EARTHQUAKE ARCHITECTURE
balancing conflicting objectives

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graduation design booklet*
Emilie van Wijnbergen

*Research report, presentation and technical drawings can be sent on request
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Figure 1: The amount of released energy at the hypocenter of the earthquake defines the magnitude (M), the radius (R) defines the experienced intensity (I) at the surface | adapted from NEN-course Vrouwenvelder (2014)
Introduction

In 2012 an earthquake measuring 3.6 on the scale of Richter struck the village of Huizinge (fig.2); this quake was the heaviest so far recorded in the region. This event shocked the community: earthquakes, a serious threat in the Netherlands? The quakes are acknowledged to be caused by the production of natural gas of the Groningen gas field. A predominant part of the building stock is built with unreinforced masonry, which performs poorly during earthquakes due to its brittle behavior and lack of ductility. Many buildings experience tears (fig.3) and are temporarily strutted to prevent collapse (fig.4-6). Besides the large scale upgrading task which lies ahead, the building community is challenged to develop a shock-proof approach for new buildings...

Figure 2: Macroseismic intensity map of Huizinge earthquake 2012 | Source: adapted from KNMI (2014)

Figure 3: Out-of-plane failure and In-plane failure of unreinforced masonry Walls | Source: Rutherford and Chekene
Figure 4: Tear at the lintel of a barn entrance in Loppersum | own image

Figure 5: Temporary steel shoring and removal of balcony out of precaution, Onderdendam | own image

Figure 6: Tear above a window arch, temporary strutting, Loppersum | own image
Research question

Earthquake engineering might seem to be a very technical subject, concerning mainly structural aspects. However, seismic principles and techniques have a large impact and pose serious limitations on the architectural design. Design strategies containing irregular plans, discontinuous elevations, ‘soft’ stories, cantilevers, asymmetric load transfer (fig.7-12) are strongly discouraged... whereas these strategies comprise most of the spatial tools which are used by architects to create functional and meaningful spaces. The question I asked myself was therefore:

How to develop an optimal design strategy dealing with the constraints posed by seismic principles on aspects such as architectural and functional quality?
Figure 8: Unfavorable elevations

Figure 9: Unfavorable (a.) and favourable (b.) elevations

Figure 10: Unfavorable plans

Figure 11: Favorable (a.) and unfavorable (b.) plans

Figure 12: Unfavourable (a.) and favourable (b.) elevations

Sources: diagrams are adapted from Arup (2014)
Research impact earthquake engineering on architecture
Research

Impact earthquake engineering on architecture

Figure 13: Modelling of seismic loads in structures | adapted from Charleson (2008)
First, the performance of existing buildings was researched. What are their weaknesses? What are their strengths? Then I mapped the main seismic strategies and principles to combat earthquake loads, of which horizontal forces (fig.13) form the greatest threat. There are basically 3 main methods (fig.14): a) resistant: making the building stiff or strong enough. This conventional method costs a lot of material. b) vibration control: creating a more flexible building, but dissipating the seismic energy. c) base isolation: reducing acceleration by changing the natural building period. Furthermore, I researched 8 guidelines (fig.15) which are based on principles such as minimizing weight (=load), preventing torsion, providing a better load transfer and dissipating energy.

**Design principles**

<table>
<thead>
<tr>
<th>a. resistant</th>
<th>b. vibration control</th>
<th>c. base isolation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Place resisting elements at perimeter</td>
<td>Build with light materials</td>
<td>Build with ductile materials</td>
</tr>
<tr>
<td>Design a regular plan and elevation</td>
<td>Adequate connections and stiff floors</td>
<td>Prevent re-entrant corners</td>
</tr>
<tr>
<td>Dissipation of seismic energy by dampers</td>
<td>Locate CoM and CoR at same place</td>
<td></td>
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</tbody>
</table>

Figure.14: The 3 main earthquake resistant construction methods | adapted from Japan property central

Figure.15: 8 seismic principles | adapted from Arup, Nexus, McCeer & Charleson
Conflicting objectives

I made an overview of objectives for the building: what is it supposed to do, in what sort of environment does it stand, what are the architectural ambitions and so on. Then I constructed a matrix, matching these building objectives and criteria on the one hand with different reinforcement techniques and strategies on the other hand (aforementioned can be found in my research report). I noticed that objectives are often conflicting with the earthquake principles or structural upgrading techniques. An example is given by showing the conflicts which arise when assessing a potential falling hazard (chimney) of a house in Loppersum (fig.16).

Original chimney: forms a falling hazard

Removed chimney: loss of function (fireplace)

Plastered chimney: loss of aesthetic quality

New chimney: loss of historic quality

Figure.16: Four alternative situations concerning the potential falling hazard of a chimney for a house at the Stationslaan, Loppersum | own images
Seismic strategy

In order to prevent subordinating aspects such as quality and function, it is important to set up an integral performance objective for the building, based on values and criteria which are defined by the several stakeholders of a project. The objectives will help to make reasonable tradeoffs during design decisions and optimize the design within the constraints.

Figure 17: Strategy for seismic design | own scheme
Figure 18: Design location, Loppersum
Earthquake management center

By learning from the weaknesses of the existing building stock, the research provided guidelines and inspiration for the design of a new building in Loppersum: the public interface for the Governmental Department for earthquakes (Rijksdienst voor Aardbevingen). This building will be a representative landmark in the region, housing office spaces, conference rooms and spaces for private consults and the handling of damage claims. An important part of the building is informing, therefore the building will also house a regional information point, a presentation area and media center (see p.30 and p.34 for the functional design). An integral performance objective was set up for the building (fig.19). Besides being a showcase for earthquake proof building, it should be inviting, architecturally pleasing and make use of sustainable principles. Its design will be showcase of how one can build for earthquakes in an innovative way, moving from heavy and stiff structures towards light and flexible methods (fig.20).

**Function**
- no back office: clear routing
- inviting public entrance
- public, semi-public and private functions

**Architecture**
- relation to architecture of the surroundings
- spectaculair appearance
- double height spaces

**Sustainable principles**
- use of renewable materials
- natural lighting
- energy generation
- water re-use

**Structure**
- showcase for earthquake proof building
- innovative techniques
- exposed structure

Figure 19: Integral performance objective
Figure 20: Structural objectives for the new building | sources from: own image, Arup, Kingspan, Andy Buchanan
Context

The location is chosen in Loppersum, which is a central point in the earthquake threatened region. The plot is located in an important part of the village: near the city hall, train station and fire station.

The surroundings are characterized mostly by small scaled masonry houses and some larger farms (fig. 21). The objective aiming to relate to this architecture would conflict when choosing bricks as materialisation: this heavy and brittle building method is not suitable for earthquakes. Therefore I chose to reference another aspect of the local architecture: the pitched roofs of the houses, farms and sheds. By creating a sequence of small scaled pitched roof volumes (fig. 22.a-d), a large internal space is created resembling the farm and shed architecture of the neighborhood. By shifting one side with respect to the other, a spectacular sequence of triangular roofplates is created (fig.22.e). The entrance and exit form an exception (fig.22.g): the first panel folds upwards and the last panel folds downwards. Respectively opening up towards the north and closing towards the south, the design responds to its climatic orientation. Furthermore, this gesture provides some tension and asymmetry in the modest and regular sequence of the façade.

| objective | relation to surrounding architecture: bricks? |
| conflict | heavy and brittle |
| solution | relate to other aspect: pitched roofs/ farms |

Figure.21: Brick architecture, in- and around Loppersum
Figure 22: Mass development | relation to the pitched roofs and farms
Figure 23: The plot lies in a central part of Loppersum, near the train station and the city hall. Accessibility of design location.

Figure 24: The plot is surrounded by small-scaled pitched roof architecture.

Figure 25: The starting point for the design is based on a rectangular grid.
Figure 26: Final design in its situation
Structure

A structural technique is applied (pre-stressed laminated timber technology) (fig. 29). This technique is in conformity with all the earthquake principles stated in the research: placing resisting elements at the perimeter of the building, using light and ductile materials, providing adequate connections, stiff floors, regular plans and making use of energy dissipation. The structure exists of timber elements, with tensioned cables running through which are clamped in the foundation. This approach allows the building to rock back and forth on its foundation (fig. 28). The tensioned cables will pull the building back upright (self-centering). The connections are designed to allow for this movement. The objective of creating an open flow of space conflicts with providing transversal seismic elements (fig. 27). The solution which has been found is the application of portal frames in the transverse direction and pretensioned shear walls in-plane of the façade. The shear walls are coupled and installed with energy dissipators: steel sacrificial elements (fig. 29b) which are allowed to yield (break) and dissipate energy. Since these elements are bolted, they can easily

- objective open space, translucent building
# conflict transversal seismic elements block passage
> solution portal frames

Figure.27: Transverse walls vs. portal frames
Figure 28: Earthquake resistant construction methods | adapted from Japan property central

Figure 29: pre-stressed laminated timber technology, courtesy of Andy Buchanan

a. Controlled rocking
b. Energy dissipation
Figure 30: 3D isometric of the structure highlighting the pre-tensioned coupled timber shear walls

Figure 31: Zoom-in of the pre-tensioned coupled timber shear walls, 3D wireframe
Figure 32: Pre-tensioned portal frame, 3d exploded view

Figure 33: 3D isometric of the structure highlighting the pre-tensioned portal frames
Entrance

The building is designed to have an inviting and translucent entrance façade (fig.37). A gradual sloping stairs guides the visitors inside, inviting them to the entrance platform. The building is put on a solid concrete base, symbolizing the steady ground floor and the detachment of- and contrast with the light timber superstructure. The portals are allowed some rocking on their foundation (fig. 34). A large brittle glass pane would not respond well to this allowed movement. Therefore the conventional glass façade is replaced by (plastic) ETFE cushions which are extremely light (minimizing inertia forces) and can deform up to 3 times their own length (allowing deformation) (fig. 36). A wooden strip frames the plastic cushion facade, and secures the sharp definition of the edges of the angled facade.

- objective translucent, inviting façade
# conflict large brittle glass pane conflicts with intended movement
> solution plastic cushion façade
  - extremely light (1% of weight of glass)
  - can deform up to 3 times its own length

Figure.34: Scheme of the potential movement of the facade portal | own image

Figure.35: 3D isonometric scheme of the building design
Figure 36: Vertical section of the front facade | own image
Figure 37: Building entrance | own image
Entrance area

The communal entrance platform provides space for information services and the entrance desk. When entering the building, visitors can look into the open office area through the glass screen (fig.38) providing them with literal insight on how employees are working on the problems caused by the seismic events. A generous stairs leads upwards to the public area and serves as a resting place for visitors (fig.39). Employees descend a few stairs to the office area (fig.40), providing a gradual transition into the concentration zone of the working space.
Figure 40: Maquette photo of the entrance desk and view for visitors into the office spaces | own image
Climate considerations

Sustainable principles are included in the scheme by making use of the buildings climatic orientation: roof panels are closed towards the south and translucent towards the north (fig.42b), allowing indirect natural light to flood into the building (fig.41). The large angled roofsurface at the exit is equipped with PV-cells (fig.41a). The angled roof naturally collects the rainwater at concentrated points, providing an excellent opportunity for the collection of rain water.

- objective exposed seismic structure
# conflict shafts necessary for ventilation, heating, cooling
> solution building services are included in the floors

The sanitary units, washbasins, kitchen, cleaning utilities are placed strategically at these locations for grey water re-use (fig.42d). Floor heating offers comfort (fig.42c). Ventilation is achieved through fresh air inlet by vents in the floor, providing the opportunity for aesthetically pleasing exposed ceilings and structure. The outlet of air is achieved by placing vents supported by mechanical pumps at the highest points of the gabled roof (fig.42e,f).

Figure 41: Maquette photo of the open roof panels viewed from the public space | own image

a. Closed towards the south: PV cells
b. Open towards the north
c. Heating scheme

d. Rain water collection and grey water re-use

e. Ventilation scheme | ground floor

f. Ventilation scheme | first floor

Figure 42: 3D isonometric climate schemes of final
Public area

When ascending the stairs one enters the public area on the first floor, designed as one open space with differentiated zones. For people with mobility problems, this floor can be reached by a transparent elevator. The public floor houses private consultation spaces (3) for the support and handling of complex damage cases, a workshop area (4) for more informal meetings and stakeholders sessions, a knowledge center (5) and exhibition & multimedia space (6) for enhancing knowledge on the subject. The spaces above the sanitary units offer informal seatings and with a nice view on the communal platforms.
Roof

The large span covering the public space is achieved by applying a folded plate structure (fig.44). The upper- and lower beam work together combining plate and bending action (fig.45). To ensure the connection of the top and bottom beam, the closed panels are equipped with a stiff Kerto Q timber plate and the translucent panels with a truss structure. The ribs of the roof panels are exposed, which provide the roof with interesting tectonics (fig.46).

| - objective | large public space |
| # conflict  | larges spans can result in heavy structures |
| > solution  | folded plate structure provides slender elements |

Figure.44: 3D isonometric scheme of the building structure with highlighted roof truss

Figure.45: A zoom-in of 3D isonometric of the building structure, indicating the collaboration of the upper- and lower beam of the roof truss

Figure.46: > Maquette photo of public space showing the sequence of roof panels and exposed supporting ribs | own image
Office area

The office area is designed along a spacious linear routing, offering space for casual meetings, coffee drinking and printing, with an open office arrangement (b) and some private offices (c). The space also offers storage, a multifunctional (h) and conference room (g).
The flexible character of the building is expressed by showing the hinged connection of the middle columns clearly in the pathway of the offices (fig. 48). The first floor is executed as a concrete timber composite floor (concrete screed, with a timber plate attached to timber floor joists by skewed screws). Besides being light, stiff and providing a concrete screed for floor heating, this floor type provides an aesthetically pleasing tectonics in the exposed ceiling of the offices.

| objective | concrete floor as stiff diaphragm, thermal mass |
| conflict | heavy floor generates high inertia forces |
| solution | concrete timber composite floor |
|           | - light and stiff |
|           | - space for floor heating of first floor |
|           | - aesthetically pleasing |
|           | - linearity of planks in exposed ceiling |

Figure 48: impression of the tectonics of the office area | own image
Figure 49: 2D scheme of allowed movement of the portal frame

Hinged connections are designed in the beam and column carrying the first floor, in order to meet the allowed movement due to the controlled rocking of the portals (fig.49). At one end of the beam a sliding connection is required: this has been achieved by creating a clearance space in the beam instead of the column (fig.50), to avoid interference with the cables running through the column.

- objective: controlled rocking of pretensioned portal frame requires a sliding connection with the first floor beam
- conflict: slot in column for sliding connection interferes with cables running through column
- solution: clearance space is made in beam, not in column

Figure 50: Zoom in of sliding connection
Figure 51: 3D exploded view of a portal frame - hinged connections are designed to cope with the allowed movement.
Side façade

The structure is designed to have asymmetric portals. The allowed movement can result in torsion in the façade, since the deflection of the portal legs can differ (fig.53). This is solved by applying narrow façade cladding panels: timber sandwhich panels. In the connections between this panels there is tolerance to cope with the deflection (fig.52). De façade openings are designed to reflect the interior programme: a vertical narrow strip of glass shows the energy dissipators between the coupled shear walls, a long horizontal window strip shows the open office spaces and the larger window openings are located on the public floor (fig.54). To provide enough flexibility, all the windows are built out of narrow strips, allowing tolerance in each frame. The sandwhich panels are clad with wooden slats, made out of Accoya wood: this is (fast-growing) Radiata Pine wood which has been treated in a sustainable way by a specific kind of vinegar to combat the nestling of insects.

- objective asymmetric portals for spectacular roof sequence
# conflict torsion in façade
> solution narrow façade cladding strips: flexible timber sandwhich panels

Figure.52: The connection between the sandwhich panels provides some tolerance | Kingspan panels

Figure.53: 3D isonometric showing potential torsion of the façade | own image
Figure 54: Maquette photo of the side façade | own image

Figure 55: Maquette photo of the side façade | own image
Presentation and cantine area

The generous stairs leading towards the second communal platform (fig. 56) offers seating space for presentations on structural upgrading or damage repair. It also houses a kitchen, bar and lunch area. After a hopefully helpful visit to the center, visitors can literally walk back a bit lighter and brighter, walking towards the sequence of translucent roof panels (fig. 58).

Figure 56: 3D isometric of the interior highlighting the presentation area

Figure 57: Maquette photo of the exit showing the exit and presenter space| own image
Figure 58: Maquette photo of the platform showing the stairs (tribune for presentation), the bar and cantine area | own image
Secondary roof structure

Primary roof structure

First floor

Ground floor

Facade

Folded plate structure

Stiff but light timber concrete composite floor slab

Light and flexible timber sandwich panel cladding

Gravity force frame

Post-tensioned portal frames

Post-tensioned shear walls

ETFE facade (plastic cushions) - light weight

energy dissipation by means of sacrificial steel elements

Figure 59: 3D exploded view of the building structure
Conclusion

The design has resulted in an exciting building, made shockproof by all kinds of innovative earthquake principles. In the process of finding optimal design solutions within the constraints, it is found that solutions have often led to interesting visuals and pleasing aesthetics. The design is intended to function as an example how architecture can cope with the new seismic circumstances of Groningen, caused by the gas production.