, strength and stiffness. Other woods like coniferous wood or deciduous wood are not intended to be laminated, because they contain substances that complicates the glueing.

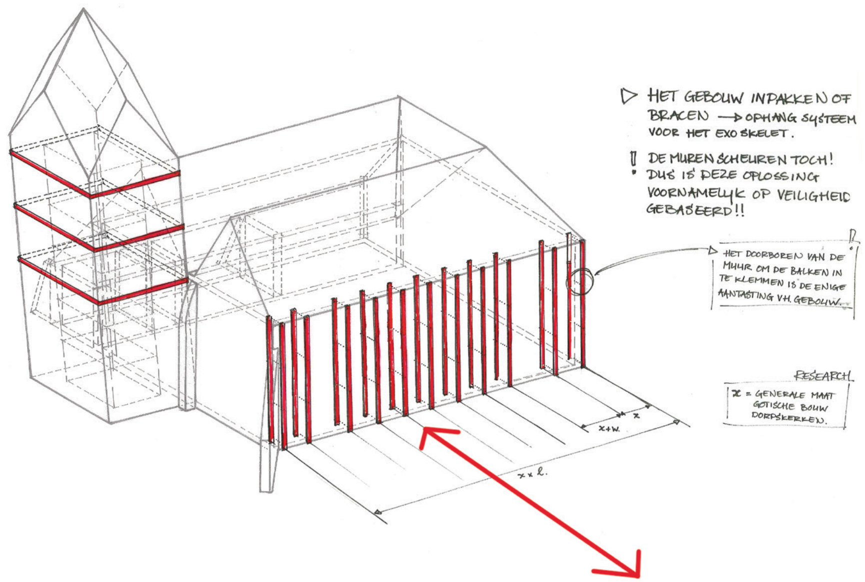


Figure 33: Illustration; Direction of the important load direction (van den Brom, 2016)

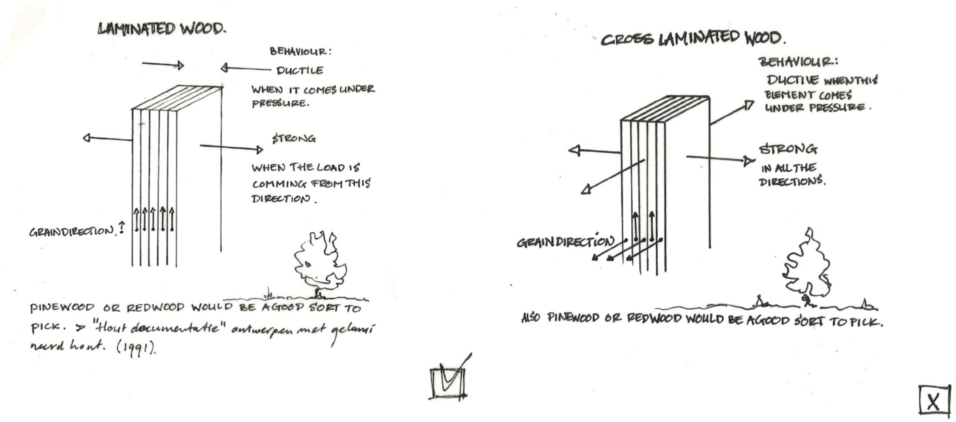


Figure 34: Illustration; Direction of the strength of laminated timber (van den Brom, 2016)

IV
Conclusion

To conclude this research paper, in this final chapter the most important conclusions are summarized.

A research was done to find the optimal solution for a scaffolding structure that will prevent damage on a church due to seismic events. This church is made of thick masonry walls, so the scaffolding structure needs to be very stiff, to be able to contribute to the baring capacity of the wall. The connections between the scaffolding structure and the stiff masonry wall need to have some flexibility, otherwise cracking will occur near these connections. Due to these two demands laminated wood is chosen as the best material to make the scaffolding structure with.

Japanese wood techniques were suggested, because they are used quite often in structures that are exposed to seismic events. In this case however, Japanese wood techniques don't seem to be the right solution. Because the scaffolding structure is used to protect a very thick masonry wall, it should be very stiff. The connections within the Japanese wood techniques are very flexible and they lack stiffness. That is why this solution is rejected.

Thus, to conclude this research paper, the following solution is proposed. For the scaffolding structure, laminated wood should be used. In the connections steel is used as well, to make the construction stiffer. This solution is stiff enough to provide enough help for the masonry wall to survive seismic events, although it will still not be enough to prevent the masonry wall from cracking at all. Small cracks are - in this case - not a problem, so this solution is satisfactionary for this church.

V
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