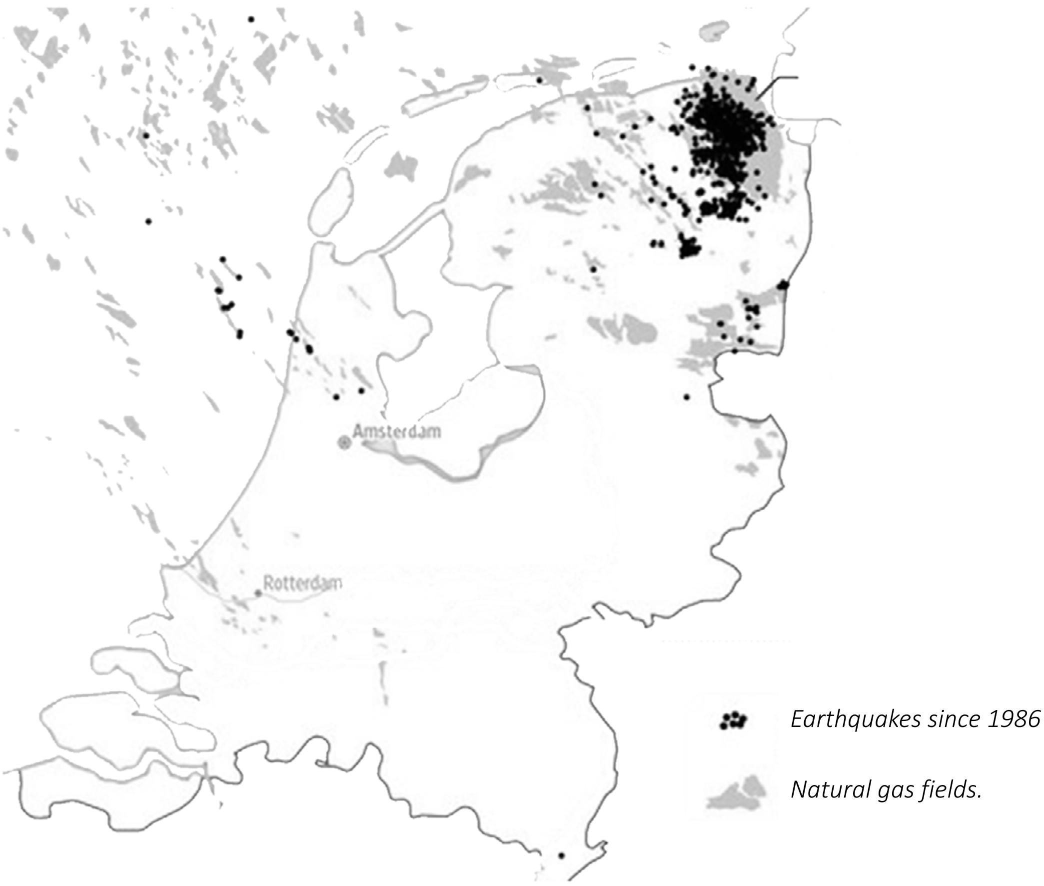
# SEISMIC - RETROFIT

*An more architectural solution to reinforce earthquake damaged masonry buildings and improve the existing architecture quality by using light-weight complementary. constructions.*




MSc Graduation
P2 Research Paper
Name: Zhenkun Zhang
4504399
Tutor: J. Schroen  Pierre Jennen

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|---|---|
| Name: | Zhenkun Zhang |
| Student Number : | 4504399 |
| Address: | Michiel de Ruyterweg, 2B |
| City: | Delft, 2628 BA. |
| Contact: | 31-615225304 |
| | zhangzhenkun07@126.com |

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|---|---|
| Title: | An architectural solution to reinforce and reuse earthquake damaged buildings. |
| Studio : | Architecture Engineerig |
| Group: | Seismic |
| Design Tutor: | Job Schroën |
| Research Tutor: | Pierre Jennen |

# Contents:

This is my research paper for my graduation at the Architectural Engineering studio of the TU Delft faculty of Architeture and the Built Environment. The research aims to find a seismic and architectural solution to retrofit earthquake damaged buildings in Groningen, which are mainly unreinforced masonry buildings. The paper is intended to function as a preparation for my graduation design, to open posibilities of retrofit buildings by wooden construction and make inspiration for the further project. I would like to thank my studio tutor Job Schroën for his adequate guidance and my research mentor, Pierre Jennen, for steering the research.

Zhenkun Zhang │ 4504399

# INTRODUCTION:

Abstract
Background & Problem Statement
Research Question & Methodologies & Relevance
Introduction of lightweight principle
Site Selection & Objective

*Figure 1:*
*Earthquake damage and retrofit intervention in Groningen.*

# 1.1 Abstract

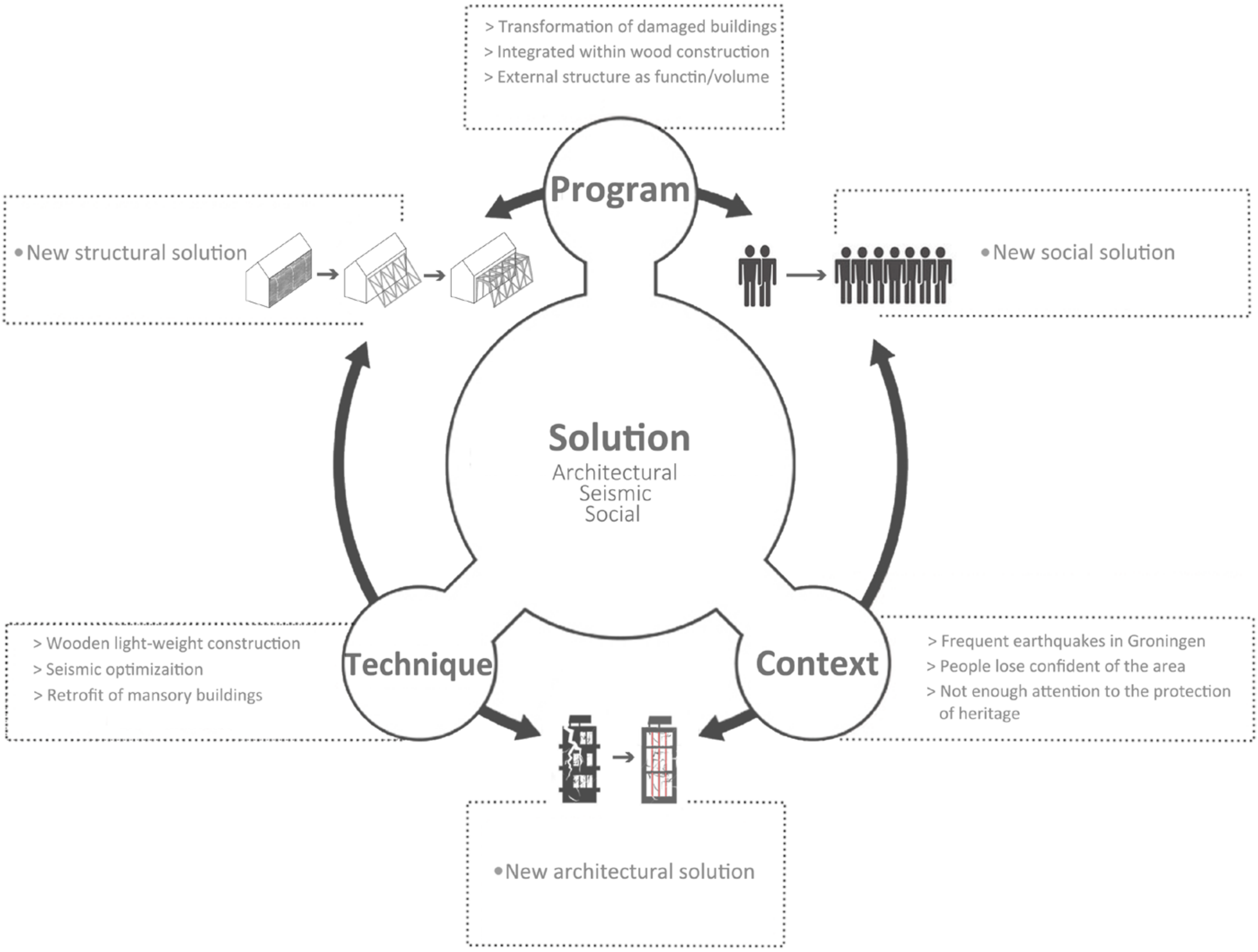


*Figure 2: Context, Program and Technology.*


**Key words:** Wood, Complementary construction, Light- weight structure, Seismic

As the seismic events in Groningen increased due to the extraction of natural gas, new retrofit strategies should be made to improve the existing stock of the damaged masonry buildings. Around 250.000 buildings are assessed (Arup, 2013) for potential strengthening in this area, which leaves the inhabitants scared and angry. This paper aims to find a seismic and architectural solution to retrofit earthquake damaged buildings, call back people's confidence of the area. On the other hand, it is expected the earthquakes will not last for more than 50 years, in order to make a removable restoration strategy, the research will focus on the complementary wood construction system as a light-weight, sustainable solution. The paper starts with the study of the earthquake damage on brick buildings --the Feasibility Analysis, follows by the optimization of light-weight wood structure and how to use it as a seismic retrofit solution. And then the assembling and optimization of spatial quality of the structural construction. Through this project, a complementary wood construction system will be studied and tested as a seismic and architectural solution to retrofit earthquake damaged buildings, to give guidance at the beginning of a restoration project, which can be furthermore proved as an example of retrofit of masonry buildings in the whole area and other areas with similar situation.

# 1.2 Background & Problem Statement


*Figure 3: Earthquakes & Damage & Restoration in Groningen.*

**Background**

Due to the extraction of natural gas, earthquake is becoming a more and more important safety issue in Groningen. In total more than 1000 earthquakes between Mo.2 and M 3.6 have been recorded since the first earthquake occurred in 1986, at least 100 thousand Groningen residents live in a home damaged by earthquakes in this area.[1]

Although earthquakes in Groningen are measured to be at low level of intensity, maximum of 3.6M, it still has a big impact in this area. First of all, they are caused by driling gas out of the soil, so the hypocentres lie at a depth of only 3 km, leads to a larger impact on a smaller scale. Moreover, most buildings in this area are not engineered for seismic resistance, unreinforced masonry is widely used in Groningen, which performs poorly during earthquakes. According to an assessment by Arup, more than 250.000 buildings in this area are potentially needed strengthening.[2] From this point of view, the greatest challenge at the moment in Groningen is to find a more appropriate solution to solve the structural problem caused by earthquake, a seismic and architectural solution to retrofit damaged masonry buildings.

Such disasters result in the people's losing confidence of the area, inhabitants are scared and anxious about their safety. And the population is decreasing year by year, especially the villages in the northern coast of Groningen, such as Warffum (suffered two earthquakes in 2012 and 2013, measured 3.6M and 3.2M), the population has decreased from 4000 after the war to currently 2500.[3] Besides,we have to take into account the coming years with heavier quakes, above the 4.1 - perhaps towards 4.5 or even higher.[4] New strategies to retrofit masonry buildings should be made to prevent further damage in the future,call back people's confidence of the area.

1 NLTimes.nl, Janene Pieters, 09, 2016

2 Arup, 2013

3 How Warffum was awakened Fri Netherlands, Louis Stiller,2015

4 Kamps, 2015

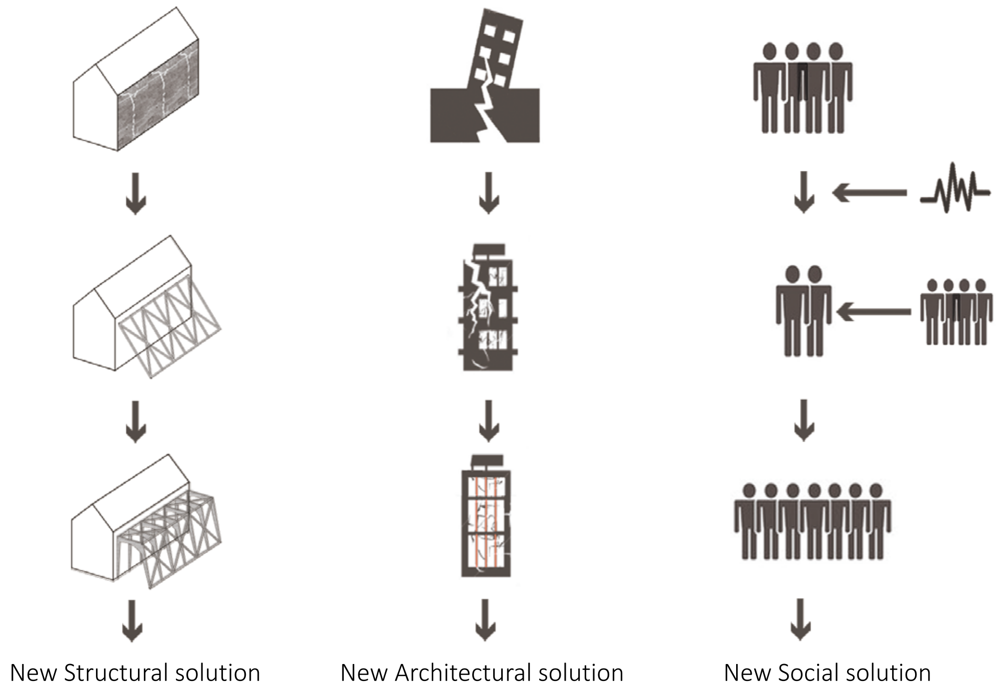


*Figure 4: Diagram of the key problems.*

**Problem Statement**

Structure Weakness
Frequent earthquakes in Groningen caused by Gas extraction.
Different degrees of damage on masonry buildings.

Architectural Weakness
Need more public facilities to ensure people's daily life.
Vacant buildings or new functional requirements.
Call back the identity of culture of Groningen.

Society Weakness
The area is now losing people -- people are losing confident of the area.
Not enough attention to prevent the damage in further quakes.
.

Building the new, or reusing the existing? As there are many masonry buildings damaged or threatened by earthquake, and it is expected the earthquake will not last for more than 50 years, I want to focus on the transformation of masonry buildings into new public space by using complementary wood construction. Also this area is facing a series of society problems. More and more people leave the place because their worry about safety issue, which leads to many vacant buildings and the lack of public facilities in this area.

In this case, the solution to deal with restoration in Groningen can not be merely based on engineering, a collaboration between architects and engineers at the beginning of the project is necessary to develope an appropriate solution not only seismic proof but also meet new social and functional requirements.

# 1.3 Research Question & Methodology & Relevance

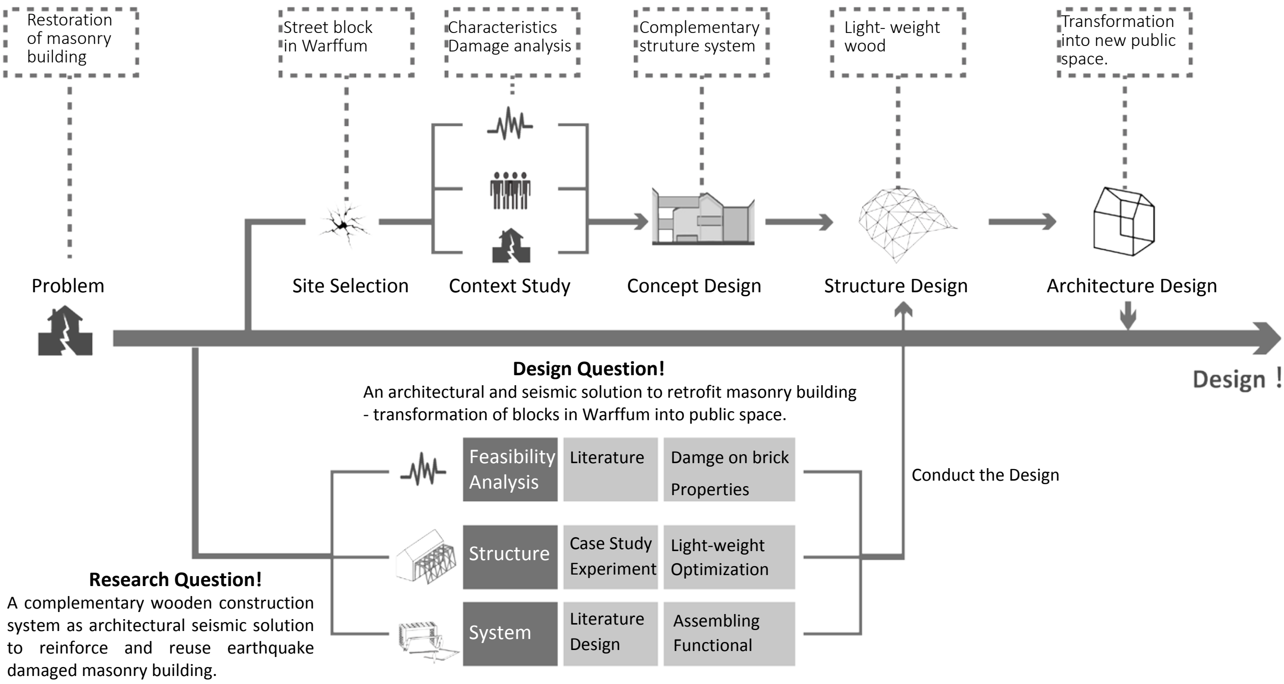


*Figure 5: Diagram of methodology and work flow.*

**Research Question**

A light-weight wood complementary construction system as an architectural solution to reinforce and reuse earthquake damaged masonry buildings.

**Relevance**

Through the understanding of how to integrate a wood complementary construction as reinforcement with in a masonry building, the research could provide possibilities of a more architectural solution to deal with the earthquake problems in Groningen, and inspirations on how to make a light weight wood construction more makeble and efficient.

The research focus on the optimization of wood light-weight structure as a seismic solution, and the functional potential of a structural construction as a architectural solution. The whole construction system could work on different scale of masonry buildings based on the analysis of different context, and be furthermore proved as an example of retrofit of masonry buildings in the whole area and other areas with similar situation

With the study of structural behavior and the optimization of light-weight wood construction, the research could support further design with more inputs of engineering knowledge, give guidance at the beginning of the design of a restoration project.

# 1.4 Introduction of lightweight principle

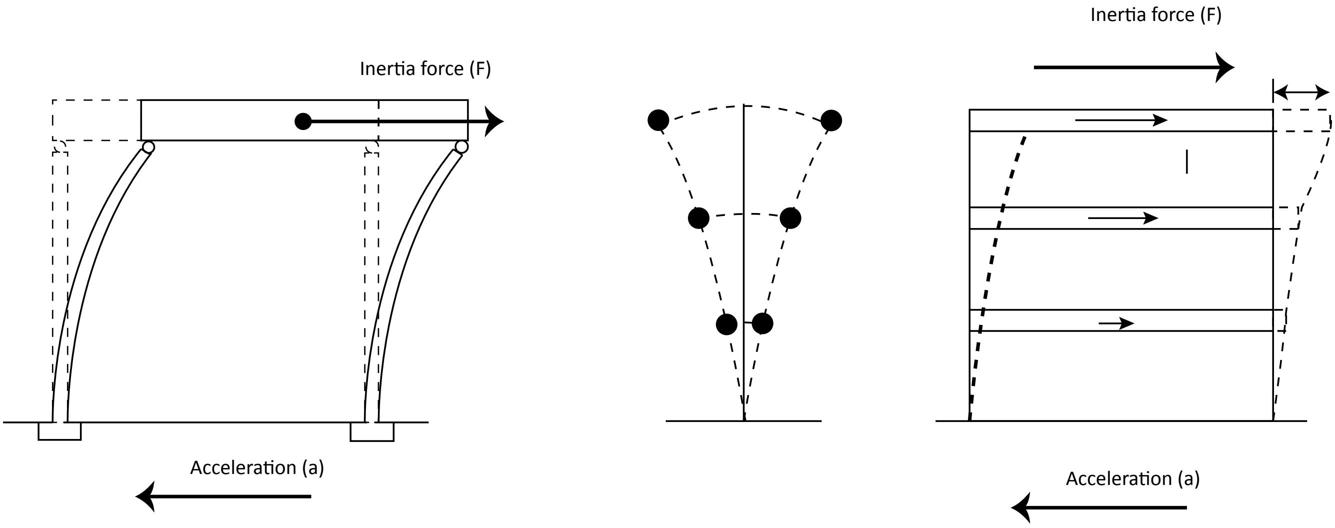


*Figure 6: Seismic force generated by masses vibrating.*

**Seismic force**

Seismic forces are inertia forces. When any object, such as a building, experiences acceleration, inertia force is generated when its mass resists the acceleration.

***F = M X a***

According to Newton's Second Law of Motion, the inertia force *F* could be quantified. M, the mass of an object, is determined by dividing its weight by the acceleration due to gravity, while *a* is the acceleration it is subject to ( Fig. 6). This is the primary equation for seismic resistant design.[1]

The seismic forces generated by masses vibrating. Heavier building attract larger seismic forces, if there is no mass, there is no inertial force. It is the same with height of the construction, because of the cantilever action of the buildings, the forces accumulate from top to bottom.[2]

In this case, the most important factor determining the inertia force in a building is its weight. Wherever possible, lighter elements of construction should be substituted for and replace those that are heavier. Buildings should be built as light-weight as practicable to reduce seismic vulnerability. (other facters determin the inertia force also need to be taken into acount: natural period of vibration, damping, response spectrum, ductility)

Unfortunately, Brick and stone masonry are the most widely used materials in Groningen, which leads to series of structural problems after earthquake. So when

1 <Seismic Design for Architects>, P16

2 <Handbook on Seismic Retrofit of Buildings>, P20

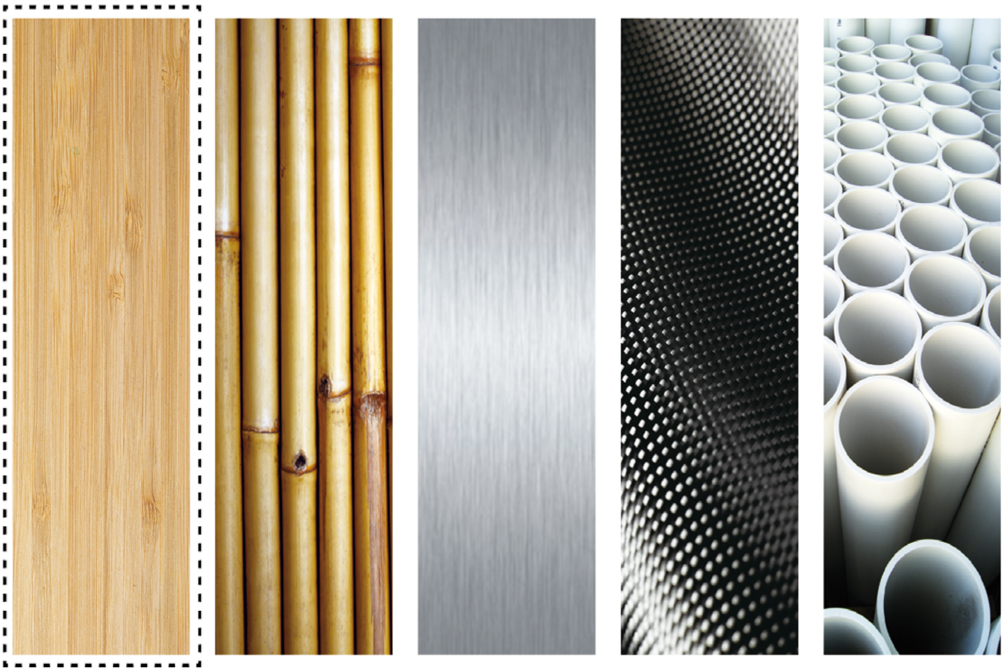

*Figure 7: Choices of light-weight moterials.*

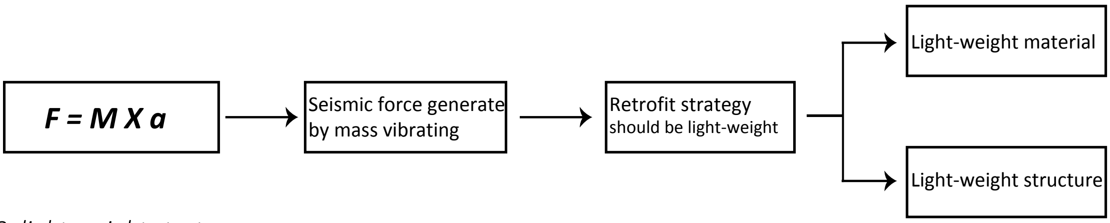


*Figure 8: light-weight strategy.*

retrofit a damaged masonry building, architects and structural engineers should always attempt to build more lightly. That is also the primary goal of this research, a complementary light-weight construction as reinforcement by using light-weight material.

**Material Choice**

Compared with other light-weight material, one of the biggest advantages of using wood is that it is a natural resource, making it readily available and economically feasible. It is remarkably strong in relation to its weight, and it provides good insulation from the cold. It carries the lowest carbon footprint of any comparable building material, which made it a perfect example of an environmentally sustainable product. More important, wood is more elastic than other light-weight material (except bamboo, not local in Groningen), which means wood has better potential as seismic proof material. Besides, wood is highly machinable, and can be fabricated into all kinds of shapes and sizes to fit practically any construction need, which will make the construction system more makeble and practical to build on site.

However, due to the ductility of wood construction and the stiff  of brick work, the wood reinforcement may not work when reaching a certain magnitude of earthquake. The brick may crak or even collapse before wood is damaged. In this case, strategies should be made to strengthen the brick first, which will be studied in the first part of the research.

# 1.5 Site Selection & Objective

*Figure 9: Site location -- Warffum.*


*Figure 10: Earthquake damages in Warffum.*

### Site Selection

Waffurm is a village in the northern part of the province of Groningen, suffered two earthquakes in 2012 and 2013, measured 3.6M and 3.2M. About forty percent of homes damaged in this village, and the population has been decreased from 4000 after the war to current 2500.[1] The public facilities begun to disappear, such as shops , decreased from 6 in 2007 to 4 in the 2013. Even the care center in Warffum was closed. Elderly people who could not live independently, had to move in the future

1 How Warffum was awakened Fri Netherlands, Louis Stiller,2015

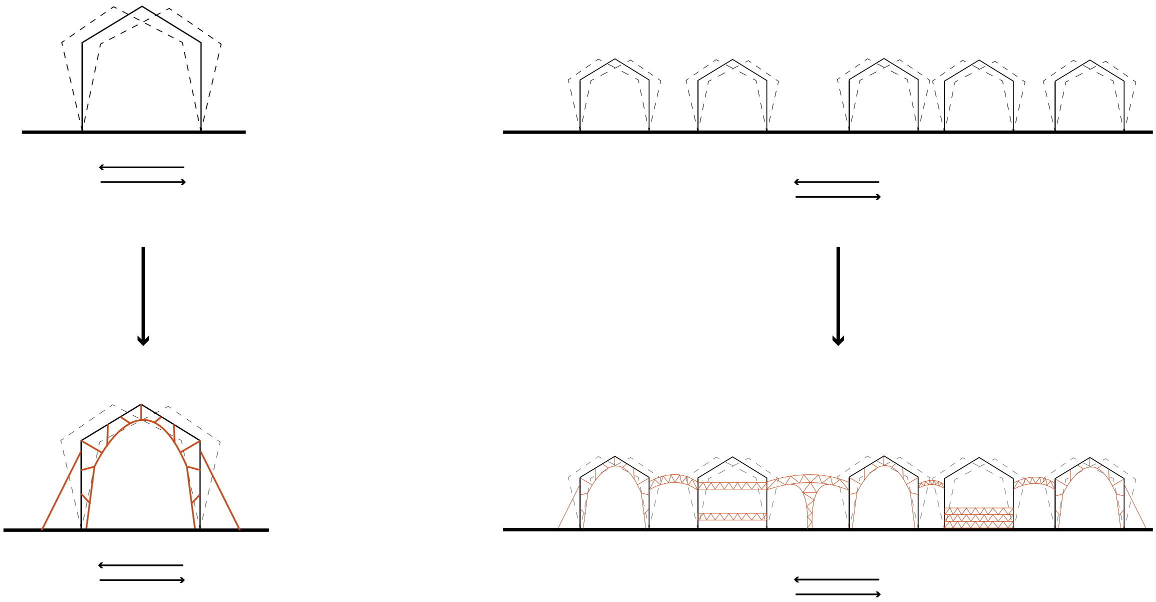

*Figure 11: Diagram of objective -- A light-weight architectural solution.*

to larger villages.  One hundred and twenty-seven small quakes occurred in Warffum in 2013, and there might be heavier quakes in the future. In this case, new strategies should be made to reinforce the masonry buildings to ensure the safety of residences and provide more public facilities for their daily life. This strategy should be practical enough, construction process and financial issue should also be taken into account.

The site is chosen as a typical community in the earthquake area in Groningen, to make sure the construction system could be applicable to different scales and other areas with similar situations.

**Objective**

The project will be the transformation of a community into new public space by using complementary wood construction as reinforcement in Warffum. And the research wiil be the technical support for the project, to solve the structural challenge: the seismic behavior and on site construction of light-weight wood construction, and the conflic between the ductility of wood and stiff of brick as wall. The project serves as an example of how to deal with earthquake damage to the local residence, which can be removed or transformed again when the context change in the future.  The architecture should be designed to fit into the landscape of Warffum and provide new space of interest for the public.

# FEASIBILITY ANALYSIS

Damage ananlysis and restoration of brick building
Feasibility analisis of using wood construction as reinforcement

*Figure 12:*
*Earthquake damage on brick wall.*

# 2.1 Damage ananlysis and restoration of brick building

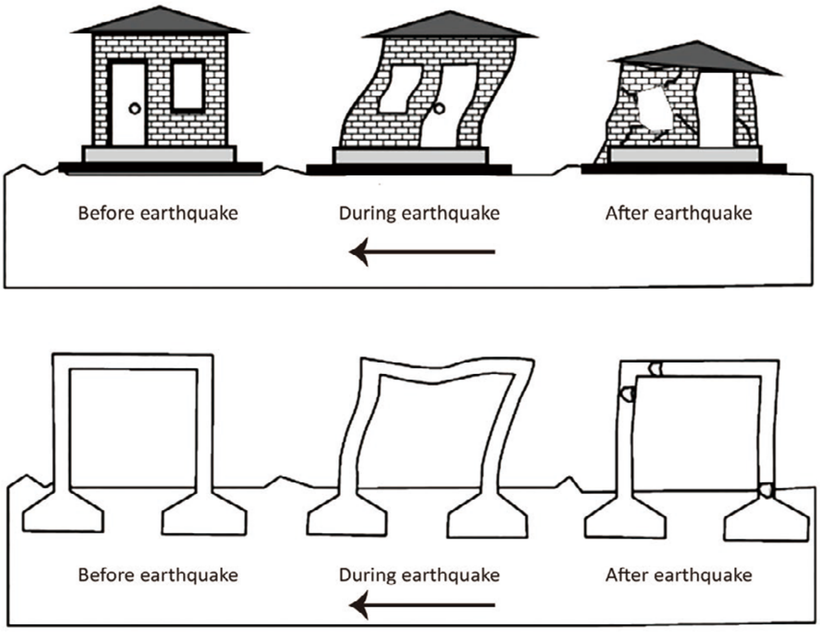


*Figure 13: Behaviours of brittle and ductile  buildings under a major earthquake.*

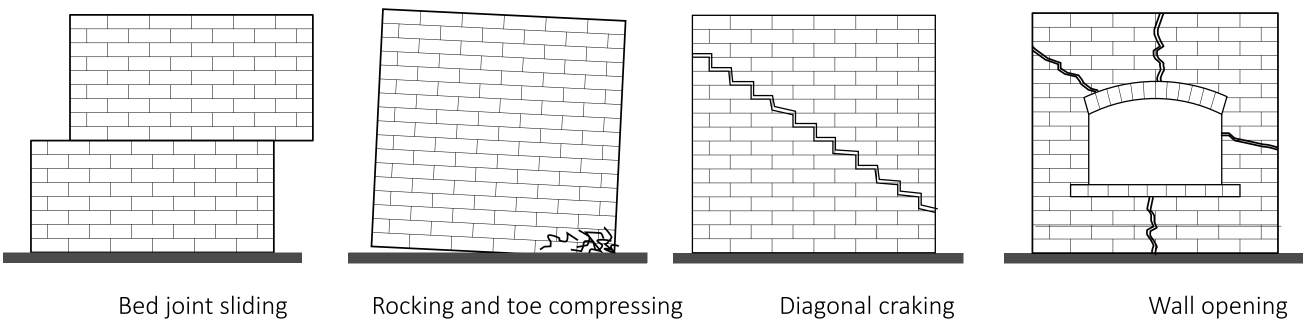


*Figure 14: Earthquake damage on brick buildings*

*Figure 15: Damage on brick buildings in Groningen.*

The vulnerability of the masonry structures to earthquakes and seismic effects have been among the most common reasons of the collapse of masonry structures. Therefore, it is crucial to define earthquake performance of the masonry structures located in the seismic zones.

### Behavior of brittle and stiffness

Seismic performance of masonry structures mostly depend on the strength and behavior of in-plane masonry walls which act as shear walls. However, materials like brick, stone and plain concrete are relatively brittle. When bricks or stones are used in masonry wall construction without adequate bond, they can fall apart suddenly, even if the walls are relatively thick (Fig 13). This indeed is how the failure of many masonry buildings occur red during earthquakes.[1]

On the other hand, the brick and stone performs stiffer than other elastic material such as wood. Stiffness is the property to measure how much the building deflects under a given load, which may be defined as the force required to cause unit deflection. The stiffer the building, the less it will deflect. Adequate stiffness in building is required, otherwise they will get severely damaged and may even collapse under certain level earthquakes. However, it is desirable for the building to behave elastically under lateral load, especially in the area most forces are under low earthquake levels, such as Groningen in Netherlands.

### Damage analysis of brick building

Evaluation of seismic performance for existing masonry buildings has been mentioned in many standards (FEMA 274, 1997; FEMA 356, 2000; EC8-3, 2005; ASCE 41-06, 2006). These standards define four failure modes for unreinforced masonry (URM) walls in seismic evaluation, namely, bed-joint sliding, rocking, diagonal tension and toe crushing (Fig,14). The first two are classified as deformation-controlled actions because lateral deflections of walls and piers can become quite large as strengths remain close to constant. On the other hand, the latter two are classified as force-controlled actions, because they occur when a certain stress is reached and can cause sudden and substantial strength deterioration.[2]

In sum, the earthquake forces create a lot of damage to brittle structures, a momentary overload, which results in crushed or subsided toes, or diagonal cracks in the corner points of the brickwork. In Groningen, there are specific problems following the building tradition. Due to the big opennings on the ground floor, the structural behavior of the brittle brick walls could be worse than the walls with smaller opennings in other areas. The opennings create big stress points during an earthquake. In this case, the brick buildings in Groningen mainly suffer from different degree of cracks, which are concentrated in the area of beam-wall connections and the arches and joints above windows and doors. Such cracks will increase due to the frequency small earthquakes, until the walls collapse. Dealing with cracks and keep the walls not falling down in frequency small earthquakes are the two mojority task for ennigeers in Groningen.

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1 <Handbook on Seismic Retrofit of Buildings>, P23-30

2 <Seismic performance evaluation of slender masonry towers: a case study>

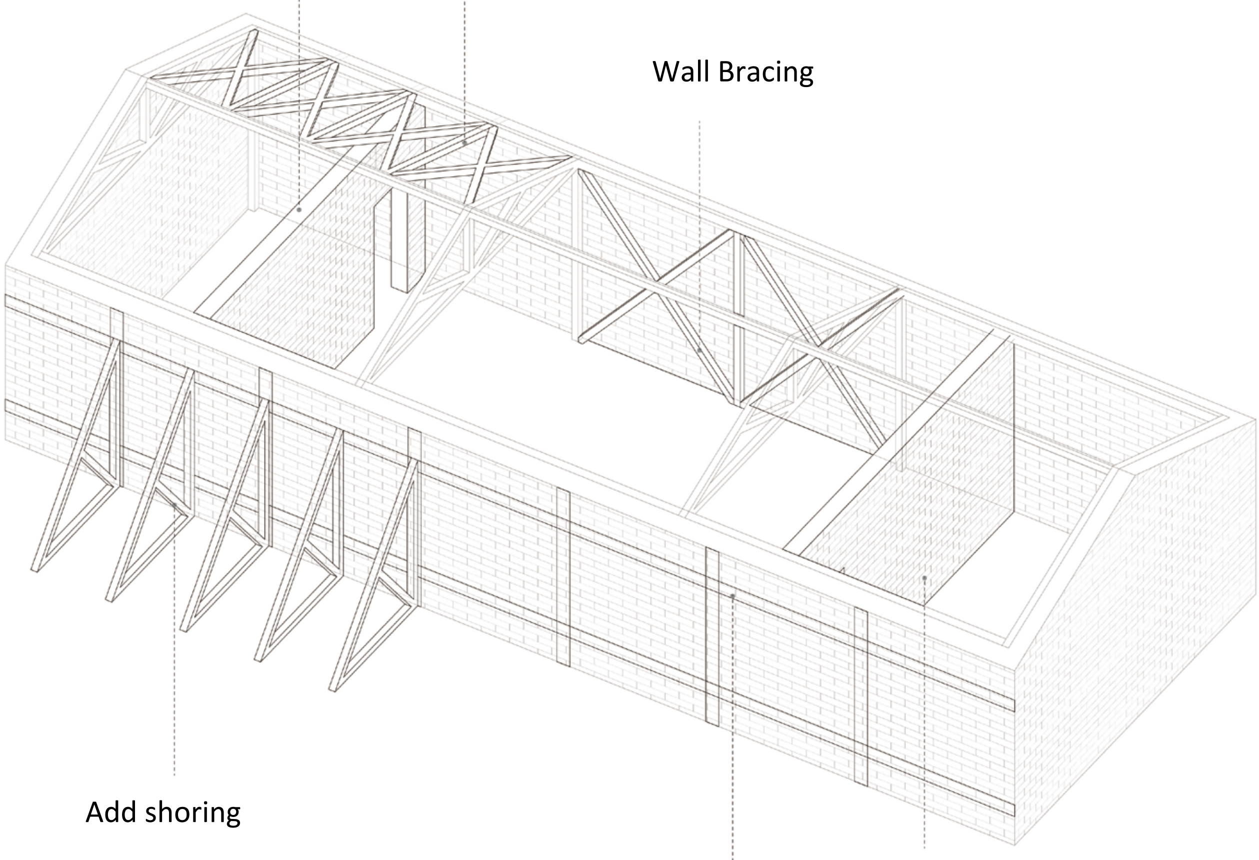



*Figure 16: Methods of seismic restoration of brick building, by author*
*Information from <Handbook on Seismic Retrofit of Buildings>*

**Strengthening of brick work**

The basic components of masonry buildings are foundations (spread wall footings), walls, floor slabs and roofs. The walls and footings are mainly made of bricks or stones, while the floor and roof slabs in modern buildings are made in reinforced concrete. These are the mainly components that need to be repaired within the restoration of a masonry building. According to the <Restrofitting of Heritage Structures>, there are mainly four ways to strengthening a masonry structure (Fig 16)[1]:

**1). Add Cross Walls:**
Unless a wall is extremely thick and well bonded, it will lack the stiffness and the strength to resist the forces acting perpendicular to it. A cross wall resists the horizontal forces acting in its own plane and increase the stiffness of the building. A masonry wall has good resistance to seismic forces acting in the direction of the wall, but it is not effective in resisting loads acting perpendicular to its plane and requires the assistance of cross walls for this purpose.

**2). Add Steel Ties:**
In order to ensure integral action of the masonry walls in the load bearing construction, horizontal bands and vertical bars are provided at the plinth, sill and lintel levels. The absence of such ties, combined with poor bonding of walls at corner junctions, is a primary cause for collapse pf many masonry buildings during an earthquake. These ties provide the desired tensile resistance to earthquake forces by tying elements together and strengthen the corner around doors and window opennings.

**3). Add Brace:**
Braces can be add to the existing frame to increase lateral strength and stiffness of a storey substantially. One significant adcantage of this method is that passive energy dissipation devices can be incorporated to increase damping / stiffness or both. Although the connection of the braces to an existing frame might be difficult, it is necessary to add roof and wall brace to increase the ductility of the building.

**4). Add Shoring**
Buildings with load bearing walls need extensive shoring. Shoring is employed to temporarily support the structure against possible settlement or even collapse. The external walls can be spported by the wall of the adjacent building by providing 'flying shores'. The shoring sysytem can be the most efficient way to provide support to the building.[2]

These are the most important and efficient methods to retrofit masonry buildings damaged from earthquake. Especially in Groningen, due to the massive cracks and the frequency small earthquakes, adding shoring and steel tie seemed to be the best solution. But when take other factors into account, such as aesthetic, function, spacial quality and finance, the solutions should be improved to meet new requirements, not being done roughly to only solve structural problem. Based on these solutions, new strategies could be invented to provide a more architectural solution.

1 <Restrofitting of Heritage Structures>
2 <Handbook on Seismic Retrofit of Buildings>

## 2.2 Feasibility analisis of using wood construction as reinforcement

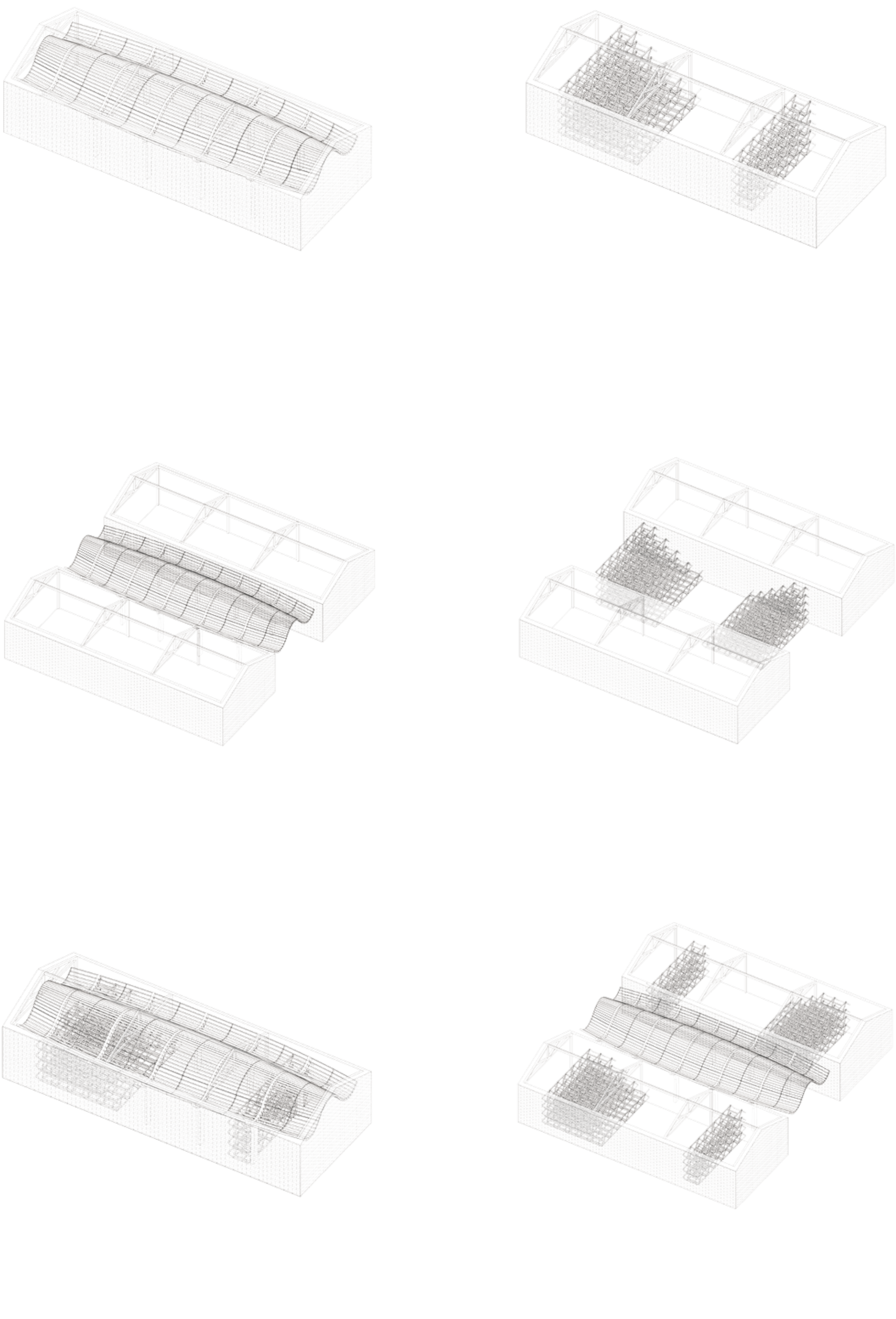


*Figure 17: . Diagram of the primary design for a more architectural solution*
*Replace of shoring and cross wall. By author.*

**Wood construction as reinforcement**

In order to solve both social and structural problems caused by earthquakes in Groningen, not only the structure needs to be renewed, the space also need to be retread or added for public activities. Thus, the engineering solutions to the earthquakes could be improved when taking more factors into account, such as aesthetic, function and finance.

Diagram on the left is the primary design for a more architectural solution to earthquakes by using wood construction. The inventions are based on the two methods to strengthening the masonry buildings: add shoring and add cross wall.

Instead of doing the shoring roughly to the external of the brick wall, the construction could be enlarged to provide extension space or installed inside as secondary structure system. Also the heavy brick-made cross walls could be replaced by light-weight wood construction with certain function, such as shelves and stages. As it is mentioned in the chapter 2.1, it is desirable for the construction to behave elastically under lateral load, especially in the area most forces are under low earthquake levels, such as Groningen. In this case, the wood construction is the best choice of reinforcement for its light-weight and elastic behavior.

However, due to the ductility of wood construction and the stiff of brick work, the wood reinforcement may not work when reaching a certain magnitude of earthquake. The brick work may crak or even collapse first before wood reinforcement is damaged. This conflic should be solved before the wood construction is designed and installed to the masonry building.

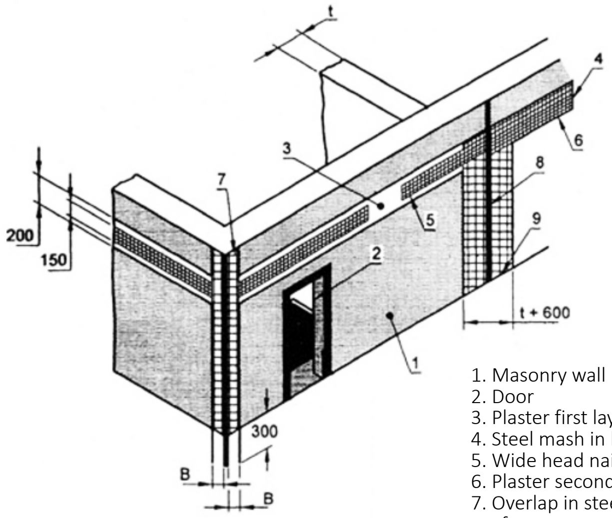
**Solution to the Conflict between Ductile behavior of wood and brittle of brick**

Adequate stiffness in building is required, otherwise they will get severely damaged and may even collapse under certain level earthquakes. In this case, the first solution to solve the conflict between two materials is to make the brick work stiffer, so that it can keep safe under certain magnitude of earthquakes, and then the external support could be provided by the complementary wood construction. This can be done in two ways.

1). Seismic tie.
To strengthening the brick wall and make it stiffer, seismic tie could be added on both horizontal and vertical direction (Fig 18). The bands build integrally in the building could make the wall act together and hence reduce the tendency to collapse out of plane. ( See how seismic tie work to strengthening wall in Chpter 2.1)

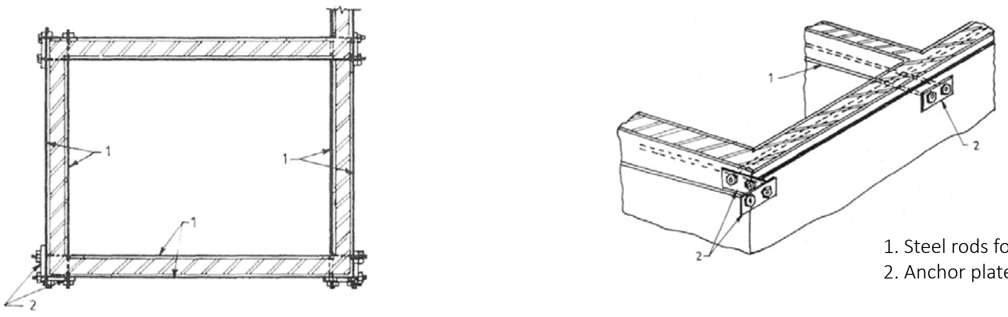
2). Pre-stressing of brick wall.
A horizontal compression state induced by horizontal wires/bars can be used to increase the shear strength of walls. Moreover, this will also improve, considerably; the connections of orthogonal walls (Fig 19). The easiest way of affecting the pre-compression is to place two steel rods on the two sides of the wall and stretching them by turnbuckles. This method is also useful to strengthen spandrel beam between two rows of opening in the case no rigid slab exists.[1]

1.<Seismic evaluation, repair and strengthening of masonry buildings - Guidelines>




1. Masonry wall
2. Door
3. Plaster first layer
4. Steel mash in belt
5. Wide head nail 150 long
6. Plaster second layer
7. Overlap in steel mesh 200 mm each side of coener.
8. Vertical seismic belts junction (going across horizontal belt)
9. Spikes for fixing mesh

*Figure 18: Solution 1, Add vertical and horizontal seismic tie.*



1. Steel rods for prestressing
2. Anchor plates

*Figure 19: Solution 2, Strengthening of walls by Pre-stressing.*

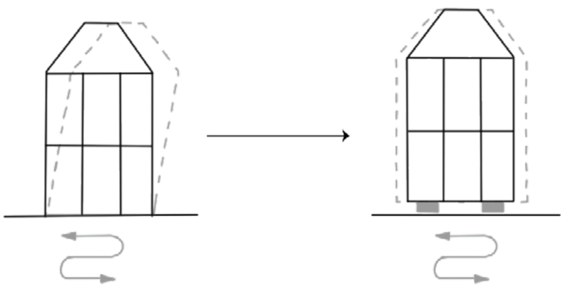


*Figure20: Solution 3, Base isolation.*

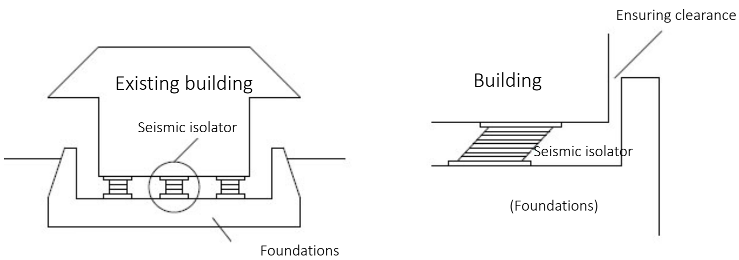



*Figure 21: Introduce damper in base isolation.*

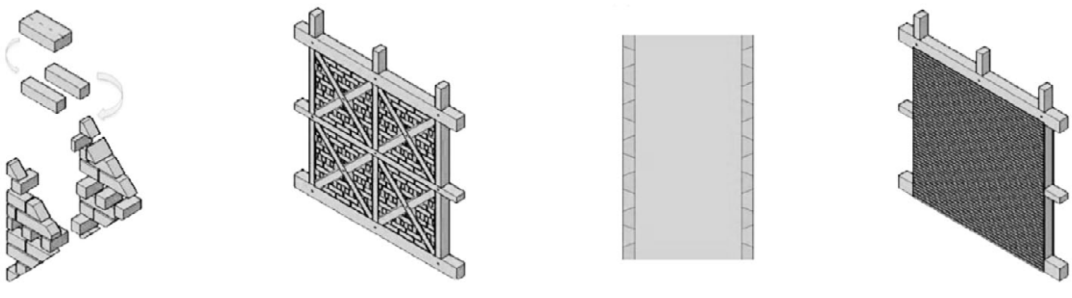


*Figure 22: Solution 4, Combine with timber, reconstruct of brick wall with timber frame.*

Another method to solve the conflic is to add base isolation to make the brick work flexible (Fig 20, 21). A seismically isolation could make the natural period of the superstructure longer and decreases the acceleration, and reduce the damage to finishes and equipment. In this sense, a seismic isolated structure is ideal for those buildings for which the maintaining of functions at the time of an earthquake is required. In addition, because seismic isolators can reduce the seismic force input to a superstructure, they are an effective countermeasure for those buildings which cannot be seismically strengthened by such measures as adding shear walls; for some buildings this can be achieved by digging under the foundations to position seismic isolators.[1]

However, when a sesmic base isolation is adopted, total construction costs will be increased by about 10% because of the cost of seismic isolators, etc. and the construction costs of the base-isolated layers need to be added as well.

One last solution is to combine the brick work with timber, bricks could be reconstruct within the timber frame. Such half-timbered structures constitute an important cultural heritage of many countries, since they represent a typical anti-seismic construction adopted worldwide. And can still be an effective method to reconstruct heavily damaged or collapsed brick work.

| | Stiffness | Flexible | Operable | Economic | Conservation |
|---|---|---|---|---|---|
| Add Seismic tie | √ | × | √ | √ | × |
| Pre-stressing | √ | × | √ | √ | √ |
| Base Isolation | × | √ | × | × | √ |
| Half-timber frame | √ | × | × | √ | × |

*Figure 23: Comparation of solutions to solve the conflic between*
*. brick work and timber work. By author.*

**Selection of solution within different condition.**

The four solutions to solve the conflic between different structural behavior of brick work and wood work are applicable in different situations. As shown in Fig 23, they have different performence in the improvement of stiffness and flexibility, different level of damage to the original structure, and different financial requirment. Among the four solution, base isolation is the one can solve the structure problem best, and keep the original of brick work, in this case, it is the best solution to solve the conflic when the finance is allowed. Add seismic tie and pre-streesing of brick work are two methods that can be easily operated on site, the improvement of stiffness can strengthen the brick work and make it safe under certain magnitude of earthquake. However, the brick work will still be threatened by the craks due to the frequency low magnitude earthquakes in the future in Groningen. The reconstruct of brick work can be done on those buildings heavily damaged during the earthquakes, the ductile of the brick can be improved significant in combination with timber frame. In this case, the selection of the solution should be different based on the ananlysis of context (Fig 24).

1. <Earthquake-resistant design for architects>

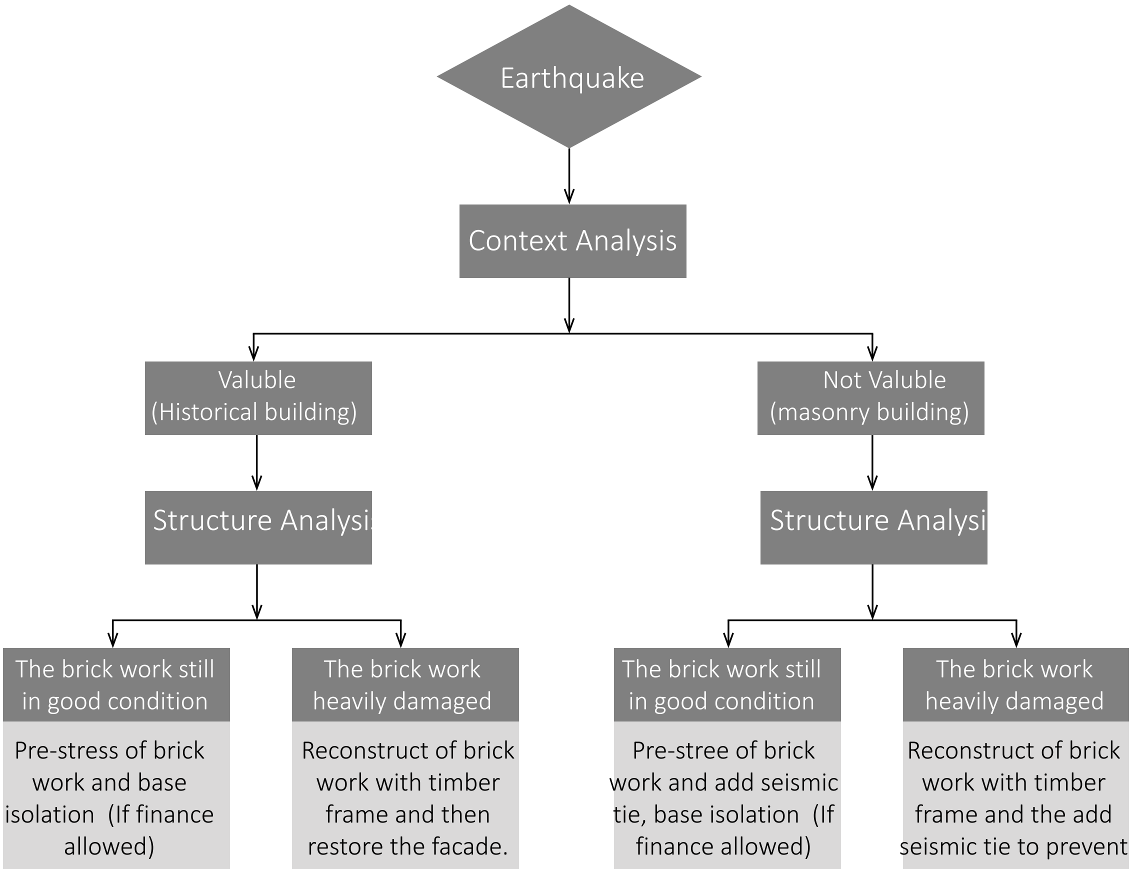



*Figure 24: Diagram of work-flow of Selection of solutions within different condition. By author.*

**Properties**

The research focus on using light-weight wood construction as shoring in the restoration process, to provide external support for the masonry work. By using light-weight material and the seismic optimization of the structure, the mass of the construction could be minimized. Also the elastic behavior of wood construction is demanded in the frequency small earthquake area such as Groningen.

On the other hand, the wood construction can be flexible and easily remove from the masonry work in the futhure, and the external space can be well served as function volume to provide public space for the neighbor. Moreover, the construction of wood structure could be fast and sustainable, the components can be optimized costumized according to different situation.

In sum, the restoration of masonry building includes two parts of work. First is the repair and strength of original brick work. Second part is the extra support mainly consists of external shoring and indoor secondary structure.

In order to ensure the wood complementary structure work as renforcement for the masonry building. The conflic between different structural behavior of two materials has to be solved before the wood construction is added. Through the research, the paper give a guidence of how to select an appropriate solution based on different situaton. And the preliminary research on how to use wood construction as extra support, which will be further researched in the next part of the paper.

# COMPLEMENTARY LIGHT WEIGHT CONSTRUCTIUON

Light-weight wood shoring construction with folded surface
Light-weight wood elements
The light-weight material

*Figure 25:*
*Light-weight construction*

# 3.1 Light-weight wood shoring construction with folded surface.

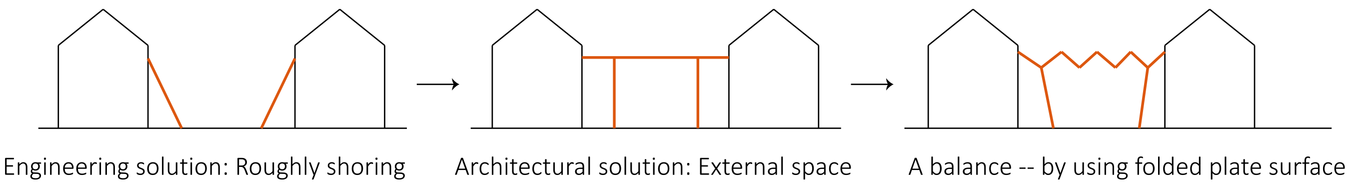



*Figure 26: Diagram of new proposal. By author.*

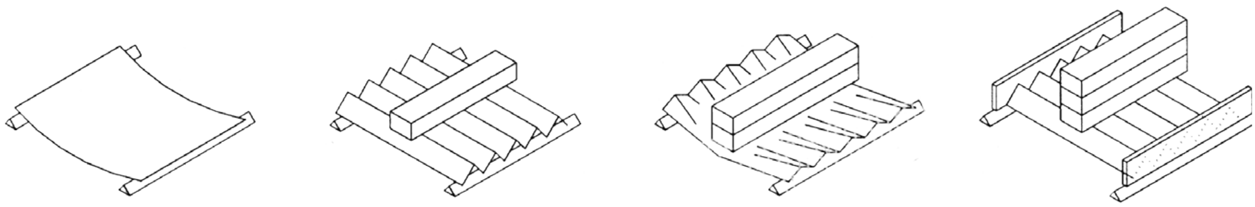


*Figure 27: Effect of foldong on folded surface. By author.*

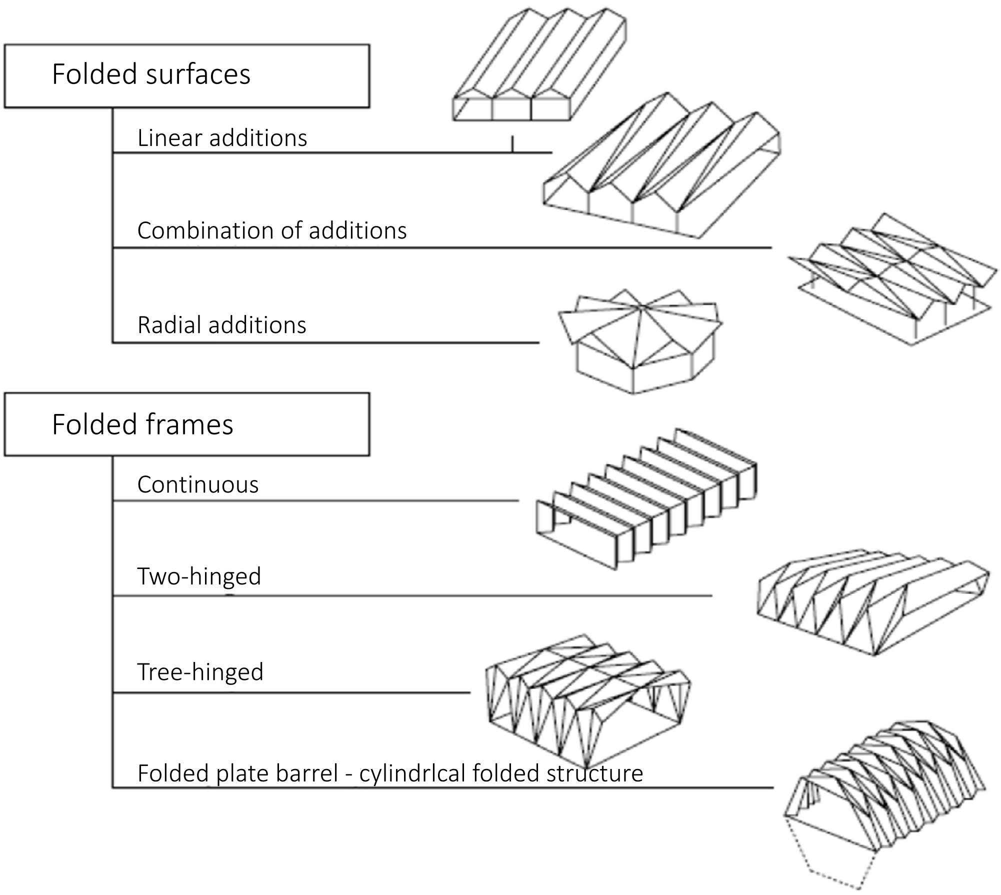



*Figure 28: Application of folded light-weigt structure.*

**Light - weight construction as shoring.**

Instead of doing the shoring roughly to the external of the brick wall, the construction could be enlarged to provide extension space or installed inside as secondary structure system (Fig 17, diagram of the primary design for a more architectural solution in chapter 2.2). Such as the 'flying shoring' to support the external walls of two adjacent buildings, the space under the structure elements can be used as exterior for public activities. However, with the increase of the span of the structure, the stability of construction during earthquake became weaker. A balance between structural requirement and functional use should be made, and the invention of a more effective proposal to provide external support and space as well (Fig 26). In this paper, an addition light-weight construction is optimized as shoring for the masonry building by using folded surface.

**Gain strength and stiffness by folded surface.**

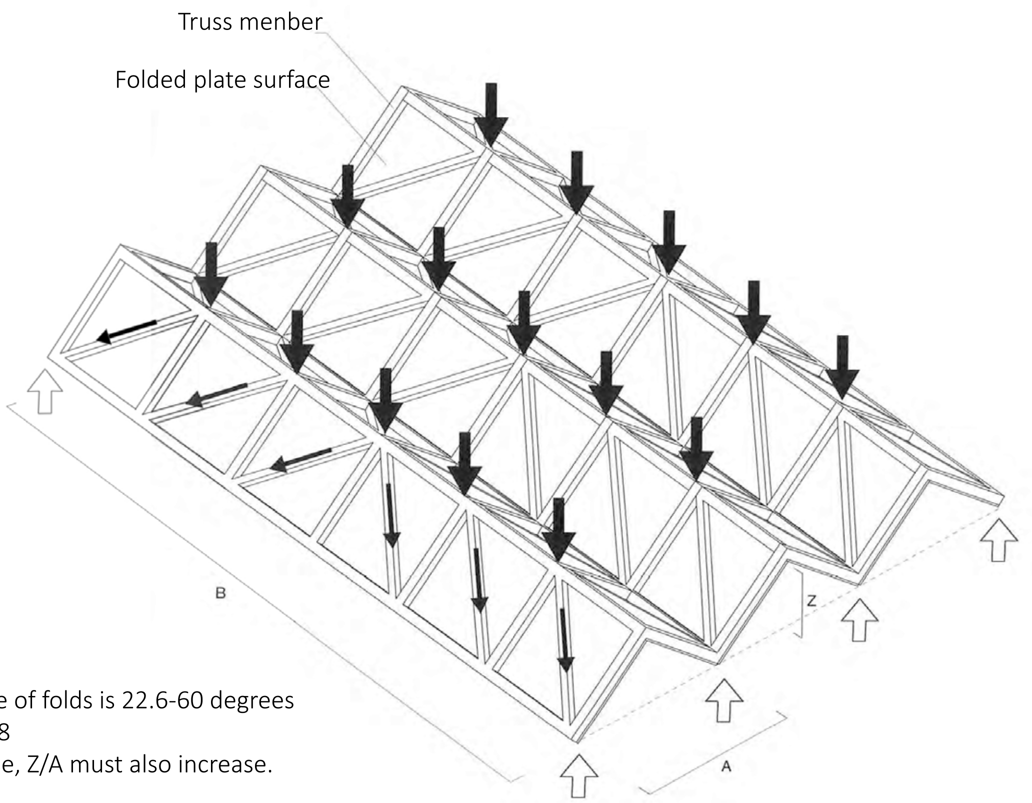
The strength and stiffness of the construction will generated significantly with folded surface. The effect of folding on folded surface can be visualized with a sheet of paper. A flat paper deforms even under its own weight. Folding the paper adds strength and stiffness; yet under heavy load the folds may buckle. To secure the folds at both ends increases stability against buckling (Fig 27).[1] The strength and stiffness of folded construction is achieved primarily by proper design of the structure, and to a lesser extent, by thickness and dimension of the elements that form it. Adequate stiffness in constructions is required, so that they won't get damaged or collapse under certain level earthquakes. Also the use of wood will increase the elasticity behavior of the construction during an earthquake. In this case, the application of wood folded light - weight construction could be a good solution to provide both structural shoring and attached exterior space. In this chapter, the structural behavior of folded structure and basic forms, patterns will be studied.

**Application of folded structure**

The basic idea of folded construction is striving to achieve more constructive height and greater rigidity and reduce the net weight of the structural element. Folded structures are among the most cost-effective constructions, they use less material because of their high stiffness in the plane of maximum bending in the direction of the range. Folded structures are spatial structures formed by the elements in the plane, different in form and materialization. Based on the geometric shape folded structures can be divided into folded surfaces and folded frames (Fig 28). Such structure have found the application in architectural buildings and engineering structures especially in roof, floor and wall construction.[2]

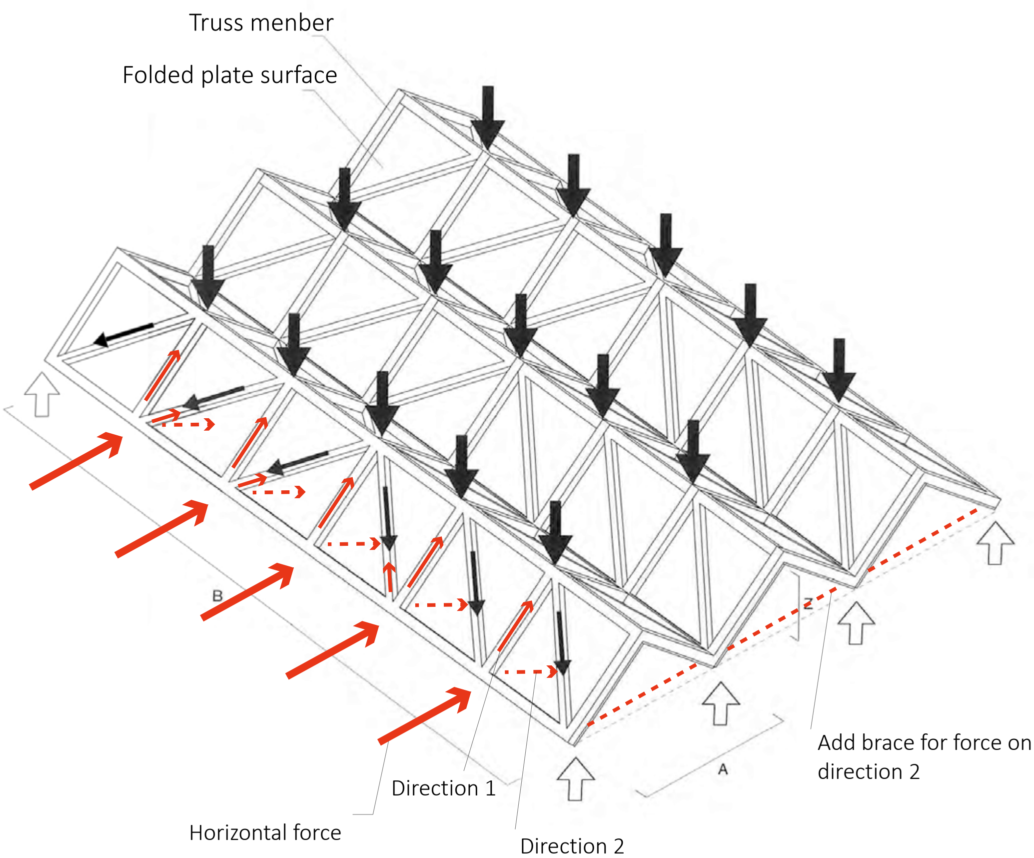
By using folded structures different spatial forms can be made. The straight elements forming a folded construction can be of various shapes: rectangular, trapezoidal or triangular. By combining these elements we get different forms resulting in a variety of shapes and remarkable architectural expression, and different spatial forms can be made.

1.< Structures: Folded Plate >, Builder's engineer
2. < Folded structures in modern architecture >




When shape of folds is 22.6-60 degrees
Z/A = 0.2-0.8
As B increase, Z/A must also increase.

The internal bending and shear forces will result in tension in the top of the folds and tension in the bottom at mid span, shear stresses will be greatest close to t he supports in the plane of the folds. The folds acts like the section of a beam when resisting bending and shear forces.




Force flow when the folded truss suffer a horizontal movement during earthquakes.

*Figure 29: Flow of force for folded truss structure, By author .*

**Structural behavior and sesmic optimization of folded structure.**

The bearing capacity of full-flat panels depends on its thickness and quality of the material from which it was made. The large range of full plate becomes too thick and heavy, and as such is not economical. If we form the folded structure of the inclined panels, their vertical projection becomes the height of the folded construction, and thus enables the smaller thickness of the structural element. By the use of folded structures far greater ranges can be overcome than by the application of a full flat plate. And it will have better stability than a full flat plate.[1]

The base unit of a timber truss folded plate is composed of timber truss members triangulated to form a stiff, stable lattice. Timber truss folded plates direct the bending through the top and botom chards of the truss while shear stresses are directed through the diagonal elements. The combination of the individual elements, even if they are individually under-dimensioned, provides structural strength. The distribution of loads through timber plates produces a portal form with the truss in the upper part of the section and the folded plate in the lower. This distribution of loads along the surface and lines of the folded plate and timber truss embeds the plate and truss folded plate with an optical affective property of pleating and diamonding that remains consistent within any space it defines. A plate and truss folded plate adds diffusion to modify or dominate the acoustical affect of its macro-geometry, which can be focusing (curved) or specular (flat).

One stuctural property of using folded truss structure is it can be flexible in several ways:

1).Profile:
The protogeometry of timber plates with truss folded plates allows them to be flexible, by varying the location of the apexes of the folds, ranging from spanning two supporting walls, to a basic three-sided "portal" section, to a highly folded nave section.

2). Scale:
The rate and scales of the folds can vary, changing the overall subdivision of the section.

3). Depth:
The depth of the folds can also vary according to the scale and rate of subdivision of the overall plate. The deeper the foldes, the more structural depth they gain, thus the more structural depth is availablr for the truss.

4). Affect:
The affective property of timber plates with truss folded plates can be multiplied when the base unit imbricates or intertwines with external factors, such as asymmetries that respond to the physical constraints of the site, environmental considerations, programmatic concerns, etc.[2]

1. < Folded structures in modern architecture >
2. < Function of form>

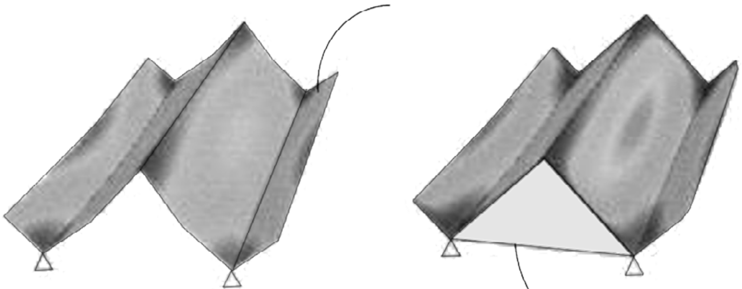



*Figure 30: Effect of proper boundary supports*

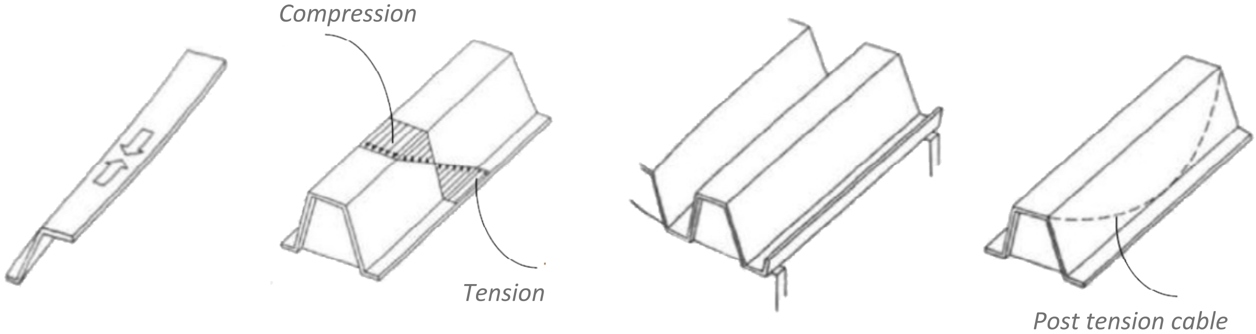



*Figure 31: Other ways of stabilizing the folded structure*

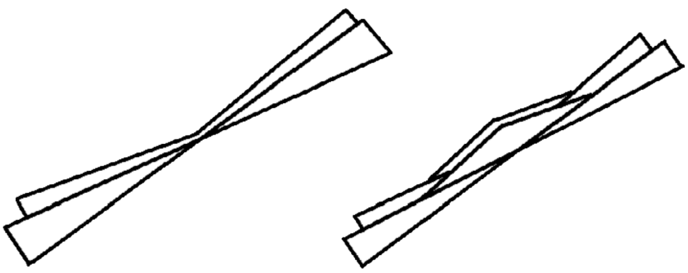


*Figure 32: Hinges (left) and how they can be avoided globally by neighbouring folds that have a construction height (right)*

As shown in Fig 29.1, the vertical force such as gravity could transit through the truss member. The internal bending and shear forces will result in tension in the top of the folds and tension in the bottom at mid span, the folds acts like the section of a beam when resisting bending and shear forces.

However, when the folded truss suffer from horizontal forces such as inertia forces during earthquakes the force will transit through two directions. In this case, the structure should be strengthened for the truss member could only transit one direction of force into tension, braces should be added to improve the stability of the structure when suffer a horizontal force. (Fig 29.2).

Moreover, the stability of the structure should be improved. The support conditions for plates are important for stiffness and deformations. Since the inner plates are supporting each other, the largest deformation occur at the free edges at the boundaries. Free edges are less stiff, therefore it is not optimal to have a free edge in the compression zone due to the large risk of lateral buckling.

If we look at a simple folded systems with two planar plates joined at one single fold in the span direction (Figure 30.1)). The system shows large end deflection and instability when loaded, and the deformation in the middle is extensive. By securing the edges by a narrow plate, the instabilities are reduced (Figure 30.2). Best results are obtained if the added plate continues to the neutral axis of the system but not further since the cantilever then gets too large. We can see that the system is quite weak if it is not transversely stiffened to preserve the geometry during loading. A stiff diaphragm at the supporting ends makes the plate system much stiffer and the system now has the possibility to take significant loads. (Figure 30.3)

Plates in compression are easily subjected to lateral buckling if they are not laterally braced (Figure 31.1). To minimize this problem in folded plate structures free edges can be placed in the tension zone (Figure 31.2). Even if the free edges are in the tension zone they are not very stiff and can be stiffened by being bent or locally braced (Figure 31.3). Also post tensioning can be used to stiffen the plates in an efficient way even if it is mostly used in reinforced concrete plates (Figure 31.4).[1]

In complex folded plate structures it is not easy to determine stability, the simplest way is usually to consider the elevation view parallel to the main span and check for locations where the overall depth is reduced to only the plate thickness. These areas will behave as hinges since the out of plane bending strength of the plate is very small compared to the bending strength of the rest of the system. Hinges can be avoided by having adjacent plates that provide the required structural depth to give an overall stiff structure. Hinges in some places might be advantageous, making the structure work as a hinged frame, although more than three hinges in each section will result in a mechanism.[2] (Figure 32).

Also the mass of the structure could be minimized by using folded truss instead of folded plates. This will increase the seismic behavior of the structure significantly.

1. < Structural Folding A parametric design method for origami architecture>.
2. < Folded structures in modern architecture >.

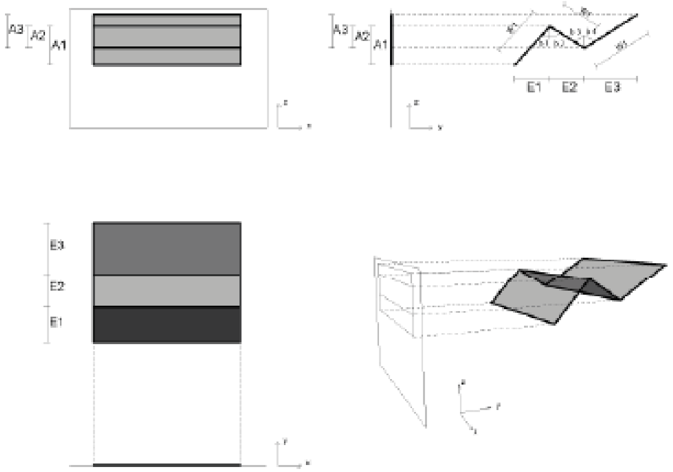



Figure 33: Extrusion of a zigzag line to parallel corrugation .

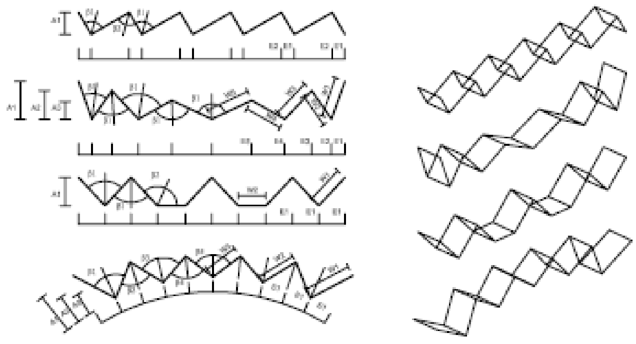


Figure 34: Typical profiles of parallel corrugations

**Parallel Corrugations**

The most basic folding is a corrugation of parallel mountain and valley folds. It can be described as an extrusion of a zigzag line along a straight line (Fig. 33). The zigzag line (plane yz) is characterised by the extension and the amplitude of its segments. The projection of the corrugation to the vertical plane xz shows a series of parallel lines defined by the amplitude of the segments whereas in the horizontal plane xy the extensions of the segments define a series of parallel lines.

The form of parallel corrugations can be manifold. Extension is the main parameter characterizing a series of parallel folds. It defines direction and magnitude of the deploying creases. Its direction can either be straight, bent or take an arbitrary curvilinear or polygonal form. Magnitude varies between an entirely closed and a completely opened state. Extension length and amplitude vary with magnitude. Amplitude of valley and mountain folds outlines the shape along the extension line. Resulting shapes of amplitude variation can be multiple. Outcome of constant amplitude is a parallel line to the extension direction. Other typical variations are constantly growing or diminishing of amplitude. Local or general variations of amplitude can be used to adapt folded plate structures to stress.

The higher the amplitude, the stronger the resistance of the folded plate structure. The order of mountain and valley folds does also strongly qualify the appearance of a series of parallel folds. Usually valley and mountain folds alternate. (Fig. 34).[1]

1. < ORIGAMI – Folded Plate Structures, Architecture>

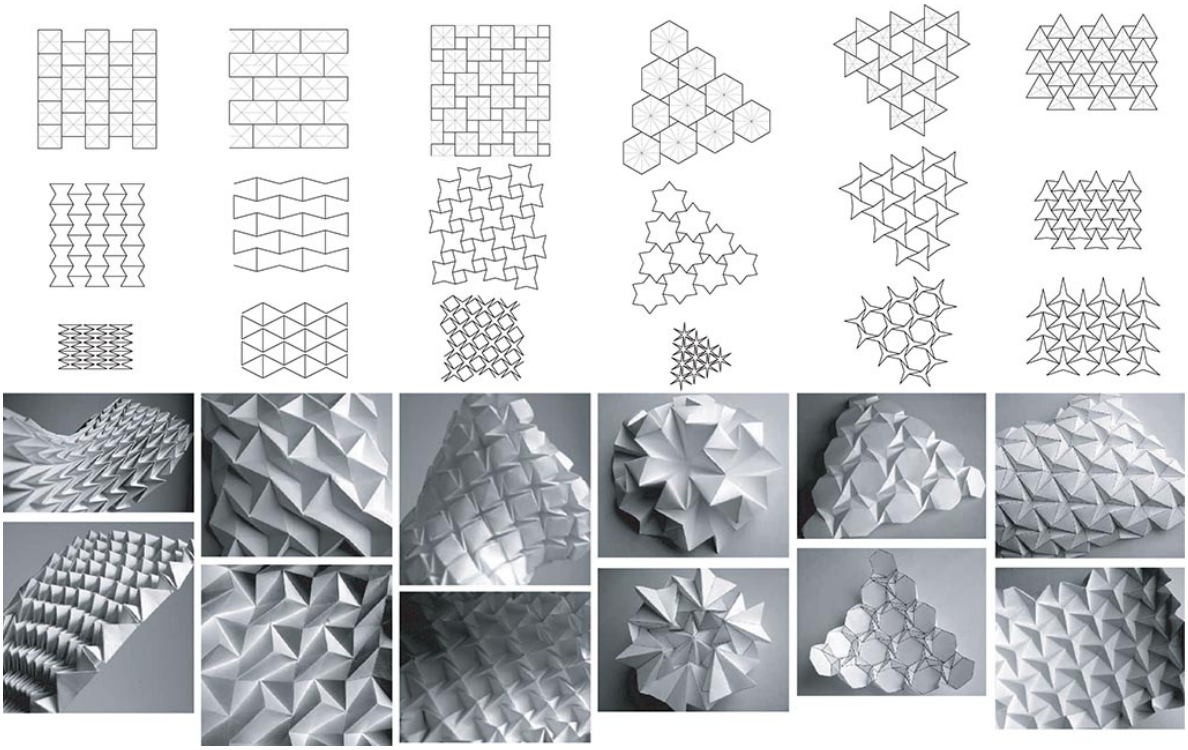
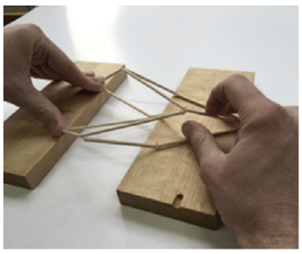


*Figure 35: Typical patterns of folded structure.*

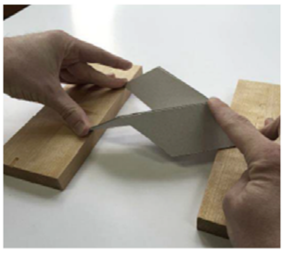
## Pattern

Pattern is another factor that influence the shape and the stability of a folded structure. The patterns can be varied, and should be choosen according to their ability to be shaped into different forms, and their structural properties since each pattern has a certain stiffness and are able to take bending and compression loads in some modes if other directions are locked (Figure 35). [1]

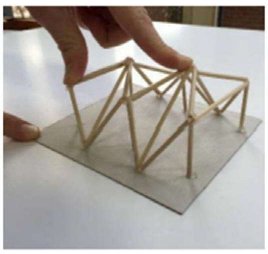
Three patterns are identified to be particularly interesting for architectural and structural applications: Yoshimura pattern, Miura Ori pattern and Diagonal pattern. These patterns have different structural properties. For example, Miura-ori pattern , the tessellation consists of quadrilateral faces, in each non-boundary node four faces and four edges meet. As a plate structure and given that enough boundary constraints are provided, it is stable, but since the faces are not triangular it is expected that the structure is not stable when made as a lattice structure. On the other hand, the faces of the diamond pattern consists of triangular surfaces, it can be stable both as a lattice structure and as a plate structure but that it benefits from having connections along the whole plate edge and from the plates going whole the way to the vertices. (More patterns see in Appendix 2)



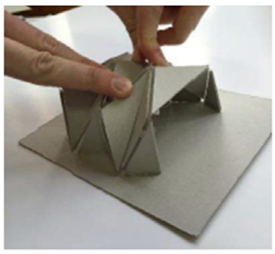
*Miura-ori pattern by lattice.*



*Miura-ori pattern by plate.*



*Diamond pattern by lattice.*



*Diamond pattern by plate.*

1. < ORIGAMI – Folded Plate Structures, Architecture>

# 3.1 Light-weight wood elements.

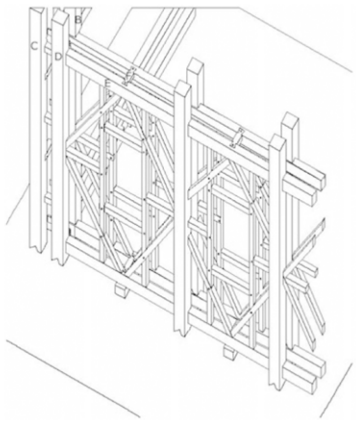


*Figure 36: Timber frame for wall.*

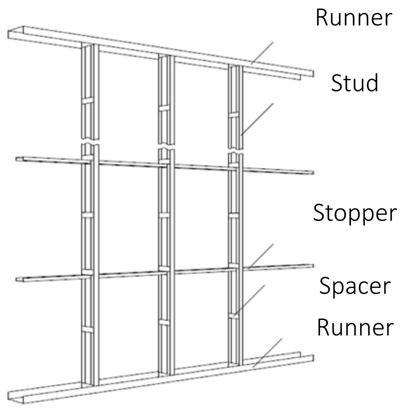



*Figure 37: Light gauge steel furring for wall.*

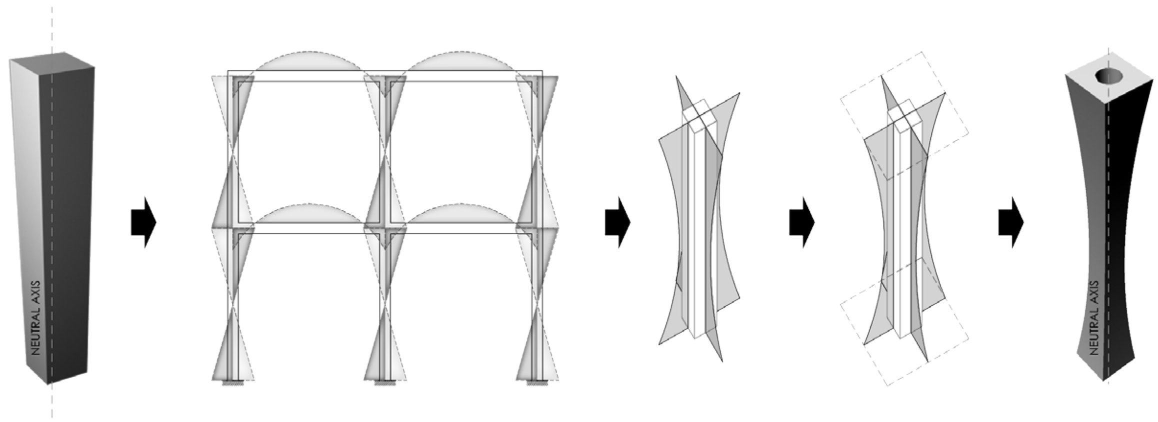



*Figure 38: Reponsive optimizition of columns, by Wilfredo .*

To improve the sesmic behavior of the building, not only the attached construction should be light- weight to reduce the mass of the building, but also the indoor elements should be optimized.

**Structural elements**

The heavy brick works such as cross walls could be replaced by constructions made by light-weight materials such as wood and steel. For example, timber frame is widely used in ancient seismic resistant design. The perimetrical timber structure of the main building is represented with double parallel frames.(Fig 36) The inclined members of the main frames are arranged close to the framing corner, to provide the opening required for windows. They confer a timber frame stiffness improvement to in-plane

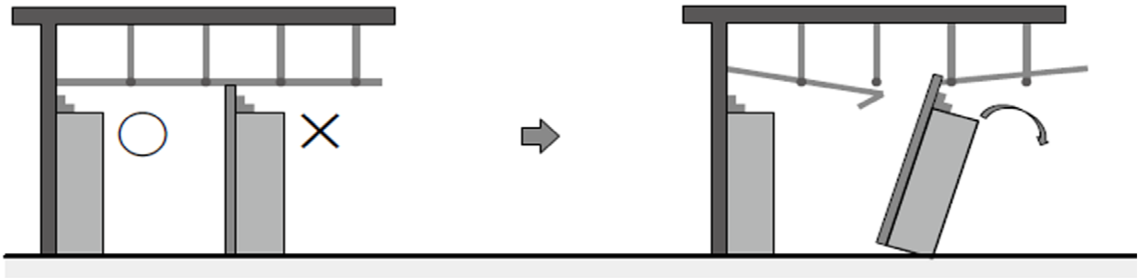


*Figure 39: Heavy furniture fixed to a partition wall which was installed after the ceiling work may damage the wall and the ceiling and overturn during an earthquake.*

seismic actions. Such bracings are continuous for the whole façade, including the attic storey.[1]

The optimizition of partition walls is also very important to improve the seismic proof of the building. Instead of heavy brick elements in traditional Dutch buildings, the partition walls can be  made by the screw fastening of boards to backings of wooden or light gauge steel studs (Fig 37), which can be customized according to different demand and easily to build on site and remove.

On the other hand, the structural elements could be optimized so that the properties of the material can be utilized maximum. As shown in Figure 38, the structural elements can be responsive to the Earth dynamics and aren’t completely adapted to the ecosystem flows of forces. In Wilfredo's research, reinforced concrete was conceived emulating a bone structural properties where the collagen provides tension resistance such as steel bars, and mineral provides resistance to compression such as concrete.[2]  The structure is driven by the natural flow of the force generated by an earthquake within the material. Such proposal becomes highly efficient for seismic vulnerable zones because the total base shear (earthquake force intensity) was reduced due to the effect of lateral loads.

These proposals all imply a reduction of material use for structures, whcich make the building lighter. By using new forms and new materials, the original heavy structural elements can be repalced by lighter elements which designed  according to different demands,

**Non structural elements**

Interior furnitures and other elements have no direct relation to the collapse of buildings because they are not structural building elements which support a building. However, they play an important role in a real-life situation. Moreover, if the non structural elements break or deform, they can prevent escape and are a potential hazard. Prevention and reduction of damage should be considered in design.

The critical overturning acceleration of non structural elements during earthquakes

1. <Historical Earthquake-Resistant Timber Frames in the Mediterranean Area>

2. <Structuring Biomimicry, Improving Building’s Resiliency>

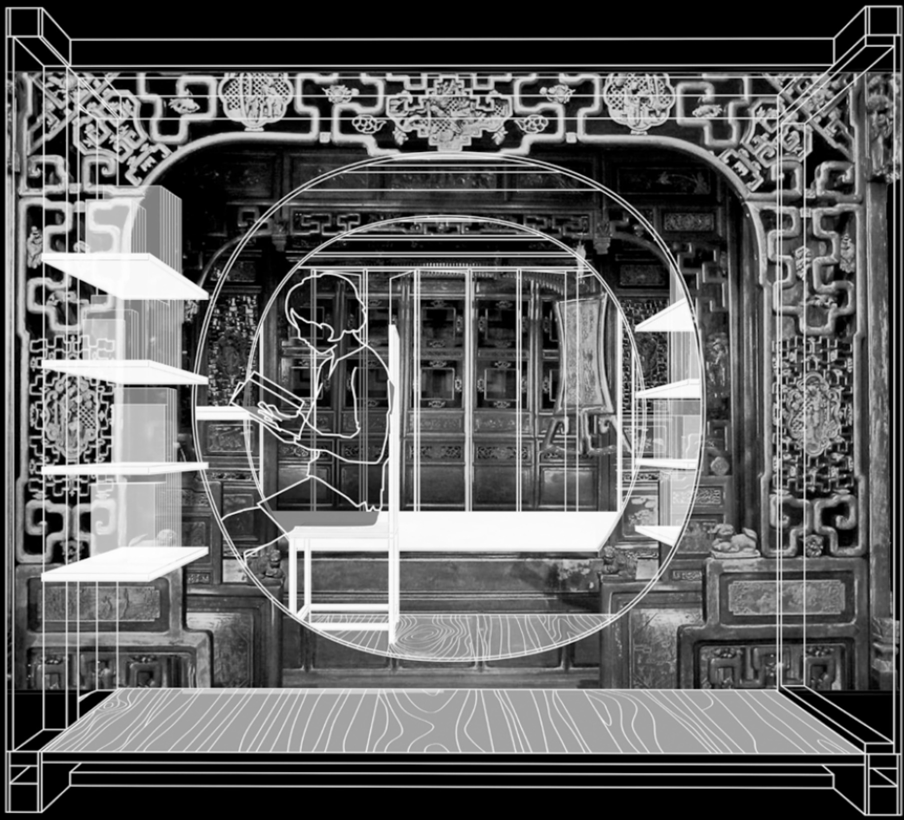


*Figure 40: Room in ancient Chinese architecture. By author*

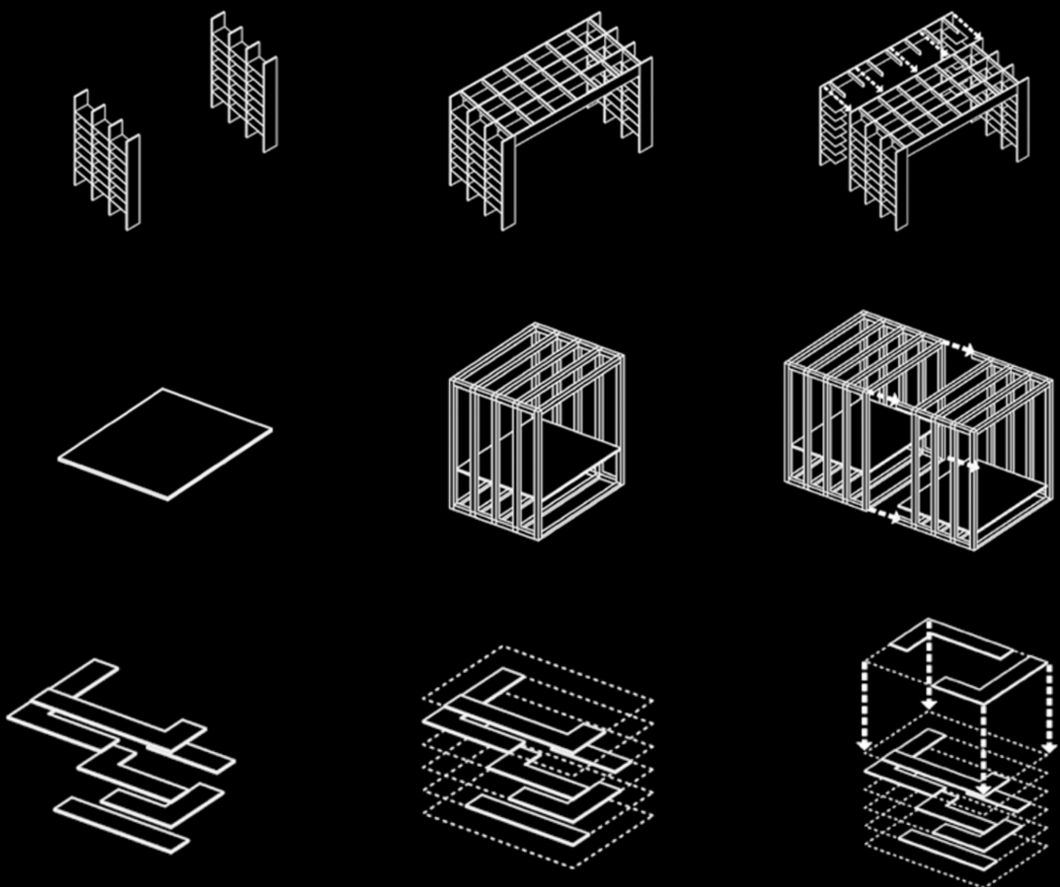


*Figure 41: A generated indoor construction system, combine structural elements with non structural elements. by author.*

varies depending on the dimensions of the elements, and when the acceleration exceeds the elements such as furniture is likely to overturn. The best way to solve this problem is to reduce the mass of the furniture and fix the furniture to the structure of the building as well.

It should be noted that inadequate fixing may cause greater damage, than no fixing. When furniture is fixed, it is important to confirm that the walls or floors to which furniture is fixed have adequate strength. The strength required for fixing furniture varies depending on the weight of the furniture. Therefore, including assumed stored objects, furniture should be fixed to walls or floors with sufficient strength. At the Great East Japan Earthquake, heavy furniture which had been fixed to partition walls installed after the ceiling work broke the wall and the ceiling and overturned (Figure 39).[1]

However, in reality, furniture is usually brought in to the building by the occupants, and in preparation for such a case, wall furring should be strengthened to enable the fixing of furniture, and occupants should be informed which sections of walls can be used for fixing. In this case, a new proposal should be made to avoid inadequate fixting caused by clients unconsciously, a more proper solution should be made to fix the non structure elements better to the structure, and reduce the dimension and mass of the elements as well.

**A combined proposal**

The combination of furniture and structural elements is widely used in ancient architecture in China. As shown in figure 40, the room can be composed by several furnitures which are served as structural elements as well. In this room, the structural elements such as walls and columns are designed with certain function. They are enlarged to provide space for human activities, these combined elements are an important part of ornament in ancient Chinese architecture.

Base on the idea of combine non structural elements such as furniture with structural elements, the fixing problems can be solved in the design stage. Diagram on the left shows three preliminary designs of how to combine a certain function with structural elements. These elements can be generated by small units which can be customized and assembled fast on site.

1). The shelves can be formed and combined with Rib structure system. These can be part of the interior walls, roofs, which are alterable.

2). The beds can be formed and combined with Box-type structure system. And the conctruction can be the basic structure and the division of interior space.

3). The cupboards can be formed and combined with plank structure system. These can be attached to the walls and generated with small units.

All these elements can be modular monomers and can be removed or added easily according to different demands, by using light-weight materials and structure forms, the new proposal could reduce the mass of the building, increase the elastic behavior of the construction significantly, and solve the problem of overturning of furnitures during earthquakes.

1. <Earthquake-resistant Design for Architects>

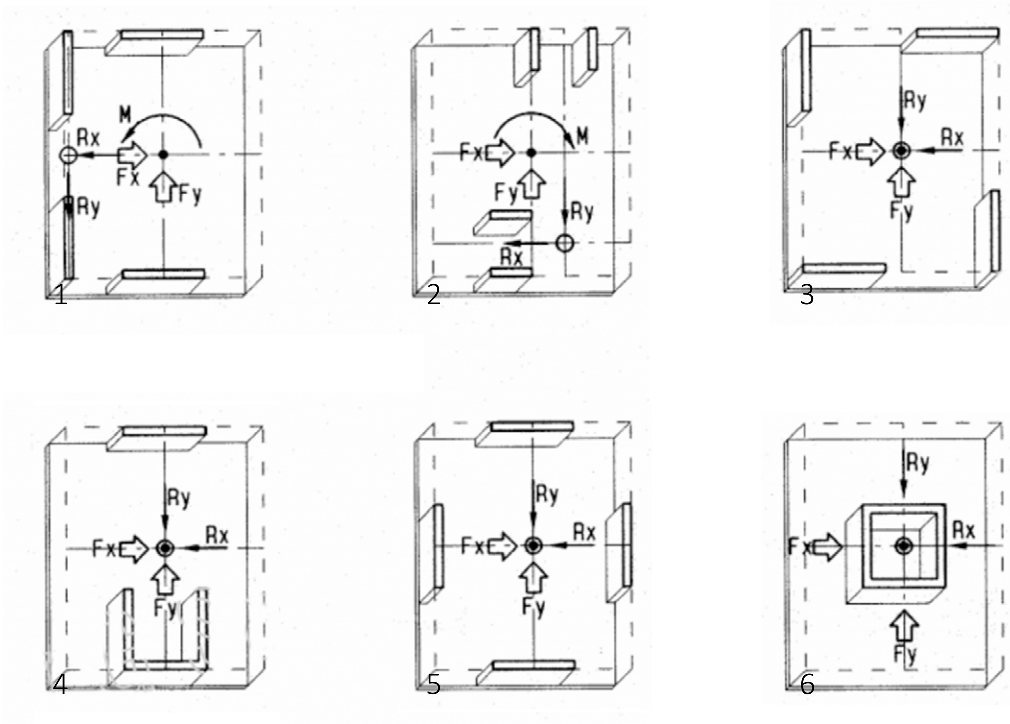



*Figure 42: Comparation of torsion under seismic load of different plans.*

However, in reality, it is difficult to fix all furniture to walls or floors, and when design with the elements that combine both furniture and structural elements, it is necessary to have a well-planned layout of furniture to reduce earthquake damage.

1. Arrangements that cause less overturning.
2. Separation of living space and storage space.
3. Layout of furniture taking into consideration any evacuation route.
4. Avoid placing furniture by windows

Offset between center of mass and center of resistance causes eccentricity which causes torsion under seismic load (Fig 42). In this case, a proper arrangements of elements is the very important to prevent overturning of elements. For example, plan 5 provides greater resistance against torsion than plan 6 due to wider wall spacing. Plan 6 provides greater bending resistance because walls act together as core and thus provide a greater moment of inertia.

Moreover, it is reported that the damage caused by the overturning of furniture greatly decreases if a seismically isolated structure is adopted because the acceleration response decreases. Even when the adoption of a seismically isolated structure for the whole building is difficult, used appropriately, the modern day seismic isolation floors which provide partial isolation or seismic isolation tables to protect art objects are available and effective.[1]

1. <Earthquake-resistant Design for Architects>

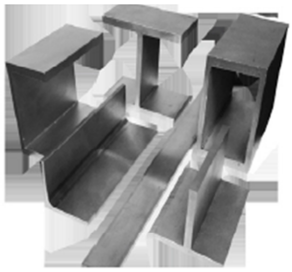
## 3.3 The light-weight material

**Wood**

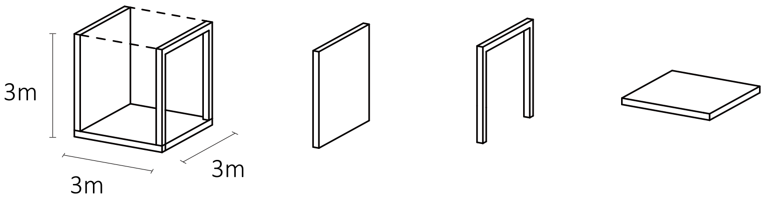
**Bamboo**

**Cardboard**

**Steel**



| | Wood | Bamboo | Cardboard | Steel |
|---|---|---|---|---|
| MASSA | 400-800 kg/m³ | 600 kg/m³, compressed 1050 kg/m³ | 691-1200 kg/m³ | 7800 kg/m³ |
| COMPRESSION STRENGHT | 24 N/mm² | 6.6 N/mm² | 8.1 N/mm² | 235 N/mm² |
| BENDING STRENGHT | 24 N/mm² | 8.5 N/mm² | 6.9 N/mm² | 235 N/mm² |
| TENSILE STRENGHT | 16 N/mm² | 25 N/mm² | 8.1 N/mm² | 235 N/mm² |
| ELASTIC MODUL | 16700 tN/mm² 8500 | 18400 tensile N/mm² 20700 compre | 1000N/mm² 1500 | 210000 tN/mm² |




Shear wall 3 x 3 x 0.2 = 1.8 m³

Frame (0.2 x 0.2 x 3) x 3 = 0.36 m³

Diaphram 3 x 3 x 0.1 = 0.9 m³

**Wood**

Shear wall
3 x 3 x 0.2 x 800 = 1440 kg
Frame
(0.2 x 0.2 x 3) x 3 x 800= 288kg
Diaphram
3 x 3 x 0.1 x 800 = 720 kg

**Total**
**2448 kg**

**Bamboo**

Shear wall
3 x 3 x 0.2 x 1050 = 1890 kg
Frame
(0.2 x 0.2 x 3) x 3 x 600= 216kg
Diaphram
3 x 3 x 0.1 x 1050 = 945 kg

**Total**
**3051 kg**

**Cardboard**

Shear wall
3 x 3 x 0.2 x 1200 = 2160 kg
Frame
(0.2 x 0.2 x 3) x 3 x 691= 249kg
Diaphram
3 x 3 x 0.1 x 1200 = 1080 kg

**Total**
**3489 kg**

**Steel**

Shear wall x 0.4
3 x 3 x 0.2 x 7800 x 0.4 = 5616 kg
Frame
(0.2 x 0.2 x 3) x 3 x 7800= 2808kg
Diaphram x 0.4
3 x 3 x 0.1 x 7800 x 0.4 = 2808 kg

**Total**
**11232 kg**

*Figure 43: Comparation of light-weight materials. By author*

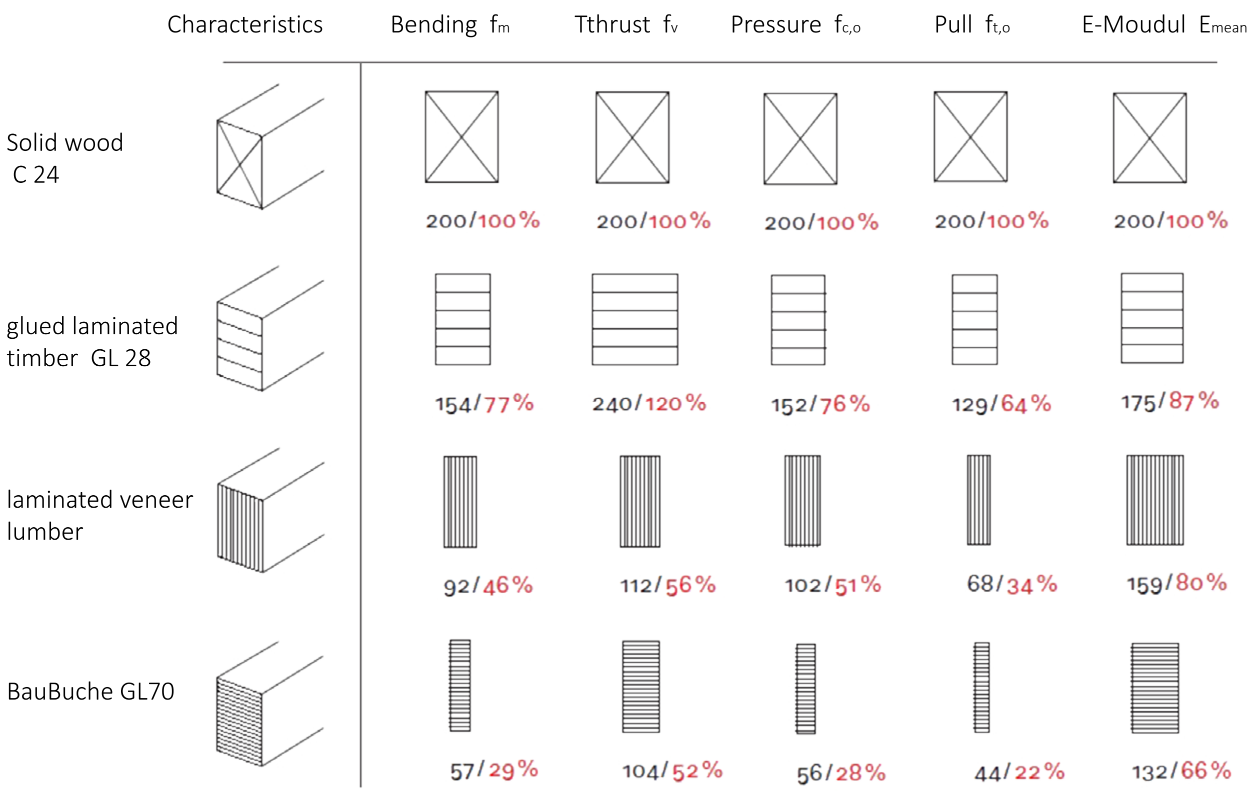



*Figure 44: Comparation of consumption of wood materials at same load.*

**Light weight material**

It is easier to understand the significance of those numbers comparing wood with other materials. The efficiency of timber is mainly because of the lightness associated with its high strength, the modulus of elasticity or the stiffness is almost one tenth of structural steel. As shown in Fig 43, compared with other light-weight materials, wood can provide extra protection of earthquake movement for the reduce of building mass. The ratio of strength over density of the timber pole, indicating material efficiency, is almost 2 times higher than cardboard and 1.5 times higher than steel.

Bamboo is another light-weight material that has high strength in combination with low mass and with higher ratio of strength over density, almost 1.5 times than timber. And they are all natural resource, making them readily available and economically feasible. However, timber is much more widely used than bamboo. Fist of all, timber provides good insulation from the cold and carries the lowest carbon footprint of any comparable building material, which made it a perfect example of an environmentally sustainable product. Also wood is highly machinable, and can be fabricated into all kinds of shapes and sizes to fit practically any construction need, which makes the construction system more makeble and practical to build on site. More over, due to the construction technology, timber can be better combined with exsiting brick work, which is necessary in Groningen.

## Wood

The high strength and stiffness of wood allows smaller cross-sections, which in turn means major savings in material consumption. The dimensioning of a structure is determined by various properties, depending on the particular application, which means the selection of wood products should be made according to different structural behacior. For example, in the case of single-span beams, deformation (stiffness) is generally the key factor, whereas with continuous beams, it is bending strength or shear strength; and with columns and frameworks, it is compressive and tensile strength. The table on the left (Fig 44) shows the amount of material saved by using GL28 glued laminated timber, spruce laminated veneer lumber and BauBuche GL70 respectively, in comparison with C24 solid wood (normal construction timber). It is clear that pruce laminated veneer lumber and Baubuche Gl 70 save more material than glued laminated timber and solid wood when reaching same strength. In this case, this two products are more proper for earthquake resistant projects.

Moreover, due to different fabrication and construction technology, wood materials have different texture, colour and different  kinds of product, which varied in the shape and scale. The further research of the choices between different wood products will be studied in the future based on the project.

*Figure 45: Varied colour and texture od wood material.*

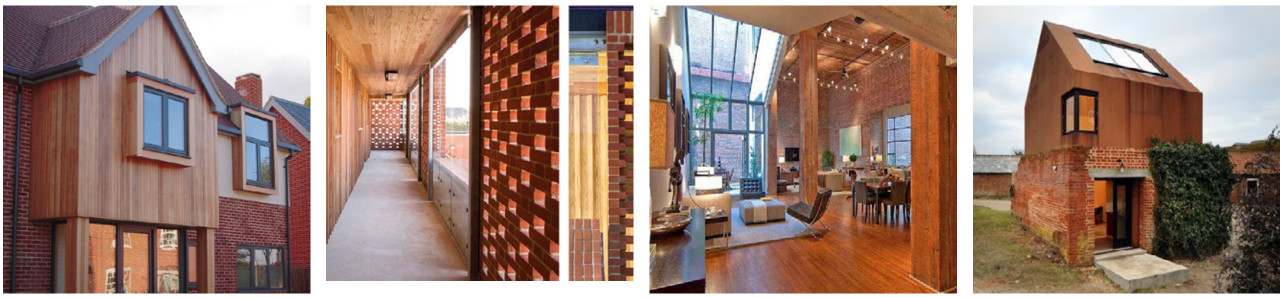
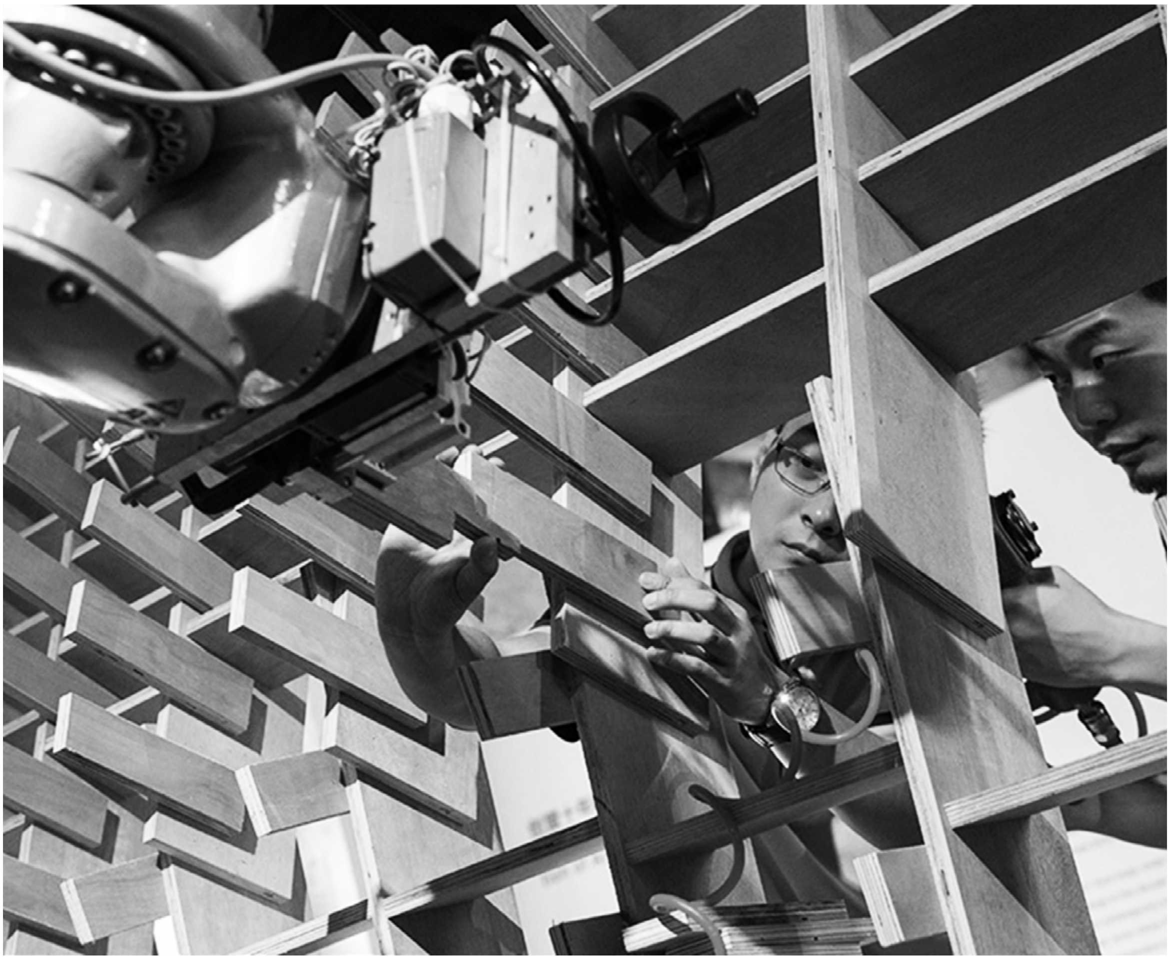


*Figure 46: Wood construction combined with brick.*

*Figure 47: Varied shapes and forms achieved by wood.*

# OPTIMIZATION OF RESTORATION SYSTEM



Seismic optimization of the restoration construction
Optimization of the restoration system

*Figure 48:*
*Restoration process*

# 4.1 Seismic optimization of the restoration construction

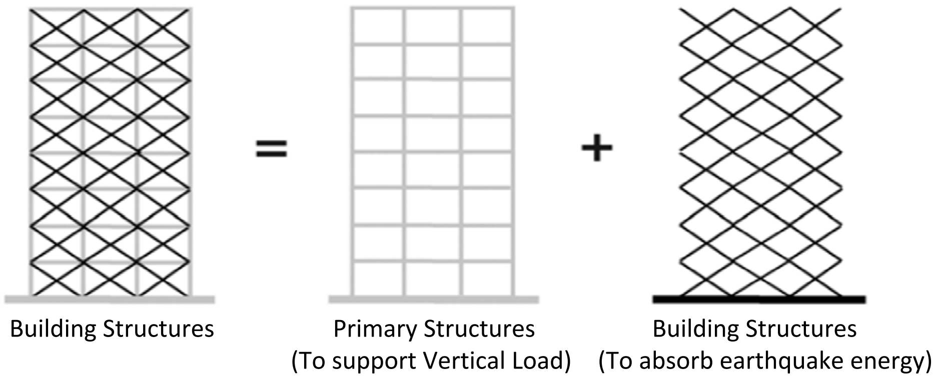



*Figure 49: Concept of damag-controlled structures.*

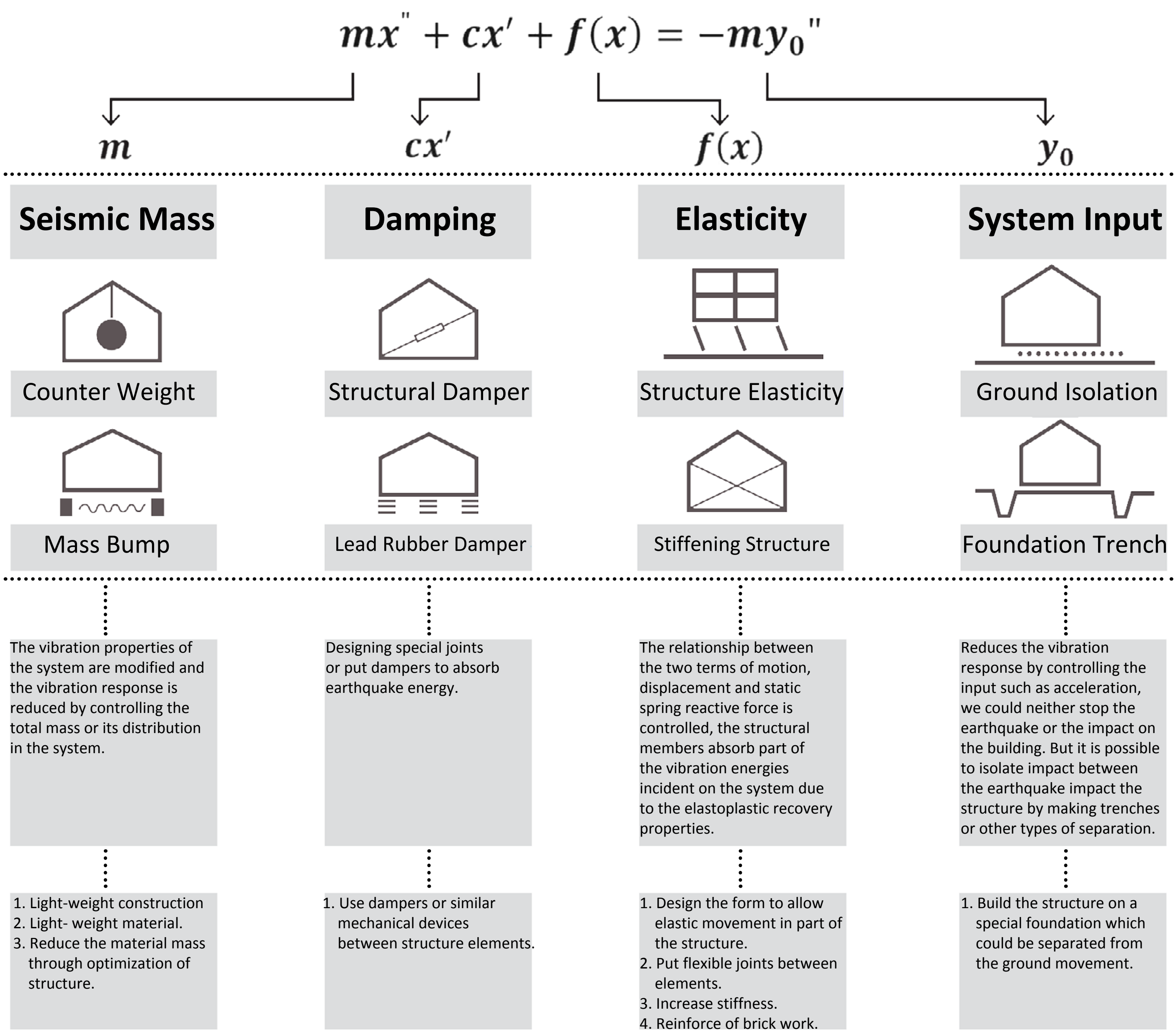



*Figure 50: The equation of motion, different variables involved in sesmic design, ways to improve the seismic structural behavior of the existing masonry building and the complementary wood construction. By author*

In order to optimize the structural restoration system for better performance under earthquake loads, understanding about the response of structure to seismic actions is important to achieve more comprehensive design of the complmenrary construction system to retrofit mansory buildings.

**Response controlled structures for earthquake environment**

Traditionally, while designing structures to withstand vibrations due to earthquakes or wind, the aim was to make the structure vibration resistant by improving its strength, durability and stiffness. In seismic affected countries, more advanced solutions have been applied, devices to prevent the propagation of vibrations or to absorb seismic energy could be installed in buildings to improve earthquake resistance (Fig 49). The primary structure is designed to behave elastically and to retain its building service functions even during a servere earthquake ground motion. And the second is the energy disspating system that aims to control the effects of the lateral forces and deformations resulting from earthquake ground motion.[1]

However, those advanced solutions could hardly be installed in Groningen because they are designed for much intense seismic actions and are too costly for normal buildings. In this case, new ideas which are suitable for the local context should be made based on the understanding of mechanics behind those seismic design solutions. Through the research of principles of "response controlled structures", a simplified overview of how seismic energy affects building structures is studied to optmize the complementary construction system (Fig 49).

**The Equation of motion**

The Respond Controlled Structures is a system of structure in which vibrations are predicted and reduced by damping. In this structure system, the seismic force is described in the following equation of motion:

$$mx'' + cx' + f(x) = -my_0''$$

| | |
|---|---|
| $f_{(x)} = k \cdot x$ | the mass of the building. |
| $x$ | the reactive force developed in the system. |
| $cx'$ | the quantitative response of displacement. |
| $x'$ | the counter-force created by damping. |
| $mx''$ | the speed. |
| $x''$ | the force corresponding to the building's acceleration. |
| $my_0''$ | the acceleration. |
| | the total seismic force created by ground movement. |

To control the quantitative response of the system to external force, (displacement, velocity and spring reactive force developed in the system) It is necessary to control the shape parameters of the system, namely, k (elasticity), c (damping factor) and m (seismic mass) in the above equation of motion or the magnitude of external force

1. < Damage Controlled Structures for Extreme Loading >

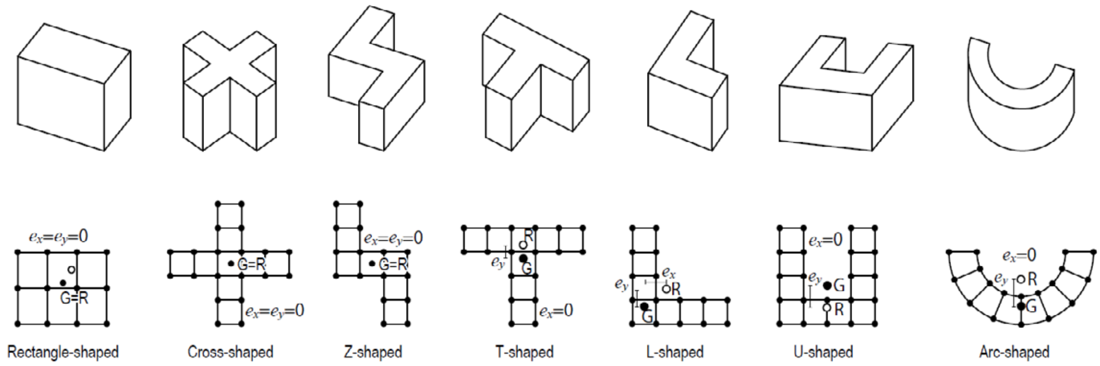



*Figure 51: Shape of construction.*

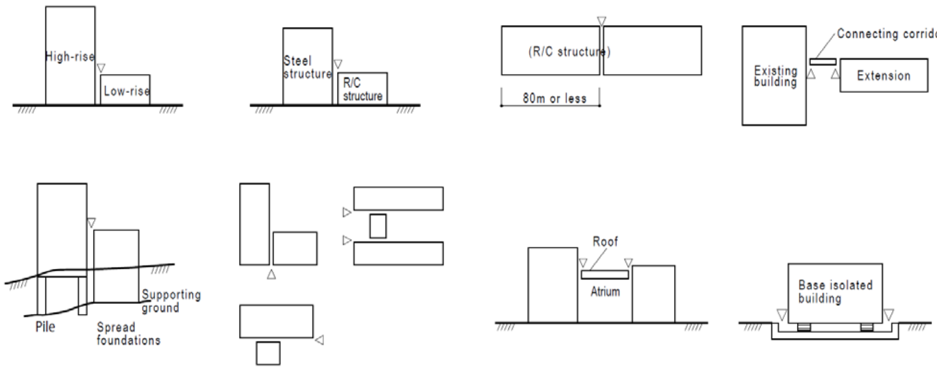



*Figure 52: Expansion joints*

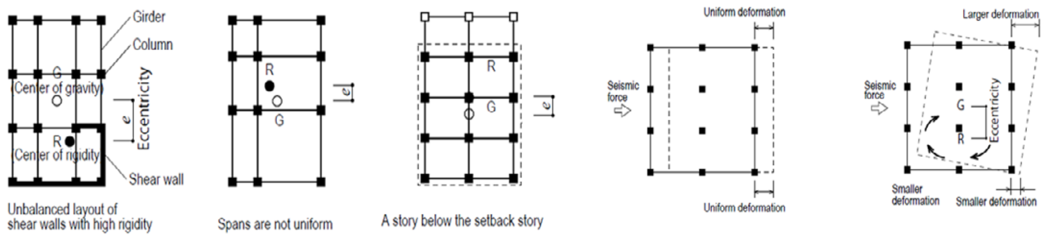
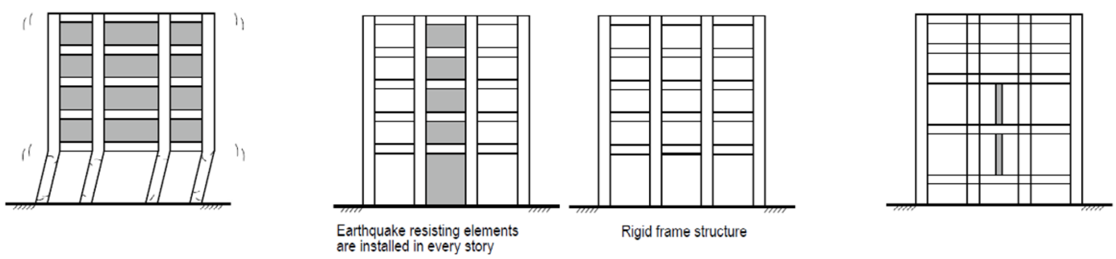



*Figure 53: Planar balance*




Story collapse of a pilotis-style building | Examples of frame style | Installation of studs

*Figure 54: Concept of damag-controlled structures.*

incident on the system (y' in the expression above)[1]

Based on the research in previous chapters and the optimizition by response controlled structure system, there are several ways to improve the seismic structural behavior of the existing masonry building and the complementary wood construction (Fig 50).

**Other principles involve in the structure system:**

There are also many other seismic principles should be involved in the optimization of the construction system.

**1). Shape of the construction (Fig 51)**

The basic idea is to make the construction shape as regular as possible and to ensure its structural frame as a whole is well-balanced. As seen by recently damaged examples, an un-balanced construction in terms of plan or elevation is prone to suffer earthquake damage. Moover, It should be noted that not only obviously irregular-shaped buildings, but also apparently regular-shaped buildings can be unbalanced in terms of earthquake resistant performance. However, an unbalanced building can be made well-balanced by incorporating structural frames and changing the building construction, although such work may increase the cost.

**2). Expansion joints (Fig 52)**

Expansion joints are used to control harmful behaviors in terms of structure caused by fluctuating factors including external forces such as earthquake and wind, temperature change, drying shrinkage, and differential settlement and to ensure structural safety, functions, and good appearance.

**3). Good planar balance (Fig 53)**

A structural element that resists this seismic force is called an earthquake resisting element. When shear walls and columns which are effective as earthquake resisting elements are unbalanced in the stories of a building, the building as a whole may suffer unexpectedly great damage at the time of an earthquake.

**4). Avoid of low rigidity part of construction (Fig 54)**

A difference in structure rigidity and strength or different types of structures in constructions can cause damage at intermediate part in a building.[2]

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1. <Japan Building Center, & Export Committee on Advanced Technology for Building Structures>

2. <Earthquake-resistant Design for Architects>

## 4.2 Optimization of the restoration system

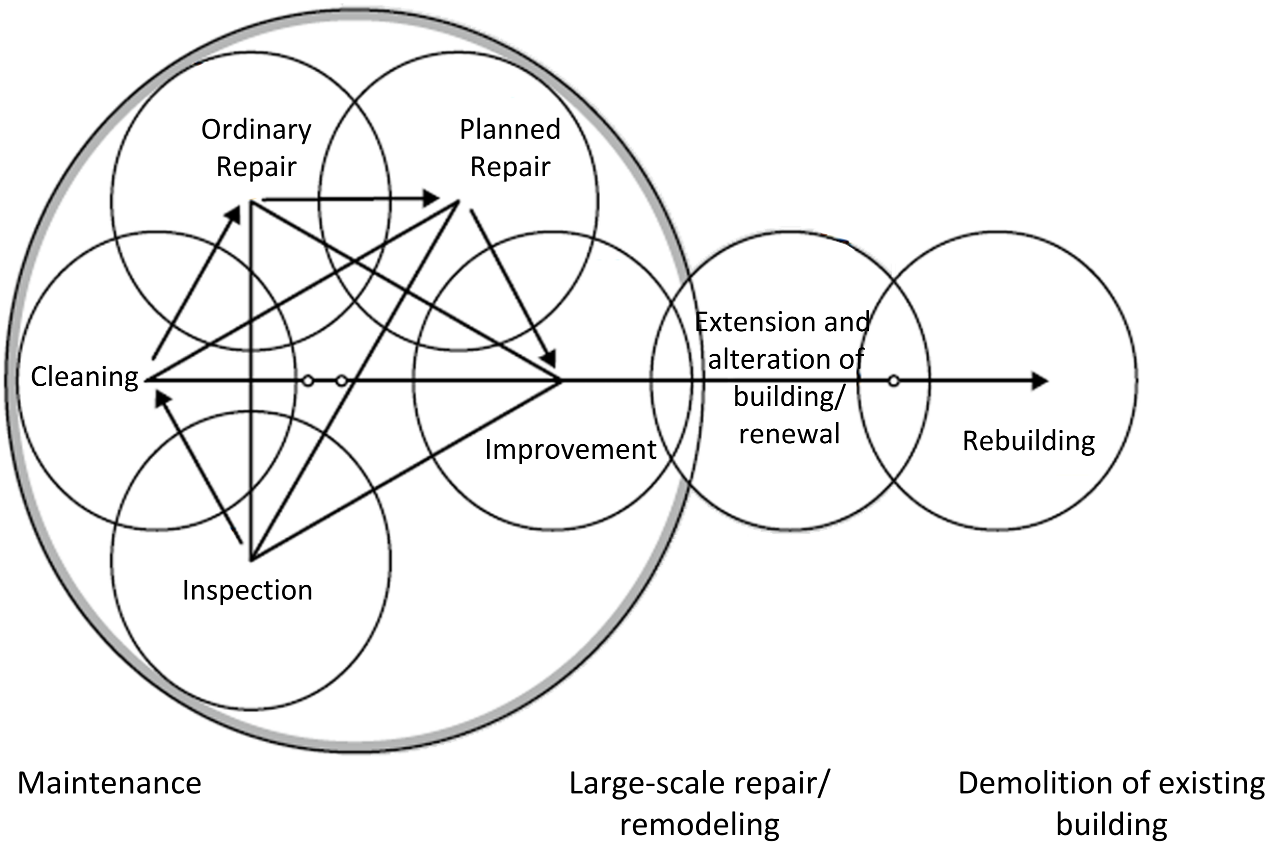


*Figure 55: A conceptual diagram of maintenance, improvement, renewal, and rebuilding.*

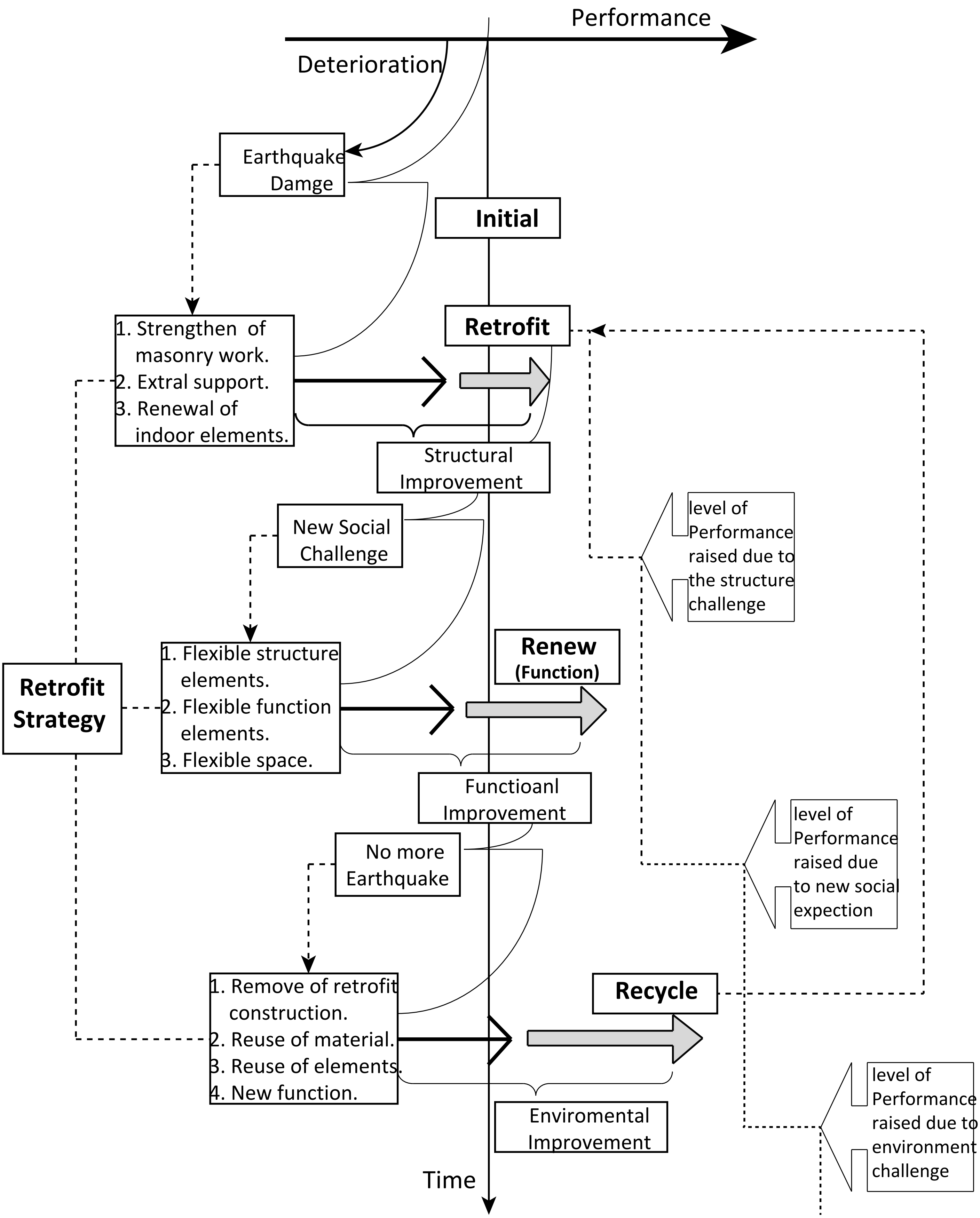


*Figure 56: Diagram of optimization of restoration system, taking a life-long time into account. By author*

**Life-long maintenance of the building**

The wasteful days of “scrap and build” construction are now shifting to the years of appreciation of “stock.” Maintenance, along with repair and improvement of a building start at the completion of construction (Fig 54). Today, systems for creating a sustainable society through careful maintenance and renewal of buildings for hundreds of years are desired. Well-maintained buildings will become more and more regal over time, with a feeling of increasing history and character.

However, when earthquake involves in this process, the maintenance system need to be optimized because of the higher structural standard and new social and architectural challenge.

**Life-long maintenance of the building involve earthquakes -- restoration**

Similar with the maintenance system, the restoration of buildings should take a life-long time of building into account. In this case, the whole process could be devided into three stages (Fig 55):

1.) Retrofit:

In order to repair and prevent earthquake damages, several strategies should be made to improve the structural behavior of the building. Based on the previous research, this is mainly consist of three parts of work: the strengthen of original mansory work, provide extral support by light-weight construction and the renewal of indoor elements by light-weigt elements.

2.) Renew:

The new context of earthquake not only bring higher structural standard, but also new social expections. Due to the lose of public facilities and increase of vacant buildings, the complementary constructions should be flexible and the existing structure and space shoul be renewed to meet new requirements.

3.) Recycle:

As it is reported earthquakes will only last for 50 years in Groningen, the restoration construction should be removble. When the earthquake period ends, the elements could be reuse to design for new function construction. Also during the earthquake period, the broken elements could be recycled to design for new stucture elements (stage 1).

In sum, the restoration of earthquake damaged buildings should not only focus on the repair of exsiting structure, a life-long time span of the improvement of performance of buildings should be taken into account. The construction should be flexible to fit the change of context. Moreover, strategies should be made to recycle the broken or useless structure elements after earthquake period in the further design stage of the project.

# CONCLUSION:

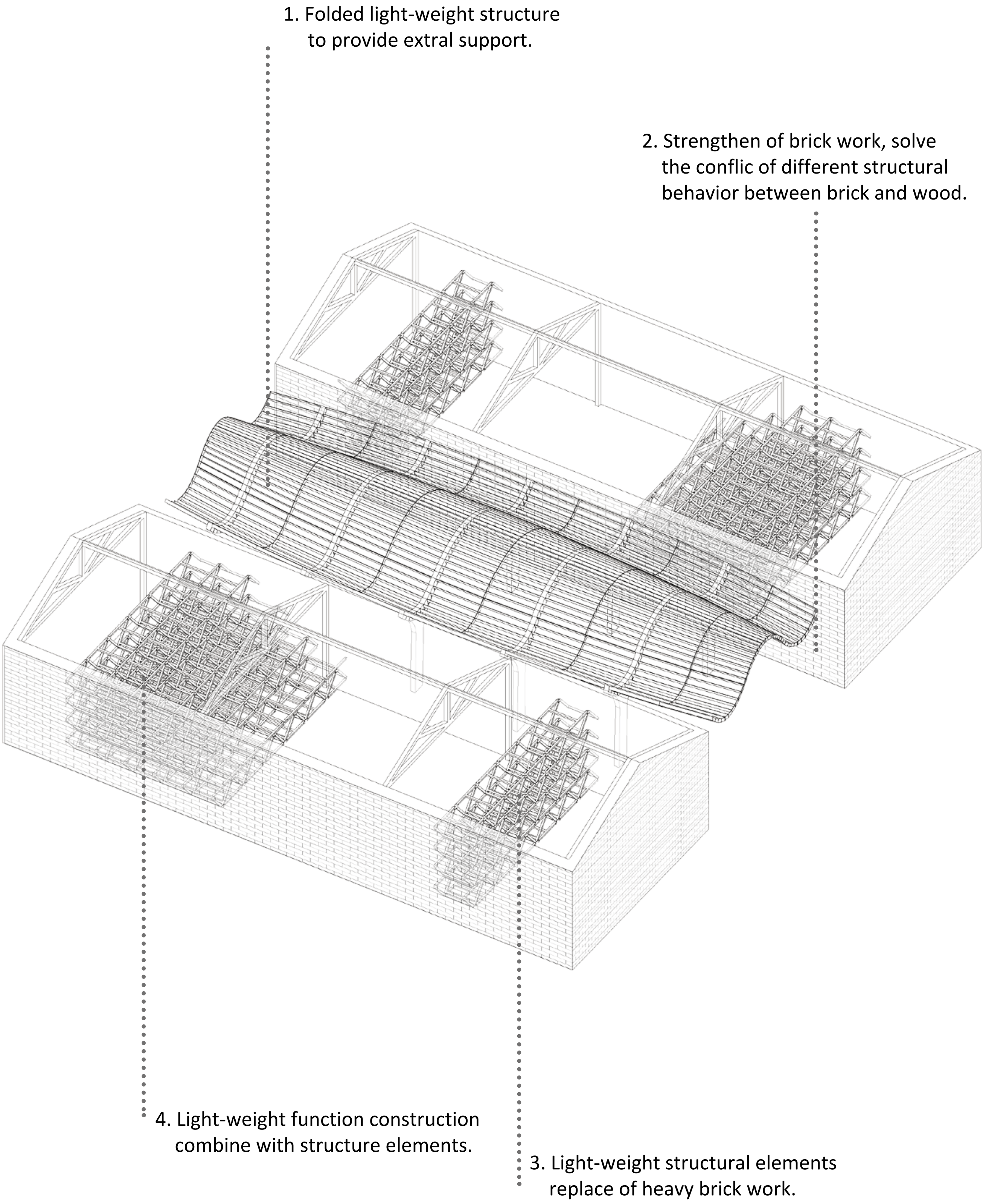


*Figure 57: Diagram of a more architectural and seismic solution by using light-weight constructions.*

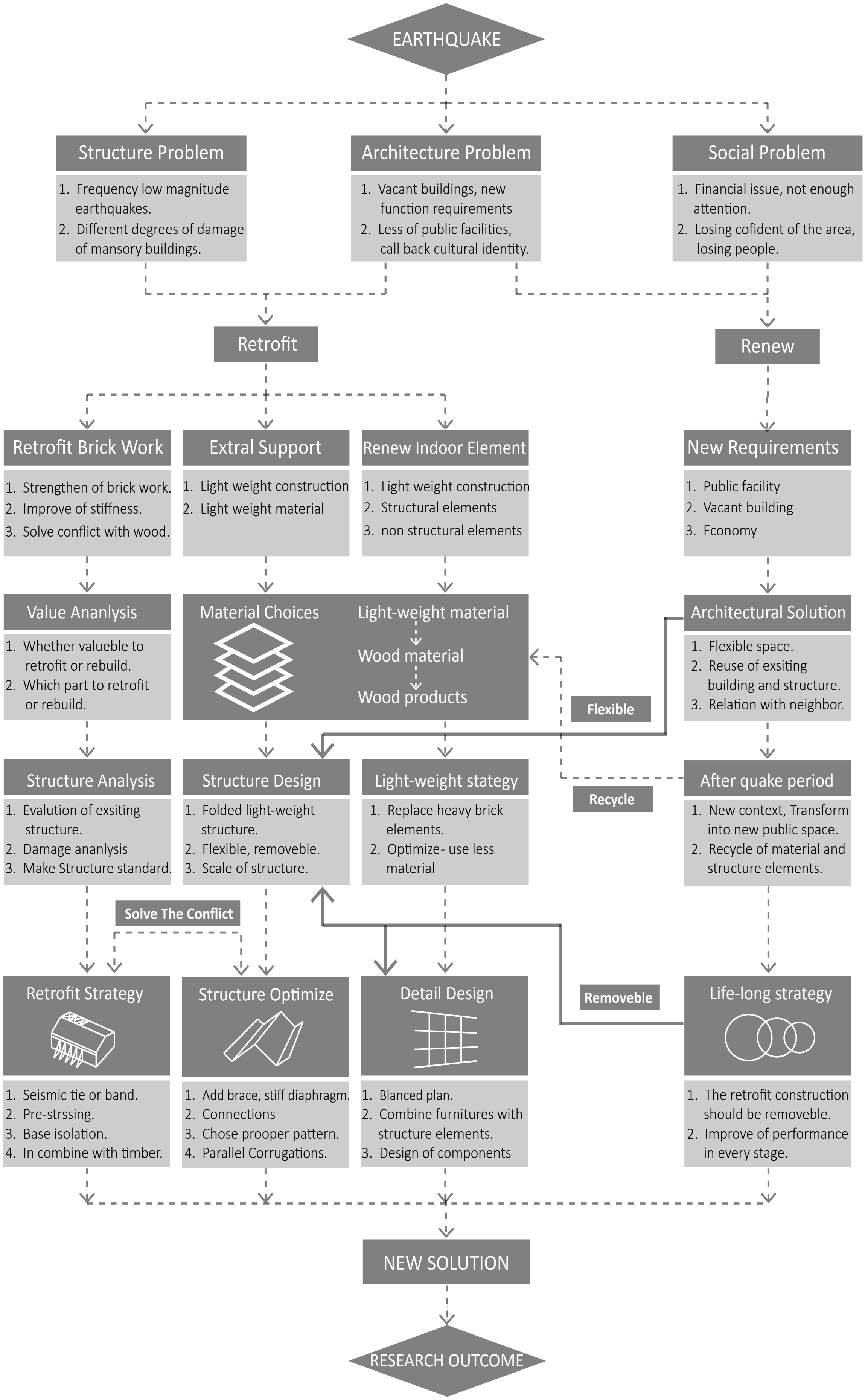


*Figure 58: Diagram of research outcome.*

Since earthquake issues are totally new to the Netherlands, very few studies have been made on the earthquake resistant design. Most retrofit strategy such as extra shoring are roughly done to the existing masonry buildings. Moreover, the frequency earthquakes have caused a series of social problems, especially the losing of public facilities and the increase of vacant earthquake damaged buildings. In this case, new strategies have to be made to solve both structure and social problems.

On the other hand, it is difficult to bring existing building standards and theories from other locations of the world and build differently in Groningen to adjust to the problem. It will be irresponsible to the local context and the rich building tradition of the north Netherlands. Also as it is reported earthquakes will only last for 50 years in Groningen, the retrofit strategy should be flexible and remveble. Therefore, a more critical study to apply seismic design solutions is necessary to make inventions to solve the problems.

The research focus on an more architectural and seismic proof solution to retrofit earthquake damaged masonry buildings by using light-weight complementary wood constructions. In this restoration system, structure elements are developed as volume to provide public space (Fig 57). The research paper presented the exploration and invention of the restoration system in three parts: the retrofit of brick work, extral support by light-weight structure and the renew of indoor elements by light-weight elements.

The retrofit of brick work aims to repair exsiting damage caused by earthquakes and solve the conflict of different structural behavior between brick and wood. Due to the ductility of wood construction and the stiff of brick work, the wood reinforcement may not work when reaching a certain magnitude of earthquake. The brick work may crak or even collapse first before wood reinforcement is damaged. Through the research, solutions to solve this problem could be made based on the analysis of structure and context: seismic tie, pre-stressing, base isolation and reconstuct with timber frame.

By using light-weight structure and material, the external shoring in the restoration of mansory building is enlarged to provide extension space,the space under the structure elements can be used as exterior for public activities. However, with the increase of the span of the structure, the stability of construction during earthquake became weaker. Through the research, a more effective proposal is made to gain strength and stiffness by folded surface. A proper profile and pattern can help to save the material and gain stability efectively. Also this proposal need to be optimized to against horizontal movement during earthquakes such as add stiff diaphragm and pre tension.

The third part of the restoration system is the renew of heavy indoor elements. Heavy brick works such as cross walls could be replaced by constructions made by light-weight materials and the structural elements could be optimized so that the properties of the material can be utilized maximum such as the responsive design of columns. Through the research, a new propasal is made to combine non structural elements and structural elements, not only solve the fixing problems of non structural elements such as furnitures but also provide a flexible interior space.

Moreover, all three parts of the restoration system can be optimized based on the understanding of response controlled structures system. To control the quantitative response of the system to external force, several factors have to be taken into account and controlled, such as shape parameters, elasticity, damping factor and seismic mass. These are the principles to make inventions and optimization of the complementary construction system.

**Reflections**

The research provide a more architectural proposal to retrofit earthquake damaged masonry buildings, not only focus on the structure challenge, but also amis to improve the architrctural performance of existing buildings. This is mainly done through two methods: provide extral volume by light-weight construction as shoring, and the renew of indoor elements. The invention and optimization of restoration system is based on the special situation in Groningen. The frequency low magnitude earthquakes in Groningen requires certain degree of elasticity of the structure. And the rich building tradition of the north Netherlands make the architecture culture in Groningen valuble to be reserved. Moreover, the losing of public facilities and the increase of vacant buildings make it necessary to make strategies to improve existing stock of masonry buildings.

Also, some of the research questions could not be fully answered within the limit amount of time in this paper. For example, the structural performance of different patterns of folded structure. And the solutions are designed based on the reduce of seismic impact and making the structure light-weight and stiff enough to resist seismic loads. More factors have to be taken into account in the practical project, such as the connections and the limitation of different wood products. However, this is not the end of the graduation research, the study will continue in the further design process.

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# LIST OF FIGURES: