The design of a multifunctional exhibition hall

*When acoustics integrate with the structural design.*
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Preface

This master thesis is the finalization of the last year of my master track of Building Technology at the faculty of Architecture at Delft University of technology. The subject of this thesis is the result of my interest for structure and the possibilities of integrating this with the architectural design. This thesis gave the opportunity to combine the knowledge obtained in the past 5 years of my study with my personal interest in acoustics and thus this thesis will extend my fields and depths of knowledge. During the development of the design, shape studies were an important part and showed that shapes for the different functions often conflict, narrowing down the possibilities for the ‘ideal’ design.

I would like to thank ir. J.E.P. Smits and dr. ir. arch. M.J. Tenpierik for their guidance during the graduation process. Also I would like to thank Wiep Juckers, facility manager of the WTC-expo for her cooperation.

Lotte Roosmarijn Baerends
Abstract

This report describes the development of a multifunctional building and the research that supports the design. The question was “what are the characteristics of a multifunctional exhibition hall of which the structural design is integrated with the variable acoustical design and of which the acoustic properties are used as decisive factors in the visual appearance of the design?” Combining acoustical shapes with structural design can lead to intriguing forms. Using computer analysis, literature studies and case-studies a concept design was developed.

As a foundation for the design the existing exhibition complex WTC expo Leeuwarden was used. The new hall replaces an existing hall and thus it has to be an addition to the functionality of the building, rather than a replacement. This has been done by not creating a hall only functional as an exhibition hall but as a concert (amplified music) hall, acoustical music hall and speech hall as well. Especially the acoustical music hall should meet very specific acoustical properties. The other functions have different acoustical properties. The other functions have different acoustical properties. The exhibition hall requires an empty floor plan, which results in a challenging structural design scope as well. To minimize the amount of materials needed for the structure the aim is to integrate the acoustical shape and materialisation with the structural design.

Literature study explains the relation between sound waves, frequencies, reflections and how they contribute to the experience of the audience in a concert hall or auditorium. Important elements for the experience of the receiver of the sound are envelopment, reverberation, clarity and loudness. Envelopment depends on the sound direction as perceived by the receiver. A larger variety of sound directions results in a better envelopment, which is desirable for music related functions. Reverberation time, clarity and loudness can be analysed objectively. The current shapes of concert halls are derived from optimization of either view or envelopment, but not both. The rectangular and hexagonal shaped concert halls are the most successful in combining a good view and envelopment.

Folding techniques have been inventoried. By folding the roof or wall, a surface is created which can diffuse the lateral sound reflections and create a better envelopment. The angle of the folds and direction of the surfaces strongly influences the envelopment. They function best when the folding lines are parallel to the main sound direction.

The exhibition building in Turin, designed by Nervi, shows how a structure with a large span can be reached with a minimum amount of material. Nervi also designed the UNESCO conference building in Paris. This building is an example how structure can be combined with the acoustical shape of a hall. While these projects where used as an inspiration, ‘de Spiegel’ in Zwolle is an example how moving elements and changing volumes can change the reverberation time and clarity of a hall.

Based on the literature study and case studies, a concept was developed where a folding technique is used to create the wanted diffusion in the concert and acoustical music hall. While the folding technique also allows the structure to change its shape volume and floor surface. This way the amount of unneeded area is minimized, which reduces the climate demands. The dynamic exterior fits the changing function of the building and results in a dynamic interior as well. To create the dynamic exterior a pattern combining X- and V-folds was used. This pattern is mirrored over the centre of the hall to form the second part, resulting in a three-hinged span. Research shows that, without any additions to the structural design, the best envelopment, clarity, loudness, reverberation and echogram is reached by using 16 of the folded ribs, which have a width of 10 meter when they are unfolded.

The folding shape is also a strong structural shape. Glass fibre reinforced plastic is a lightweight material with high tensile and compressive strength and was used to create a structural shell. Due to its poor acoustical insulating properties the material rigid polystyrene foam, which is a common material in sandwich panels, was not used.
as insulation on the inside of the panel. A hard rock wool, which has a good sound absorption property, was used. Calculations have shown that a thickness of 260 mm was needed to reach a $R_c$-value of 6 $m^2 K/W$. This results in a theoretical $R_w$-value (sound resistance) of 97 dB. The hinge used for the connection of the composite panels is a longitudinal composite fabric hinge developed by Vosmaer. This hinge is easy to fix on the building site. The hinge does not use any thermal insulation, therefore profiles are added to the outside of the structure to minimize sound leakages and thermal bridges.

The side walls of the structure change shape as well. To close off the wall triangular composite panels are sliding over each other. When the structure changes shape, the wall is able to move along.

These panels and the structural composite panels can be produced in a large hall using molds. Because of the location of the WTC expo, the composite panels can be transported by ship to the building site. If the structure would be built on a different location, the elements should be made in smaller parts and joined on the building site.

The acoustical music hall and the speech hall are designed to be the smallest configuration of the hall. The speech hall has a reverberation time of 0.78 seconds and a clarity (C50) of 2.0 dB. The acoustical music hall has a reverberation time of 2.28 seconds and a clarity (C80) of -0.8 dB, these results are desirable. The transformation between these two functions is achieved by flipping the panels of the internal wall. These panels function as doors at some locations, but their main purpose is to contribute to the acoustical design, as one side of the panels is perforated and functions as an absorbing surface while the other side reflects most of the sound. Panels can be added to the side of the entrance doors to absorb sound as well. When the hall is used for a speech related function a reflector is placed above the stage, to reflect sound more directly rather than diffuse. The back side of the reflector is an absorbing surface as well. Because the panels behind the stage can be flipped to reflect or to absorb sound, a large variety of reverberation can be created between 0.78 and 2.28 seconds.
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1. Introduction

At this moment there is a large variety in the size and architecture of exhibition halls that are being used as multifunctional buildings. These buildings are generally not known for their pleasing appearance. In reality they are known for the variety of functions and activities that take place inside the building. This variety of functions and activities is not being reflected to the buildings surroundings, as the outside as well as the inside commonly looks like a rectangular box.

1.1 Problem statement
A modern approach of architecture states ‘Form Follows Function’. An interesting approach to architecture with famous examples by Le Corbusier and Mies van der Rohe. This approach could be interpreted as a form which follows the program functions. For example the functions in an exhibition hall demand a large roof span, which is a defining factor for the construction. However when we look at the commonly used rectangular shape of an exhibition hall with a truss structure, it can be questioned if a flat roof is an desirable shape from a structural point of view as well as the acoustical point of view.

Exhibition halls (jaarbeurzen) are mainly used for commercial exhibitions. These exhibitions can divers from book exhibitions to boat exhibitions. In order to be able to manage these diverse exhibitions the halls are designed to cover a large surface, without any obstructions on ground floor level. The exhibition halls are also occasionally being used for music events such as concerts. If an exhibition hall would be designed to have convenient acoustical properties for music themed functions, it would be more multifunctional. Meaning the exhibition hall could be used more frequently.

1.2 Goal
When these problems are stated in a more positive manner, they are points for improvement which can be translated into an interesting design challenge. The ideal shape from a structural point of view could be detrimental for the acoustical performance in the exposition hall and vice versa. However if the structural and acoustical shapes would coincide, it would strengthen the architectural design. Therefore the goal of this graduation is to create an integral design for an exhibition hall located in the Netherlands. The design is an extension of an existing exhibition hall. In the design the shape (form) should be primarily functional from an acoustical point of view, but also when it comes to construction and functionality. To ensure multifunctionality variable acoustics will be needed in the exhibition hall. In addition a pragmatic design approach will be used during the design process, so the principles of the design can be repeated when similar design issues occur.

1.3 Research question
The substance of the research is as follows. “What are the characteristics of a multifunctional exhibition hall of which the structural design is integrated with the variable acoustical design and of which the acoustic properties are used as decisive factors in the visual appearance of the design?”

1.4 Methodology
To create a structural and acoustical integrated design, which meets the set goal, the design is divided in multiple components: design scope, theoretical frame work, concept design, final design and analysis. This division can also be found in the structure of this report. These components are parts of the pragmatic design method and will be clarified below.

Design scope
It is important to gain insight into the requirements for an exhibition hall. This will partially be done by analysing the existing precedents and partially by researching the imposed preconditions and program requirements.

Theoretical framework
In order to achieve the goal it is important to gain theoretical insight on the different aspects of the design: structural shapes, acoustical shapes and material properties. This will be done using literature studies.
**Concept design**

In this phase the theoretical knowledge gained in the previous phase will be combined to create variants of an integrated design. By analysing these variants a substantiated choice can be made for a concept design. These analyses are executed using ANSYS, which is a finite element software program, and CATT-acoustics. The concept design will focus on the structural shape and acoustical shapes.

**Final design**

In this phase the integral design methodology will be carried on to develop the final design. Meaning design, development and research are inseparably connected in this design process. (Eekhout, 1997) In this process, the design will be visualized using drawings and models. Where the focus was on the global shape and dimensions, the focus will now shift to detailing building components. However this does not exclude changes in the global shape, nor does it mean the research is finalized, because of the integral design methodology, which connects all components of a design together.

**Analysis**

In this phase the design will be analysed to see to what extend the goal has been reached. This will be done by analysing the drawings, using a finite element software program (ANSYS) for structural calculations and by using the software program CATT-Acoustics for the acoustical properties.

The different phases of this process can be distinguished in the graduation report, although they form a cyclical process during the design phase. See figure 1.1.1.
2. Design scope

The project design will show an alternative design for two of the exposition halls, which are part of the expo-complex in the city Leeuwarden, located in the Netherlands. This complex is also referred to as the WTC-expo. The analysis of the expo-complex will create an understanding of how the design works (routing, functions, etc.). Based on the analysis the requirements can be determined.

2.1 WTC-expo analysis

2.1.1 Location

The Expo-complex is located on the west border of the city Leeuwarden. On the east side of the building there is a road, connecting the building with public transport utilities and the city infrastructure. East of this road a residential district is located. A business park is located on the west side of the building. Thus the building is located on the border between the residential and commercial buildings. See figure 2.1.1 and 2.1.2.

2.1.2 Functions

The current Expo-centre accommodates a variety of functions (WTC Expo, 2014):

- Conference rooms
- Exhibition halls
- Hotel
- Catering/Restaurant
- Holland Casino
- Office space
- Parking lots
• Indoor ice rink
There are multiple exhibition halls in the building complex:
1. Friezenhal 1+2  10.260 m²
2. Friezenhal 3  2.000 m²
3. Batavierenbalkon  2.000 m²
4. WTC passage  3.500 m²
5. Frankenhal  5.700 m²
6. Saksenhal  8.925 m²
7. Keltenhal  4.080 m²
The total surface of the exhibition halls covers 36.465 m². Most of the exhibition halls have a height of 8 meters. The smaller exhibition halls (Batavierenbalkon, Friezenhal 3 and WTC passage) have an height of respectively 3, 8 and 4 meters. The expo-complex has a maximum capacity of 30.000 people.

The exhibition halls are used for multiple events such as exhibitions, but also for music events, in example the Fryske Music Night and Taptoe Groningen. The acoustical properties of the exhibition halls are important for these music events, especially for the acoustical events. When an exhibition hall is being used for a music event, usually only one hall is being used. However for exhibitions, multiple halls are being used.

The WTC passage is the main entrance of the expo-complex on the west side and can be reached from the parking lots, which are located in the business park. The WTC passage is used for exhibitions, but also functions as an hallway creating connections between
the exhibition halls and other functions. In addition to the internal connections there are also multiple exits in each of the halls. This has to do with fire safety.

There are 4 groups of toilets spread across the expo-complex, which are made available for visitors. Each group consists out of approximately 16 toilets (8 for men and 8 for women). Catering can be located at multiple locations and is portable.

According to Mrs. Wiep Juckers (personal communication, 6th May 2014), the facility manager of the WTC expo complex, there are a few desirable improvements to the current building design:
- More roof insulation, because of the sound and noise transmission.
- Increase the height of the complex to a minimum of 14 meters.
- Replace the current lighting with dimming LEDs.

### 2.2 Program of requirements

In order to be able to go into more detail, this thesis will be focussing on a new design for the Saksenhal and Keltenhal. The program of requirements is based on the current functions and surfaces of the Expo-complex. The requirements can be divided into function, dimensions, building physics and the effects this will have on the design, functionality and construction.

#### 2.2.1 Functions

The Saksenhal and Keltenhal can be used for commercial exhibitions and music events. The halls have to be usable for a variety of these events. There are no toilets located in these 2 exhibition halls.
- Exhibitions
- Amplified music events (concerts)
- Acoustical music events (orchestra, etc.)
- Speech related performances (theatre, opera, etc.)

These functions require a design with variable acoustics. The spatial quality would be increased if the 2 halls could function as one hall as well as 2 separate halls. Also to maintain the connections and routing, the halls should have a connection to the WTC passage. Electricity and water supply is needed in both halls.

#### 2.2.2 Dimensions

The exhibition area is divided over 2 halls. These halls share similar requirements for dimensions. The dimensions vary because of the variable functions and are listed below.
- Floor surface: 1.710 [m²] - 13.005 [m²]
- Free height: 7,0 [m] - 16,7 [m]
- Volume: 12.000 [m³] - 182.070 [m³]
- Doors: minimum 5,94 meters width and 6 meters height

The dimensions for each function are listed in table 2.1. The floor surface for the exhibition function is based on the existing surface. The floor surfaces and amount of visitors for the acoustic music function and speech function are based on the maximum surface formulated by Beranek (Beranek, 2004). The height for the amplified music function (>14m) is based on the demands of the owner of the WTC expo. The heights for the acoustical music function can be calculated using the following formula:

<table>
<thead>
<tr>
<th>Function</th>
<th>Floor surface</th>
<th>Room volume</th>
<th>Room height</th>
<th>Visitors</th>
<th>Reverberation time</th>
<th>Objective clarity (C)</th>
<th>Loudness (G 500/1000 Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exhibition</td>
<td>13.005 [m²]</td>
<td>182.070 [m³]</td>
<td>&gt; 14,0 [m]</td>
<td>10.710</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>Amplified music</td>
<td>6.500 [m²]</td>
<td>84.500 [m³]</td>
<td>&gt; 14,0 [m]</td>
<td>5.355</td>
<td>1,0 - 1,6 [s]</td>
<td>C80 0,0 - 2,2 [dB]</td>
<td>5,0 - 15,7 [dB]</td>
</tr>
<tr>
<td>Acoustic music</td>
<td>1.710 [m²]</td>
<td>28.600 [m³]</td>
<td>16,7 [m]</td>
<td>3.000</td>
<td>2,0 - 2,3 [s]</td>
<td>C80 -3,0 - 0,0 [dB]</td>
<td>1,5 - 5,5 [dB]</td>
</tr>
<tr>
<td>Speech function</td>
<td>1.710 [m²]</td>
<td>12.000 [m³]</td>
<td>7,0 [m]</td>
<td>3.000</td>
<td>&lt; 0,8 [s]</td>
<td>U50 &gt; 1,5 [dB]</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

Table 2.1 List of requirements
Source: (Barron, 1993; Beranek, 2004; Nederlof, 2005; Nijs, 2014)
\[
\frac{V}{N} = 4,1 \times \left(\frac{S_{\text{floor}}}{25}\right)^{0.20}
\]

Which results in a total volume of 28.500 m³. When dividing the volume with the floor surface this results in a room height of 16,7 m. For the speech function the height can be calculated by using an average volume of 4 m³ per visitor, resulting in a total volume of 12.000 m³. The volume divided by the floor surfaces results in a height of 7 meters.

2.2.3 Building physics
There are multiple important building physical properties that have to be taken into account in a multifunctional exhibition hall.
- Variable acoustics
- Sound insulation (decrease sound pollution to the surrounding)
- Water tightness
- Building temperature
- Ventilation
- Variable lighting

These properties have to be sufficient for a maximum capacity of approximately 10.710 people and a minimum capacity of 3.000 people.

The acoustic performance of a hall or room is related to the reverberation time. The desirable reverberation time depends on the volume of the room and the function, see table 2.1. Compared to a small room, a longer reverberation time is more desirable in a large room. For a variable acoustic design, it is important to create the possibility to vary the reverberation time. The reverberation time that has to be taken into account for each function is listed below. Variation of the reverberation time can be influenced by size, which is taken into account in the dimensions in table 2.1, another solution could be adding absorption to the room to reduce the reverberation time. An estimation can be given using the following formula:

\[
T = \frac{1}{6} \times \frac{V}{A}
\]

\[T = \text{reverberation time}\]
\[V = \text{volume}\]
\[A = \text{absorption surface}\]

To estimate the needed absorption when changing from acoustical function to speech function we assume the volume stays constant. Meaning for the acoustical function:

\[A = 2.160 \text{ [m}^2\text{]}\]

For the estimation we assume this surface can be reached with the surface of the audience. The formula for a speech function is as follows:

\[A = 4.750 \text{ [m}^2\text{]}\]

Which means approximately 2.600 [m²] of absorption surface has to be added. The total available surface in the hall is approximately 4.532 [m²]. Now the absorption coefficient can be calculated:

\[
\bar{a} = \frac{2.600}{4.532} = 0.55 \text{ à 0.6}
\]

This shows that the variable reverberation time can also be reached using absorption material, as higher absorption coefficients can be reached.

Other acoustical requirements, such as objective clarity and total sound level are listed in table 2.1 and clarified in chapter 3.1.

2.2.4 Construction and design
The construction is an important part of the design and should be designed according to the following guidelines.
- Shape optimized for structural force flows through the construction and acoustics.
- Acoustical shape integrated in the construction.
- Structural material selection with consideration of sustainability and acoustical properties.

Using these guidelines will influence the architectural design. The visual outcome of the design should be a reflection of the structural and acoustical requirements. The facade should create an attractive view for the inhabitants of Leeuwarden. Also it should reflect the different volumes, which were created on the inside of the building.

2.3 Preconditions
The WTC-expo is in possession of a large land estate. The new exhibition hall will be built at
the location where currently the Saksenhal and Keltenhal are located. For this design we assume these 2 halls are broken down to create an open surface where the new hall can be placed (building envelope). The parking lots which are located in this area can either be relocated or discarded. The building envelope has a surface of 26,600 m² (width of 140 meters and a length of 190 meters). Within this area the new exhibition halls have to be located. The minimum required built floor area is 13,005 m² which is 49% of the building envelope.

When the current halls are removed, a building edge opens. The new hall has to contain a connection between the existing hall (WTC passage). The connection is located on the building edge. The east side of the building is facing the city (residential area) and a road, which connects the city with the motorway structure of the Netherlands. This area has potential to create a iconic view for the expo-complex.

Preconditions listed:
- Building envelope: 140 x 190 meters, 26,600 m².
- Minimum built floor area: 13,005 m² (49% of the building envelope).
- Maximum built floor area: 14,630 m² (55% of the building envelope).
- Connection between the existing building and the new exhibition halls.
- Iconic view from the city centre.
3. Theoretical framework

Before the acoustical and structural design can be created and understood it is necessary to gain insight into structural forces, acoustical behaviour, materialisation and the influence of shapes.

3.1 Acoustics

The shape, materialisation and relief present in a room has a large influence on the acoustical performance of a room. To know how a room performs, information is needed on the behaviour of sound and noise.

3.1.1 Sound in general

Sound or a sound wave is a physical disturbance of a molecular structure, such as water, air or a solid material. The disturbances are changes in pressure, which are caused by vibrating objects. When we speak of sound these disturbances are large enough to be noticeable for human hearing. The desired sound waves are termed sound, while the unwanted sound waves are termed noise. Sound waves can be defined by their frequencies. Frequency is defined as the number of wave cycles that occur in 1 second. A wave cycle has 5 stages, neutral pressure, high pressure, neutral pressure, low pressure and neutral pressure again. See figure 3.1.1 The length of a wave cycle is termed Lambda.

The waves that can be heard by human hearing and are desired are termed sound. These waves have a frequency of 20 Hz to 20,000 Hz and are defined as audible frequencies. Any frequency lower than 20 Hz is called infrasonic and can be experienced as a vibration. Any frequency above 20 kHz is called ultrasonic. An orchestra for example produces frequencies varying between 25 Hz to 13,000 Hz.

Sound is transmitted to the human hearing organ by pressure. The organ uses the sound pressure to determine the average sound pressure, termed effective sound pressure. Sound pressure can be scaled using the logarithmic unit dB. This scale is termed sound pressure level.

\[ L_p = 10\log \frac{p_{\text{eff}}^2}{p_0^2} \]

In this formula the L(p) is the sound pressure level, p(\text{eff}) is the sound pressure in Pa and p(0) is 0,00002 Pa. (Linden & Zeegers, 2006; Salter, 1998)

The purest tones would be created by waves with a constant frequency and are named periodical waves. In reality these waves seldom occur. Sound waves are practically always a combination of different frequencies. The combination of frequencies is being referred to as spectrum. (Salter, 1998)

Sound moves with a certain speed through air. This depends on temperature and humidity, the approximate speed is 344 meters per second. Sound has a different speeds through different mediums. For example sound has a speed of 1.450 meters per second through water, and a speed of 5.100 meters per second.
through aluminium. Although sound has a high speed through air, it can have much larger speeds through other mediums. The speed of sound, frequency and wave length are related with each other in the following formula:

$$c = f \times \lambda$$

In this formula the $c$ represents the speed of sound through a certain medium, $f$ stands for frequency and $\lambda$ is the wave length. (Linden & Zeegers, 2006)

It was already mentioned that sound waves derive from vibrations. These vibrations are caused by a source, termed a sound source. Other factors in the acoustical experience is the listener or receiver and the path in between the source and receiver. The path goes through a medium, which is mainly air, but can also be a combination of different mediums. Most of the sources do not emit the same amount of sound pressure level in every direction. Therefore a sound source can be directional. (Salter, 1998)

Direct sound is a sound wave which reaches the receiver directly, without any reflections and thus it uses the shortest route to reach the receiver. A diffuse sound field depends on the reflected sound waves that indirectly reach the receiver. The direct sound waves will be more intense compared to the indirect sound waves. The build-up of the diffuse sound field is known as reverberation. Reverberation time can be defined as the time elapsed from when the sound source is disabled, until the sound pressure level has been lowered 60 dB. See figure 3.1.3. Important influences on the desired reverberation time in a specific room are the volume and the function. Reverberation feels more natural in a large room, while it is not desirable in a small room. Different functions also require different reverberation times. For example when a speech is given, a large reverberation will make it hard to understand what is being said. An orchestra on the other hand relies on the reverberation time. The reverberation time is influenced by the sound absorption, transmission and reflection properties of a specific room.

When a sound wave hits the surface of
a construction, the wave can be partially reflected, transmitted or absorbed. Usually it is a combination of these possibilities. The amount of transmitted sound is very small, compared to the amount of absorbed and reflected sound. The porosity of a (construction) material influences the absorption coefficient. A tough material is more suitable for the reflection of sound, while a porous material is suitable for sound absorption. When a sound wave is reflected on a surface, there will be an incoming wave and a reflected wave. The neutral point of the wave is located on the surface. Meaning the peak with the highest fluctuation can be found at 1/4 \( \lambda \) distance from the surface. Sound insulation is most efficient at the amplitude of the sound wave. For high frequencies, this distance can be large. For example a frequency of 63 Hz which has a wave length in air of 5.4 meter, the efficiency distance is 1.35 meters.

Sound absorption can either be caused by resonance or by friction in porous materials. When sound is absorbed by friction the wave is transformed from movement to heat. In order to do so the material has to be porous, so the wave can enter the material. Also the material should have a low airflow resistance, so not too much sound can be reflected. As mentioned before the optimal location for these materials is at a distance of 1/4 of the wave length. In some cases this will be a large distance, therefore often is chosen to use a cavity between the construction and insulation material, for example in lowered ceilings. The other possibility is resonance. Each object has a frequency which triggers resonance. Acoustical panels have been designed with openings. They resonate with frequencies between 300 Hz and 1.500 Hz. The resonance causes the air trapped behind the panel to function like a spring. When the cavity is filled with absorption material, friction occurs and the absorption is expanded to a wider frequency range. The total sound absorption of a room can be found by multiplying the absorption coefficient with the surface and adding the outcome from each different surface.

### 3.1.2 Variable acoustics

The reverberation time of a hall can vary. Examples are known where concrete rooms, containing a large cubic volume, are located at different levels of the hall. These concrete rooms can be opened or closed with heavy doors. According to Sabines formula for the reverberation time, an increase of volume should result in an increase of reverberation time.

\[
T = \frac{K \times V}{S \times \bar{\alpha}}
\]

In this formula \( T \) is the reverberation time in seconds. \( K \) is constant with a value of 0.16 in a metric unit system. \( S \) is the room surface and \( \bar{\alpha} \) is the average absorption coefficient in the room. Experience has learned that this is not always correct. Another option to create a variable reverberation time using volume is an orchestra shell, which can be removed to increase the reverberation time. When using acoustic volumes which can be added to the original volume, the reverberation time can be varied more precise by creating the possibility to open one door or by opening multiple doors and by placing retractable curtains from the ceiling. In case of an opera the fly tower above the stage should contain absorbing materials, such as deployed acoustical curtains to lower the reverberation time. When a similar hall is used for concerts a sharper can be applied underneath the fly tower to reflect the sounds, rather than absorbing the sound to increase the reverberation time. (Beranek, 2004)

Whether a design is successful for a speech function depends on the intelligibility of spoken text. This can simple be tested by the testing the intelligibility of a word embedded in a simple sentence. Determining whether a concert hall has successful acoustics is
more complex. The acoustical experience of a concert hall depends on at least the following dimensions:

1. Clarity
2. Reverberant response
3. Envelopment
4. Intimacy
5. Loudness

1. Clarity. The clarity in a concert hall is necessary to understand every detail of a piece of music. Clarity can be experienced as clear sound, muddy sound or something in between.

2. Reverberant response. The reverberation response of the concert hall should be appropriate for the function. Reverberation can give a room a dead or live experience.

3. Envelopment. The receiver (audience) should have the experience of feeling surrounded by sound. Therefore the sound should be constricted and thus it should not only be received from the front side of the receiver or by direct sound only. An expansive envelope experience is more preferable.

4. Intimate. It is desirable for a concert hall to have an intimate experience, rather than a remote experience.

5. Loudness. The loudness for a concert hall should be appropriate for the music piece. It should not be experienced as too loud or too quiet.

Linking the subjective dimensions to a design is not easy. As an intermediate between the design and the subjective response, objective measures are described:

1. Early decay time
2. Objective clarity (early to late sound index)
3. Objective envelopment (early lateral energy fraction)
4. Total sound level

These dimensions can be used to give an approximation of how successful the acoustical space will be.

1. Early decay time. This is a measure to show the sound decay. It expresses the time in which the sound level has dropped 10 dB. In diffuse sound fields, with a linear sound decay the early decay time appears to be equal to the reverberation time.
2. Objective clarity. This measure relates the balance between the perceived clarity and the reverberation time. The early sound includes the direct sound. This dimension is expressed as C80 for music or C50 for speech related functions. C50 uses a time span of 50 ms.

Objective clarity (dB) = \( \frac{\text{Energy arriving within 80 ms of direct sound}}{\text{Energy arriving later than 80 ms after direct sound}} \)

3. Objective envelopment. This measure relates to the subjective enveloped measure or the perceived spatial impression and is influenced by the sound level of the music.

Objective envelopment = \( \frac{\text{Energy arriving laterally within 80 ms}}{\text{Total energy arriving within 80 ms of direct sound}} \)

4. Total sound level. This measure is also known as ‘strength’ or ‘Loudness’ (G). It is related to judgement. The same acoustical sound source will produce different levels of loudness (G) in different halls. (Barron, 1993) This means the loudness is not a property of the sound source, but it is a property of the room.

### 3.2 Acoustical shapes

The shape of the hall has influence on how the sound waves are reflected and distributed through the hall. This influences the previously discussed dimension ‘envelopment’.

**Concert hall shapes**

![Shoebox](Shoebox.png) ![Fan shape](Fan_shape.png) ![Horse shoe](Horse_shoe.png) ![Hexagonal](Hexagonal.png) ![Reversed fan shape](Reversed_fan_shape.png) ![Elliptical](Elliptical.png)

**Event hall shapes**

![Shoebox arch](Shoebox_arch.png) ![Shoebox pinched roof](Shoebox_pinched_roof.png) ![Shoebox](Shoebox.png)

*Fig. 3.2.1 Possible concert hall shapes*
In the history of concert halls different shapes have been used. Some have proven to be more successful than others. The most successful shape, which has also been used the most, is the ‘shoebox’ shape. The parallel walls of the hall assure early lateral reflections, which contributes to the spaciousness of the hall. This effect can be reproduced by placing panels or by placing walls shaped towards the stage. Another commonly used shape for concert halls and theatres is the ‘fan shape’, however this shape does not reflect as many early reflections. The ‘reversed fan shape’ is more functional for acoustical concerts for this reason. The ‘horse shoe shape’ and ‘elliptical shape’ are known to have focus points and therefore they are not often used for concert halls, but they are more commonly seen as theatres. The ‘hexagonal’ shape has a combination of the visual benefits and lateral reflections. (Barron, 1993)

For this design scope it is interesting to see how these different shapes function. It should also be taken into account that the hall should also be functional for exhibition function. Assuming the ‘shoebox’ shape is the most functional for this function it is also of interest to analyse typical hall (construction) shapes such as a flat roof (trusses), arch shaped roof and a pinched roof. See figure 3.2.1. These shapes have been analysed to see there lateral reflections and compare the envelopment. All of the

![Fig. 3.2.2 Early lateral reflections and direct sound diagrams](image-url)
6. The ‘Elliptical shape’ has only limited angles in which the lateral reflections reach the receiver. The lateral reflections either reach the receiver from the front or from above. This is due to the rounded walls.

These 6 diagrams focussed on the shape of the floor plan. The roof of a concert hall influences the reflections as well. Therefore 3 common roof shapes have been researched in combination with a ‘shoebox’ shaped floor plan.

7. This diagram shows an arch shaped structure where the receiver and the sound source both stand in the central line of the hall. The lateral reflections in this case are received mainly from above and the front.

8. This diagram illustrates the same roof structure, but in this case the receiver is located on a side of the floor plan. In this case the lateral reflections are only received from the front and the left side.

9. The ‘shoebox’ shaped floor plan with a pinched roof provides a better diffuse sound field. This type of roof is comparable to a flat roof, which was used in the first diagram.

From these diagrams it can be concluded that straight surfaces are desirable for the lateral reflections. The best acoustical shapes, based on this research are the ‘shoebox’ (1), The ‘hexagonal shape’ (4) and the pinched roof (9).
3.3 Folding techniques

There are different folding techniques for a construction which can reduce in size or deploy. It is important that there are no openings between the different panels, because of water tightness and insulation. Therefore the folding techniques are limited to the ones that can created out of a single sheet. With the use of the book ‘Folding techniques for designers, from sheet to form’ by Paul Jackson, different folding techniques have been selected for testing. Figure 3.3.1 shows different categories of folds that might be functional for the design. This selection was made based on visual judgement.

1. The first group contains folds termed spans. They use the X-form fold, which results in a arch shaped construction.
2. This folding technique is comparable to the previous group and is also termed spans. However these group were created with the use of V-folds.
3. This group of folding techniques is termed glide reflection, which means a motive is translated an reflected. This does not have to occur in a straight line. This type of folding does not be a structural solution, but the variation in relief might be interesting from a acoustical point of view.

(Jackson, 2011)

Testing these folds on their ability to transform limited the amount of useful folding techniques. The spans with an X-form fold transform too much in all directions if it is stretched or pushed together. The spans with the V-folds appeared to be more useful. The best span with V-fold has a perpendicular corner. From the 3rd group only the folding techniques that could be combined with this folding techniques were selected. Nevertheless the other reliefs could be an interesting addition to the concert hall regardless of the construction.

The listed folding configurations will be tested on their functioning and analysed on their acoustical effects.
- Perpendicular V-fold span with 90º angle
- Perpendicular V-fold span with 60º angle
- Perpendicular combined V-fold

See figure 3.3.2. The direction in which the sound has to travel influences the direction and diffuse effect. To see the effects again we will test the envelopment of the receiver by analysing the lateral reflections which reach the receiver within 80 ms after the direct sound wave. This will be tested using CATT-
1. The first 2 diagrams show the possibilities of the perpendicular V-fold with 90° angles. The first arrangement (a) shows only a few lateral reflections via the folded roof and wall. The few present lateral reflections occur on the junction of the roof and the wall. The second possibility (b) shows a wider variety of lateral reflections. Here the lateral reflections cause a good enveloped experience. From these diagrams it could be concluded that V-folds parallel to the direction the sound needs to travel is optimal for envelopment. However when the receiver changes position (c) There are only 3 lateral reflections traveling through the folded surfaces. So this folded shape is not desirable for envelopment throughout the room.

2. The next 2 diagrams show the same fold as the first set of diagrams, only now the
V-fold has an angle of 60°. Here (a) it is clear that there are only a few lateral reflections via the folded roof and wall. When the V-fold is applied in the other direction (b) the lateral reflections cause a less desirable enveloped acoustical effect. This eliminates the possibility of using this type of fold as a solution to combine acoustics and structure.

3. The last diagram shows a combination of flat surfaces combined with folded surfaces. In this setting (a) there is a variety of lateral reflections, creating a good enveloped acoustical experience. When the room setting is changed (b) there is only a little variation in angles of the lateral reflections. This setting is less desirable for the acoustical envelopment. The results of the research conclude that diagram 3.a is the best solution of the proposed solutions for a foldable construction.

3.4 Material properties

The program of requirements, discussed in paragraph 2.2, already listed a few demands for the materials:

- Sound insulation
- Water tightness
- Thermal insulation

These properties can be accomplished by correct detailing of the construction and the integration of insulation material in the building details. The two main fields of interest for this project (acoustics and structure) are decisive in defining the building material.

3.4.1 Acoustical material properties

The acoustical properties of a material are defined by the ratio between the amount of sound that will be absorbed by a certain material (α), the amount of sound that will be reflected (r) and the amount of sound that passes the material (t). Because the amount of passing sound is very small compared to the reflected and absorbed sound, this value is left out in the formula of the sound absorption coefficient. Thus the formula states: α=1-r (Linden & Zeegers, 2006). The sound absorption depends on the frequency of the sound waves (see paragraph 3.1.1). Therefore the sound absorption coefficient of a material is determined for 6 frequencies: 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz (Cavanaugh, Tocci, & Wilkes, 2010). Examples of the sound absorption coefficient for multiple common materials are given in table 3.1. The materials are ordered from a low sound absorption coefficient to a high sound absorption coefficient. It is obvious that absorption depends on the sound frequency. Thus a plywood cladding has a sound absorption coefficient at 125 Hz which is higher than an heavy velour fabric, which means it is more sound absorbent for this frequency. When looking at the other frequencies it becomes clear that heavy velour fabric is more absorbent then a plywood cladding.

What material and what sound absorption coefficient is desirable depends on the design of the acoustical room and its function. The material can help to accomplish the wanted reverberation time. In this specific project integration of structure and acoustics is important, therefore the acoustical material has to be structural as well. This means there is no necessity to introduce a new material to the design to improve the design for the acoustical function. When the function of the room changes to a speech function, reverberation needs to be lowered, so the amount of absorption needs to increase. This could be done by changing the interior design and adding absorbent materials such as polyurethane foam or heavy velour curtains. In paragraph 4.3 an example is given of a project with variable acoustics.

The sound absorption coefficient of the audience is also shown in table 3.1. The audience is a highly absorbent surface, but it is not permanent established in the room. When the amount of audience varies, the amount of sound absorption should not vary, to prevent the reverberation time from varying. Therefore chairs with a sound absorption coefficient similar to the audience are chosen. This can be done by using fabric and foam seat chair covers or, when using folding seats, sound absorbing panels can be placed on the bottom side of the seat, revealing the panel when the seat is not in use.
The optimal material can be determined after an acoustical analysis of the design. Also the insulation property differs per material. Table 3.2 shows a few examples of common materials. Porous materials such as mineral wool are better insulators then more rigid materials such as rigid polystyrene foam.

This should be taken into account when developing the final facade package.

### 3.4.2. Structural material properties

One of the characteristics of a large exhibition hall is the large span. In this case there is a free span of 85 meters. In order to span this distance a strong structural material is needed. A commonly used strong material for large spans is steel. Another possible material is concrete, in paragraph 4.1 a reference project is shown using concrete prefab elements. These are materials with a high density. When using these materials the structure will mainly have to carry its own weight. Another approach would be not to go for an material necessarily known for its strength, but a lightweight material, such as wood or aluminium.

In the second part of the twentieth century a large number of polymers, also named plastics, were introduced to the building engineering environment. These materials were first developed in aerospace and military industries (Addis, 2007). Some of these materials combine the properties of high strength with a low density. Examples of such polymers are carbon fibre reinforced plastics (CFRP) and glass fibre reinforced plastics (GFRP).

Table 3.2 shows important structural properties of the materials mentioned above. The table shows that the strength properties of fibre reinforced plastics (FRP's) are comparable to steel and aluminium, while the density is significantly less. While wood weighs even less, it has a low strength, which means more material is needed to compensate for the lack of strength. Another important property is the Young's modulus. The Young's modulus expresses the stiffness of a material. A material with an higher

---

**Table 3.2 Structural material properties (Ashby, 2014)**

<table>
<thead>
<tr>
<th>Materials</th>
<th>125 Hz</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1000 Hz</th>
<th>2000 Hz</th>
<th>4000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardboard (3mm)</td>
<td>5.2 dB</td>
<td>9.3 dB</td>
<td>14.2 dB</td>
<td>19.5 dB</td>
<td>24.8 dB</td>
<td></td>
</tr>
<tr>
<td>Glass fiber reinforced plastic (3 mm)</td>
<td>10.7 dB</td>
<td>15.8 dB</td>
<td>21.2 dB</td>
<td>26.7 dB</td>
<td>31.8 dB</td>
<td></td>
</tr>
<tr>
<td>Steel (3 mm)</td>
<td>21.1 dB</td>
<td>26.7 dB</td>
<td>32.4 dB</td>
<td>38.0 dB</td>
<td>42.4 dB</td>
<td></td>
</tr>
<tr>
<td>Rigid polystyrene foam (100 mm)</td>
<td>9.7 dB</td>
<td>14.3 dB</td>
<td>18.1 dB</td>
<td>17.4 dB</td>
<td>11.6 dB</td>
<td></td>
</tr>
<tr>
<td>Concrete (100 mm)</td>
<td>34.9 dB</td>
<td>35.0 dB</td>
<td>44.7 dB</td>
<td>51.4 dB</td>
<td>57.1 dB</td>
<td></td>
</tr>
<tr>
<td>Mineral wool (100 mm)</td>
<td>45.5 dB</td>
<td>51.7 dB</td>
<td>61.9 dB</td>
<td>76.3 dB</td>
<td>91.1 dB</td>
<td></td>
</tr>
</tbody>
</table>

---

**Table 3.1 Absorption coefficients for varies materials (Cavanaugh, Tocci, & Wilkes, 2010; Beranek, 2004)**

<table>
<thead>
<tr>
<th>Materials</th>
<th>125 Hz</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1000 Hz</th>
<th>2000 Hz</th>
<th>4000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete floor</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Plastered brick</td>
<td>0.13</td>
<td>0.15</td>
<td>0.02</td>
<td>0.03</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td>Glass</td>
<td>0.18</td>
<td>0.05</td>
<td>0.04</td>
<td>0.03</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Concrete block, painted</td>
<td>0.10</td>
<td>0.05</td>
<td>0.06</td>
<td>0.07</td>
<td>0.09</td>
<td>0.08</td>
</tr>
<tr>
<td>Wooden floor</td>
<td>0.10</td>
<td>0.08</td>
<td>0.07</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Plywood</td>
<td>0.28</td>
<td>0.22</td>
<td>0.17</td>
<td>0.09</td>
<td>0.10</td>
<td>0.11</td>
</tr>
<tr>
<td>Heavy velour fabric</td>
<td>0.14</td>
<td>0.35</td>
<td>0.55</td>
<td>0.72</td>
<td>0.70</td>
<td>0.65</td>
</tr>
<tr>
<td>Polyurethane foam panels (1 inch, open cell structure)</td>
<td>0.17</td>
<td>0.25</td>
<td>0.73</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>Audience (medium upholstered)</td>
<td>0.62</td>
<td>0.72</td>
<td>0.80</td>
<td>0.83</td>
<td>0.84</td>
<td>0.85</td>
</tr>
<tr>
<td>Glass fiber insulation panels (1 inch)</td>
<td>0.55</td>
<td>0.89</td>
<td>0.73</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
</tr>
</tbody>
</table>
stiffness means the construction is less likely to bend. Based on this property low carbon steel and carbon fibre reinforced plastic (CFRP) are the best materials.

Based on the structural properties in table 3.2 carbon fiber reinforced plastic (CFRP) would be the most suitable material. CFRP is seldom used as a structural material, one of the reasons is because it is more costly than glass fiber reinforced plastic (GFRP). GFRP would be a suitable alternative.

<table>
<thead>
<tr>
<th>Material</th>
<th>Young's modulus</th>
<th>Tensile strength</th>
<th>Comp. strength</th>
<th>Density</th>
<th>Poison ratio</th>
<th>Costs</th>
<th>Sound absorp.</th>
<th>Sound insul.</th>
</tr>
</thead>
<tbody>
<tr>
<td>High performance concrete</td>
<td>26 GPa</td>
<td>8 MPa</td>
<td>65 MPa</td>
<td>2600 kg/m³</td>
<td>0,24</td>
<td>0,12 €/kg</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>Low carbon steel</td>
<td>210 GPa</td>
<td>360 MPa</td>
<td>360 MPa</td>
<td>7900 kg/m³</td>
<td>0,29</td>
<td>0,41 €/kg</td>
<td>Poor</td>
<td>Very good</td>
</tr>
<tr>
<td>Aluminium</td>
<td>70 GPa</td>
<td>200 MPa</td>
<td>150 MPa</td>
<td>2700 kg/m³</td>
<td>0,33</td>
<td>1,79 €/kg</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>Glulam wood</td>
<td>13 GPa</td>
<td>10 MPa</td>
<td>10 MPa</td>
<td>600 kg/m³</td>
<td>0,28</td>
<td>1,60 €/kg</td>
<td>Average</td>
<td>Average</td>
</tr>
<tr>
<td>CFRP (carbon fiber reinforced plastic)</td>
<td>120 GPa</td>
<td>750 MPa</td>
<td>600 MPa</td>
<td>1550 kg/m³</td>
<td>0,31</td>
<td>30,00 €/kg</td>
<td>Average</td>
<td>Average</td>
</tr>
<tr>
<td>GFRP (glass fiber reinforced plastic)</td>
<td>25 GPa</td>
<td>220 MPa</td>
<td>180 MPa</td>
<td>1800 kg/m³</td>
<td>0,32</td>
<td>20,00 €/kg</td>
<td>Poor</td>
<td>Good</td>
</tr>
</tbody>
</table>

Table 3.3 Structural material properties (Ashby, 2014)
As a method to inventory the possibilities of existing projects and one design will be analysed. These projects have been chosen because of their distinctive structures, the acoustical properties or the integration of acoustics and structure.

4.1 Exhibition building, Turin
The first analysed project has a focus on construction. It is interesting because of its construction method and the large spans that have been reached. The acoustical properties are unknown, however the expected acoustical behaviour in the arch shaped construction can be analysed.

This Exhibition building was designed by Pier Luigi Nervi. They started building in 1948 in the city Turin in Italy, which means the building is located in a Mediterranean climate. They finished the long span reinforced concrete construction within 8 months. The floor plan of the exhibition hall has a rectangular shape and covers an area of approximately 73 meters x 94 meters, which equals 6.862 square meters. As a construction material prefabricated concrete elements were used in combination with in situ concrete abutments. The prefabricated elements have a length of approximately 4,5 meter and a width of 3,5 meter. The curved parts of the elements have a thickness of 0,02 meter. This small thickness was achieved by increasing the rigidity at either end of the panels. The rigidity could be increased through corrugation and transverse webs. (Joedicke & Nervi, 1957)

Although the building is not located in a temperate climate, like the Dutch climate, the building has interesting features. It shows an interesting mind-set when it comes to designing structures with a large span. Nervi achieved to design a building method where prefabricated elements in combination with in situ concrete abutments could build a...
exhibition hall in a short time. However just as interesting are the shapes used to create a rigid structure.

The acoustical properties of this building will most likely be less desirable for functions other than exhibitions, for example a concert hall. Concrete is a harsh material reflecting a lot of direct and indirect sound waves. The arch shape will cause the sound waves to reflect to the centre line of the hall, creating a variable sound experience throughout the hall, which is unwanted for concert halls. See figure 4.1.4.

![Diagram of building sections showing the sound reflection](image)

**Fig. 4.1.3** Section detail
Source: (Joedicke & Nervi, 1957)

**Fig. 4.1.4** Building sections showing the sound reflection
Based on source: (Joedicke & Nervi, 1957)
4.2 UNESCO Conference Building, Paris

This project is an interesting example of a structural and acoustical integrated design. The integration resulted in an interesting architectural design. However this design covers a small area or volume, compared to the design assignment.

The conference building is part of the UNESCO headquarters in Paris, which has been built in 1953/56. The building has been established by the collaboration of the architects Marcel Breuer, Pier Luigi Nervi and Bernard H. Zehrluss. The headquarters are a group of buildings of which the Conference Building is one.

The Conference building has a remarkable architecture, which has been integrated with the construction. The roof of the building is a folded slab construction in reinforced concrete. This structure is being supported by an up-stand beam and 2 walls on either side of the roof. These walls are constructed with similar concrete folded slabs. The concrete folded slabs do not have the strength to carry its own weight, because of the large span. Therefore the architects introduced a slab between the folds. The slab follows the compression line and is continued into the walls, creating the needed stiffness to absorb the wind moments. By the introduction of the slab following the compression lines in between of the folded slabs, a curvature in the roof and walls was created. The curvature creates a variation in the appearance of the building. Creating a more interesting experience of the building. (Joedicke & Nervi, 1957)

The folded shape of the roof construction and the wall influence the acoustical performance of the building. The shape of the construction was expected to have a beneficial effect on the acoustical performance. The relief formed with the folded concrete slabs causes the sound to scatter. The angled surfaces on the roof and walls reduces the appearance of echo’s. (Linden & Zeeegers, 2006)

Fig. 4.2.1 Floorplan UNESCO Complex
Source: (Joedicke & Nervi, 1957)

Fig. 4.2.2 Photograph facade
Source: http://www.architetti.net/it/galleria.php

Fig. 4.2.3 Photograph interior
Source: http://www.pixelcreation.fr/nc/galerie/
Fig. 4.2.4  Diagram bending moment
Source: (Joedicke & Nervi, 1957)

Fig. 4.2.5  Top: diagram tensile stress; Bottom: section
Source: (Joedicke & Nervi, 1957)
4.3 De Spiegel, Zwolle

This project design has a focus on acoustics. The design has variable acoustical properties, which has been created with moveable parts and application of different materials. The construction is less interesting in this design.

“De Spiegel” is a theatre in Zwolle. The theatre is designed by the architect Greiner van Goor in cooperation with the Peutz consultant and was completed in the year 2006. The theatre hall can be used for multiple functions, such as intimate plays, opera and symphonic concerts. These different functions require a variation in the acoustical performance of the room. Therefore the reverberation time in the room can differ from 0.9 seconds to 2.0 seconds. This variation has been reached using multiple methods.

One of the methods was creating the opportunity to vary the volume of the hall. The design started off with a compact, horseshoe type theatre, with a volume of 3,500 cubic meters. This volume has proven to be beneficial for speech related performances. A balcony at a height of 7 meters was constructed and adds 4,000 cubic meters to the acoustical volume. Adding this volume can be done by lowering or raising the ceiling. The ceiling can be lowered vertically, but also rotated towards the audience. The ceiling has a total surface of 370 square meters, divided in 3 parts. The 1 to 1.5 meter gap in between the panels functions as extra absorption. The volume of the gallery behind the ceiling, when the ceiling is lowered, is deadened by acoustical drapes. During concerts the drapes can be stored in boxes, to minimize the sound absorption. The stage can be expanded to a large orchestra stage, which adds another 3,500 cubic meters to the compact version of the theatre. This way the volume can increase more than 200%, reaching a maximum volume of 11,000 cubic meters. The capacity of the theatre changes from 850 to 1000 seats. The depths of the room vary from 18 meters to 19.5 meters on the balconies. The width varies between 18 and 21 meters. The front walls, including box seats can be rotated inwards, creating a smaller stage opening. (Alertz et al.; Luykx et al., 2007)
Even when the maximum capacity is being used, the theatre has a compact volume. This was needed for a sufficient height and the acoustic conditions of the seats. The compact volume could be realized by optimizing the sight lines, with a gradually sloped floor. (Luykx, Metkemeijer, & Vercammen, 2007)

Also other measurements were taken to create the desired acoustical performance. Adjustments to the wall were made to reduce the echoes induced by the round shape of the hall. This was done by placing diffusive wall and ceiling elements. (Alertz et al)

The materialisation of the building influences the acoustical properties of the room. The materials had certain weight requirements. The following materials were used: (Luykx, Metkemeijer, & Vercammen, 2007)

- Ceiling: multiplex and gypsum board
- Roof and floor: concrete
- Wall: heavy limestone, diffuse vertical convex elements, resopal, fibro-plate, gypsum board, mineral wool
- Diffusers: resopal (high density fibre board), curved gypsum board, wooden frame

Fig. 4.3.2 Volume diagram. Top: floorplan groundfloor and balconies; Bottom: section in concert and small theatre mode
Source: (Luykx, Metkemeijer, & Vercammen, 2007)
4.4 Folding architecture

Folding architecture can be used as a generative process. It is used as a dynamic process where the design evolves during time (Vyzoviti, 2012). In this design assignment folding architecture can also be used as a generative process, but more importantly as a dynamic process. The dynamic process will be represented in the final design as the folding technique will create a dynamic building.

4.4.1 Cardboard Banquet, Cambridge

There are not many examples of folding and dynamic architecture in the way it is used in this project. One example of a certain project is the Cardboard Banquet at the Cambridge university, shown in figure 4.4.1. This project is a pavilion made out of folded cardboards (Pleatfarmer, 2009). This project uses a x-form span folding technique. Cardboard is a relatively easy folding material and suitable for a temporary structure.

4.4.2 Hornbeam leaf canopy

When designing permanent buildings the structure becomes more complicated. An example of such construction is shown in figure 4.4.2 and 4.4.3. This roof design (canopy) is based on a plant analogue, the Hornbeam leaf. The leaf is folded like a corrugated sheet and contains series of parallelograms that differ in size, but do have the same angles. This construction gives the leaf the special ability to push outward from one point. These properties have been used for the design of the roof structure. The middle beam of the roof is used to apply vertical forces with the use of a hydraulic system. By doing so the roof will deploy, which results in beams moving along a certain trajectory, shown in figure 4.14. The trajectory is a curved line. The canopy panels are connected with hinge pins to another upright pin with rollers at the end. By using different sizes of parallelograms openings for light and ventilation where created. (Lim, 2009)

The second example already shows one of the difficulties, which is inevitable. However this was an open roof structure and therefore it did not have problems with water tightness, thermal insulation, sound insulation and how ventilation systems and lighting will work in a moving construction.
5. Concept design

5.1 Concept
The concept is developed for a multifunctional building. The multifunctionality of the building relates to the interior design as well as the exterior design. It differs for every function. The concept that derives from the multifunctionality is a dynamic building.

5.1.1 Dynamic exterior
The internal functions are dynamic and change, therefore the building physical properties change as well. When the functions change and so do the needed building physical properties, it almost seems a logical next step to create a shape shifting structure as well. In addition, the listed requirements for the different constructions show a difference in volume. This can be done by changing the height of the building or by changing the surface of the room, which can also be done by changing the volume. This shape shifting can be done with the use of the researched folding techniques. Based on the results of the acoustical research the preference goes for a folding technique where sheared and straight surfaces are combined. This folding technique can be implemented in 2 directions: horizontal, vertical. See figure 5.1.1 and 5.1.2. When applied horizontally the folded surface is not beneficial for the strength of the structure, and can easily collapse. In the vertical direction the folded surfaces do contribute to the strength of the structure. The transformation shown in figure 5.1.2 shows a possible transformation. The hall on the left is compressed and has a flat roof. The hall on the right shows an expanded phase, where the roof is higher. So this construction changes the building in multiple dimensions by using a folding technique.
This concept comes with a number of challenging difficulties. The changing shapes mean changing angles. At the 2 outer corners this is caused by the folding technique. However at the floor location and the hinge in the middle this remains unsolved. See figure 5.1.3. This is because the folded wall remains on the same 2 parallel lines when the structure is expanded or compressed, as can be seen in the front views in figure 5.1.4. The front view also shows another difficulty. The walls on the front and the backside of the building will change shapes.

The rectangle in figure 5.1.4 shows the surface which remains the same during transformation. The remaining surface changes. These difficulties affect the sound insulation, thermal insulation, and water tightness of the building.

5.1.2 Dynamic interior
As well as a dynamic exterior, the concept includes a dynamic interior. First of all the hall is an exhibition hall, which can be split and used as separate halls or as one large hall. To create more possibilities the rooms can change their surface. This is done by a moving internal wall. See the bottom illustration of figure 5.1.5. The top illustrations shows the possibility of expandable absorbing screens. As an example a festival setting is chosen where multiple stages are created using these screens. A different situation in which these screens could be used is when the hall is used for a speech function, such as a congress. The halls could improve the intelligibility by adding more absorption. When these panels are compressed the amount of absorbing surface is minimized.
The acoustics can be made dynamic as well by directing ceiling panels to reflect the first early directions more optimal.

5.1.3 Program
The program which has to fit in the hall is already discussed in chapter 2. The main part of the building remains. This part of the program is shown as grey in figure 5.1.6. Only the dynamic hall is being added to the hall as a replacement of the old exhibition halls. It is important to create a link with the passage, so it is connected with the spine of the building and the main (west) entrance. An extra entrance would be preferably added on the north-side, so in case of separation of the hall it is not necessary to pass through the hall connected to the passage.

The utilities are located in the passage, therefore they are not needed in the dynamic hall. This makes the program for this design assignment look very simple. However, when looking at the different hall sizes for the different functions it might become challenging. For example when changing the hall to 1.710 m² while maintaining the original width, the hall becomes too slender to be functional. This has to be solved in the division of the hall in different stages.

5.1.4 Architectural principles
Beside the principles that are already implemented in the concept, there are also some architectural principles which should
be implemented.

- Visual appeal to the city centre, because its large dimensions and location in the city offers the opportunity to create an recognizable icon for the city.
- It should be a building with a certain personality/expression. Most of the halls have a lightweight structure and therefore resemble a tin can, which has a lack of ambience. This principle should be taken into account in the materialisation.
- The floor plan should have as little obstacles as possible. This means a large span is required. A floor plan free of obstructions allows the user of the hall to use the space more optimal.
5.2 Shape variants
As a result of the folding research a combination of folding techniques was created to develop into a building structure.

5.2.1 Folding pattern
The folding pattern exists of a perpendicular v-fold in combination with x-folding pattern. There are 2 variants, see figure 5.2.1, 5.2.2 and 5.2.3. The angle $\alpha$, shown in figure 5.2.1, determines the angle which the paper fold will make. For the design this means the angle will influence the angle between the walls and the roof. As a flat pattern the angle between the wall and roof will always be 180 degrees. The angle $\alpha$ has to be larger than 0 degrees and smaller than 90 degrees. A small reduction of 2 lines. While the joints will still be complex, it does simplify the joints slightly. This change also influences the visual appearance of the folding technique. While there is a difference, shown in figure 5.2.2 and 5.2.3 this is not important for the architectural concept and will only be noticeable on the interior side of the building.

The folding pattern on the left in figure 5.2.1 is chosen for further development, because of the more simplified joints in the pattern. Except for a varying angle $\alpha$, the distance between the vertical lines in the folding pattern can also change. In the upcoming variants a variation in distance is tested. Distances of 3, 4 and 5 meter were used. A larger distance will mean less folds are needed to create the length needed for the exhibition hall. Another possibility is the combination of these distances. This is mainly of interest for the acoustical diffusion

angle $\alpha$ will result in a sharp angle between the wall and the roof, while a large angle $\alpha$ will result in a slight angle between the wall and the roof. When using the same dimensions, but a small and a large angle $\alpha$, the starting position of the fold will not change, however the final position will. Thus a large angle $\alpha$ results in a slower changing angle between the roof and wall, while applying the same amount of compression, in comparison with a small angle $\alpha$. This is of interest for this design, because of the different positions the hall is going to be in and the position of the roof which is most desirable for the function that is linked to the particular position.

The difference between the two variants in figure 5.2.1 is the amount of folding lines which meet in one joint. The pattern on the right varies between 2 to 8 lines per joint. By shifting the sheared lines from position only 2 to 6 lines meet per joint. This is a reduction of 2 lines. While the joints will still be complex, it does simplify the joints slightly. This change also influences the visual appearance of the folding technique. While there is a difference, shown in figure 5.2.2 and 5.2.3 this is not important for the architectural concept and will only be noticeable on the interior side of the building.

The folding pattern on the left in figure 5.2.1 is chosen for further development, because of the more simplified joints in the pattern. Except for a varying angle $\alpha$, the distance between the vertical lines in the folding pattern can also change. In the upcoming variants a variation in distance is tested. Distances of 3, 4 and 5 meter were used. A larger distance will mean less folds are needed to create the length needed for the exhibition hall. Another possibility is the combination of these distances. This is mainly of interest for the acoustical diffusion
of sound.
The tested models are shown in figure 5.2.4. The two outer positions are shown. The largest position has dimensions of 85 meter width and 150 meter length, this is shown as the transparent model in figure 5.2.4. The smallest position has dimensions of 85 meter width and 40 length, also shown in figure 5.2.4. The change in shape between the two positions becomes more clear in the sections shown next to the impression. The change in height between the different models is a result of a change in the angle $\alpha$. The section also shows the beams itself have less height in the larger position in comparison to the small position, because the material is more stretched. This rises the expectation that the larger position will be indicative for the structural analysis, as a lower profile in section is likely to have a lower moment of inertia.

The smaller positions are used for the analysis of the acoustical properties of the room. The acoustical room is half the size of the impression shown in figure 5.2.4, namely 42.5 meters width and 40 meters length. This position is decisive for the acoustical shape, because it has acoustical music functions, while the other functions in the building are less specific when it comes to the acoustical properties.

5.2.2 Analysis of acoustical effects
The three shape variants discussed in the previous paragraph where analysed using the software program CATT-acoustics. A fourth and fifth model, which combines these three shapes was also used. In the results of the analysis on the next pages, these models are named combination 1 and combination 2. There is a small difference between these 2 models, which has to do with the repetition of the different dimensions. In the model ‘combination 1’ the dimensions are repeated as followed: 4 meter, 3 meter, 5 meter, 4 meter, 3 meter, 5 meter, etc. In the second model ‘combination 2’ the dimensions are repeated differently: 3 meter, 4 meter, 5 meter, 4 meter, 3 meter. These models are shown in figure 5.2.5. The two different types of repetition were chosen to see if the order of slabs influences the result.

These five models are compared to the sixth model, which is a rectangular box, with
approximately the same dimension and volume as the other tested models.

**Lateral reflections**
The first set of results is shown on the next four pages. The results show the lateral reflections in the first 80 ms, because these reflections are the most important for acoustical music. In each model the sound source is located in the centre of the stage with a height of 1.7 meters. The sound is directed straight forward into the room. On the left pages the results are shown for a person in the audience who is located on the same centre line as the sound source. On the right pages the same settings are used, only the person in the audience is moved 10 meters to the right of the centre line. The acoustical models have a defined audience plane, which absorbs sound, meaning there won’t be reflections shown on this surface. During the analysis default absorption properties of CATT-acoustics have been used. For the walls, ceiling, and floor this is a value of 0.10. The results show the calculations for the first 5 classes of reflections.

- **Class 0** (red): 0 reflections (direct sound)
- **Class 1** (green): 1 lateral reflection
- **Class 2** (dark blue): 2 lateral reflections
- **Class 3** (yellow): 3 lateral reflections
- **Class 4** (light blue): 4 lateral reflections
- **Class 5** (pink): 5 lateral reflections

The results show two properties of the models, which are important:
1. **The envelopment**
2. **Spread of sound over time**

1. All the models with the receiver on the same central line as the sound source have a good envelopment, meaning they receive sound from multiple directions. This results in an experience as if the receiver is surrounded by sound. The exception is the rectangular model where only sound from the front and the back is received, while sound from the sides is desirable as well. The model with 5 meter slabs also shows slightly less lateral reflections, however they still provide the receiver with a good envelopment.

When the receiver is located out of the centre, the results are different. The 3 and 4 meter slab models appear to have less lateral reflections, however they still have a good envelopment. The rectangular shape has a lot more lateral reflection and an improved envelopment. The 5 meter slabs, combination 1 and combination 2 models show a very good envelopment and large amount of lateral reflections.

2. The spread of sound over time is shown in the echogram of the models. It is desirable to have a lot of early sound. A lot of early sound in comparison to late sound means a good clarity of sound. The desirable C80 value depends on the type of music. For C50 applies that a higher value is better. When the receiver is located on the centre line, the echogram of the combination 2 model stands out. There is more energy in the lateral reflection in comparison to the rectangular box and the other models. There is also a pretty equal spread of the reflections over time. When the receivers are located out of the centre, the echogram of the rectangular box shows a good spread of the sound reflections over time, with a lot of energy. The 5 meter slabs model also have a good echogram, with a lot of energy. The echogram also shows a lot of early reflections, some even before the first 20 ms.

Based on these results the 5 meter slabs appear to be the most favourable.

---

**Fig. 5.2.5 a Model ‘Combination 1’**

**Fig. 5.2.5 b Model ‘Combination 2’**
Extensive acoustical calculations
To get a complete representation of the acoustical properties at the audience plane, a complete analysis has been made of for the audience plane. The analysis has been made using a default material, with little absorption. By changing the materials in the room, results can change as well. The direct sound and the delays of the direct sound is similar for every model.

The objective clarity (C80) is used for music functions, while objective clarity (C50) is used for speech functions. So for this model the objective clarity (C80) is most important. In the program of requirements a value of approximately -3 dB to 0 dB was defined for the C80 value. All the models show values between -1 and -3 dB. The rectangular box has a lower objective clarity (C80) with an average of around -4 dB. The model with the highest objective clarity is the model with 5 meter slabs, this becomes even more clear when looking at the objective clarity (C50).

Another value defined in the program of requirements is the loudness. This value should be 1,5 to 5,5 dB. In the model of the rectangular box there is an average of approximately 9 dB. The other models have a lower loudness, namely an average of approximately 7 dB. The model with the 3 meter slabs have a slightly lower loudness.

The reverberation time of a room with these
<table>
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<th>Combination 1</th>
<th>Combination 2</th>
<th>Rectangular shape</th>
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<tbody>
<tr>
<td>Direct SLP</td>
<td>Delay direct sound</td>
<td>Objective clarity (C80)</td>
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<td></td>
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<td>Objective clarity (C50)</td>
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dimensions and an acoustical function should be about 1,8 to 2,3 seconds. The model shows quite a large variation in reverberation time. The rectangular room has a reverberation time which goes of the scale, meaning that almost everywhere in the audience there is a reverberation time larger than 3,4 seconds. In the other models the reverberation time differs from 1,5 seconds in the front, to 2,9 seconds in the corners. The model with the 5 meter slabs has a lower reverberation time, compared to the other five models. Here the reverberation time varies between 1,5 seconds in the front to 2,6 seconds on the side of the audience.

All the results show a clear division between the centreline and the remaining part of the audience plane. Preferably this would be distributed more equally. However overall results show that the folding shape of the models improve the classic rectangular box, when assuming the final materialisation will be less absorbent. The model with the 5 meter slabs has an even better performance compared to the other tested models. This conclusion is valid for the analysis of lateral reflections as well as the extensive acoustical calculations.

Before these calculations where done, more analysis was done on the lateral reflection. These calculations where used to research the direction of the folding pattern in combination with the main direction of the
5.2.3 *Analysis of force flows*

By using a folding pattern instead of flat sheets, the structure gains strength. In this structural analysis the goal is to determine the dimensions of the structural elements. The material used in this analysis is GFRP (glass fiber reinforced plastic) with a rigid polystyrene foam in between. This was chosen because of the integration of structural material with the building physical demands. The height of rigid polystyrene foam which is needed for the insulation, is located in between two structural sheets of GFRP. This height helps increase the moment of inertia of the structural elements.

In the structural analysis the three different dimensions of slabs (3 meter, 4 meter and 5 meter) are analysed in the largest position (see figure 5.2.4), because the folded slabs are in there least strong position. The first part of the analysis consists of the global dimensioning of the elements. This is needed to determine starting dimensions for the finite element analysis and as a calculation check to see if the result of the finite element analysis is realistic. The second part of the analysis is the finite element analysis. This is a more precise calculation of structural elements.

### Global dimensioning

For every model the same material properties were used and the same load cases were applied. Load factors where applied to calculate the forces and displacements in their ultimate limit state. The section of the structure being calculated was assumed to be rigid. The loads and material properties are listed below:

**Material properties**

*Material:* Glass fiber reinforced plastic  
*Density:* 1,90E+03 kg/m³  
*Young’s modulus (E):* 2,50E+04 N/mm²  
*Tensile strength:* 2,40E+02 N/mm²  
*Comp. strength:* 2,00E+02 N/mm²  
*(Ashby, 2014)*

**Load factors**

*Load factor G:* 1,20  
*Load factor Q:* 1,30  
*G = permanent load*  
*Q = live load*  
*(Gerrits, 2008)*

**Loads**

*Permanent load [G]*  
\[
\text{Density} \times A(\text{section}) \times \text{load factor G}
\]

*Live load [Q]*  
\[
1 \text{ kN}/m² \times b1 \times \text{load factor Q}
\]

*Wind force [pw]*  
\[
1,24 \text{ kN}/m² \times b1
\]

*Snow load*  
\[
0,56 \text{ kN}/m² \times b1 \times \text{load factor Q}
\]

*(Kamerling, 2004)*

The exact forces depend on the model’s specific properties. With all properties combined, the data was entered in the calculation program Matrixframe. For the calculation one section of the model has been analysed as if it is a 'kniespant'. The section across the 'kniespant' changes. At the corners the beam has a V-shape, which changes into a W-shape in the mid-sections. For the calculations in Matrixframe the moment of inertia of the profile at the corner sections was used. There was assumed the profile is hollow, with a casing of GFRP. Because the corner section profile has a larger moment of inertia, the displacement will not be accurate.

The data of the global dimensioning for the three different dimensions are shown on the next pages.
Model: 3 meter slabs

For the model with slabs with a dimension of 3 meters the following calculations were made. The sheets of GFRP have a thickness of 70 mm on both sides of the section. The following data shows that the force flows in the material itself are far under the limit. The problem is the displacement. The deflection of the material is still above limit. The solution for this model might not be to add more thickness to the material, but to have a smaller width or a larger height of the construction.

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<td>Lever arm [z]</td>
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<td>Moment of resistance [W]</td>
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<td>Wind force [pw]</td>
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<td>Snow load</td>
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<th>Deflection requirements</th>
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<td>Deflection vertical [u]</td>
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<th>Verification calculation mid-section</th>
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<td>Normal stress [N]</td>
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<td>Shear stress [V]</td>
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<td>Bending moment [M]</td>
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<td>Normal stress [N]</td>
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<tr>
<td>Shear stress [V]</td>
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Model: 4 meter slabs
In this global dimensioning a thickness of 10 mm was used for the GFRP sheets. Whereas the deflection was the decisive factor in the model with the 3 meter slabs, here the compressive strength and tensile stress where decisive for the thickness of the GFRP.

Dimensions
Width \([b1]\) 7,50m
Height \([h]\) 29,00m
Length \([l]\) 85,00m
Stretched width \([b2]\) 8,00m

Corner-section properties
Section surface \([A]\) 1,65E+5 mm²
Moment of inertia \([M]\) 3,74E+10 mm⁴
Lever arm \([z]\) 2,00E+3 mm
Moment of resistance \([W]\) 1,87E+7 mm³

Mid-section properties
Section surface \([A]\) 1,65E+5 mm²
Moment of inertia \([M]\) 1,06E+10 mm⁴
Lever arm \([z]\) 1,00E+3 mm
Moment of resistance \([W]\) 1,06E+7 mm³

Forces
Dead load \([G]\) 3,76kN/m
Live load \([Q]\) 9,75kN/m
Wind force \([pw]\) 9,30kN/m
Snow load 5,46kN/m

Deflection requirements
Deflection horizontal \([u]\) 0,097 m
Deflection vertical \([u]\) 0,340 m

Verification reflection
Deflection horizontal \([u]\) 0,045 m
Deflection vertical \([u]\) 0,028 m

Occurring forces corner-section
Bending moment \([M]\) -2304kNm
Normal stress \([N]\) -802,4kN
Shear stress \([V]\) 343,7kN

Verification calculation corner-section
Bending stress -1,23E+2 N/mm
Stress -4,87E+0 N/mm
Compressive stress -1,28E+2 N/mm
Tensile stress 1,18E+2 N/mm

Occurring forces mid-section
Bending moment \([M]\) 2000kNm
Normal stress \([N]\) -659,35kN
Shear stress \([V]\) 45,65kN

Verification calculation mid-section
Bending stress 1,89E+2 N/mm
Stress -4,00E+0 N/mm
Tensile stress 1,85E+2 N/mm
Compressive stress -1,93E+2 N/mm
**Model: 5 meter slabs**

In this structural model the GRFP sheets should have a thickness of 30 mm. The decisive factor in this calculation was the deflection, just as in the calculation of the 3 meter slabs.

**Dimensions**

- Width \([b1]\) 9,38 m
- Height \([h]\) 24,50 m
- Length \([l]\) 85,00 m
- Stretched width \([b2]\) 10,00 m

**Corner-section properties**

- Section surface \([A]\) \(6,08E+5\) mm\(^2\)
- Moment of inertia \([I]\) \(1,63E+11\) mm\(^4\)
- Lever arm \([z]\) \(9,80E+2\) mm
- Moment of resistance \([W]\) \(1,67E+8\) mm\(^3\)

**Mid-section properties**

- Section surface \([A]\) \(6,08E+5\) mm\(^2\)
- Moment of inertia \([I]\) \(4,62E+10\) mm\(^4\)
- Lever arm \([z]\) \(4,90E+2\) mm
- Moment of resistance \([W]\) \(9,43E+7\) mm\(^3\)

**Forces**

- Dead load \([G]\) 13,87 kN/m
- Live load \([Q]\) 12,19 kN/m
- Wind force \([pw]\) 11,63 kN/m
- Snow load 6,83 kN/m

**Deflection requirements**

<table>
<thead>
<tr>
<th>Deflection horizontal ([u])</th>
<th>0,082 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deflection vertical ([u])</td>
<td>0,340 m</td>
</tr>
</tbody>
</table>

**Verification reflection**

<table>
<thead>
<tr>
<th>Deflection horizontal ([u])</th>
<th>0,046 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deflection vertical ([u])</td>
<td>0,093 m</td>
</tr>
</tbody>
</table>

**Occurred forces corner-section**

<table>
<thead>
<tr>
<th>Bending moment ([M])</th>
<th>-5686 kNm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal stress ([N])</td>
<td>-1548,3 kN</td>
</tr>
<tr>
<td>Shear stress ([V])</td>
<td>687,4 kN</td>
</tr>
</tbody>
</table>

**Verification calculation corner-section**

<table>
<thead>
<tr>
<th>Bending stress</th>
<th>-3,41E+1 N/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress</td>
<td>-2,54E+0 N/mm</td>
</tr>
<tr>
<td>Compressive stress</td>
<td>-3,67E+1 N/mm</td>
</tr>
<tr>
<td>Tensile stress</td>
<td>3,16E+1 N/mm</td>
</tr>
</tbody>
</table>

**Occurred forces mid-section**

<table>
<thead>
<tr>
<th>Bending moment ([M])</th>
<th>3000 kNm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal stress ([N])</td>
<td>-1340,2 kN</td>
</tr>
<tr>
<td>Shear stress ([V])</td>
<td>129,95 kN</td>
</tr>
</tbody>
</table>

**Verification calculation mid-section**

<table>
<thead>
<tr>
<th>Bending stress</th>
<th>3,18E+1 N/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress</td>
<td>-2,20E+0 N/mm</td>
</tr>
<tr>
<td>Tensile stress</td>
<td>2,96E+1 N/mm</td>
</tr>
<tr>
<td>Compressive stress</td>
<td>-3,40E+1 N/mm</td>
</tr>
</tbody>
</table>
Finite element analysis
The finite element analysis has been done using the program ANSYS Workbench 14.5. For every one of the five following models the same data for material properties and forces was used.

Material model nr.1  GFRP  
Glass fiber reinforced plastic  
Density  1,97e+03 kg/m³  
Linear Isotropic  
EX (young’s modulus) 2,50e+10 Pa  
PRXY (poison ratio) 0,315  
Compressive strength 207 MPa  
Tensile strength 241 MPa

Material model nr.2  
Rigid polystyrene foam  
Density  5,30e+01 kg/m³  
Linear Isotropic  
EX (young’s modulus) 3,00e+07 Pa  
PRXY (poison ratio) 0,3  
Compressive strength 1,00 MPa  
Tensile strength 1,20 MPa

Element type  
Type 1 3D 4node Shell181

Forces  
Snow load  0,728e+03 Pa  
Wind load  1,364e+03 Pa  
Gravity  -9,81e-03 m/s²

The allowable deflection differs for every model. For the analysis the maximum and minimum principal stresses where used to determine what the highest tensile and compressive forces are in the models. The additional displacement is decisive for the deflection.

Model: 3 meter slabs
The displacement in the finite element model is a decisive component. By adjusting the section used for the model, the displacement was decreased to a horizontal displacement of 0,08 meters and a vertical displacement of 0,11 meters. The allowable horizontal displacement for this model is 0,08 meters. For the vertical displacement this is a value of 0,34 meters. So in this case the horizontal displacement was the decisive factor and both displacements are within the limits. These values are calculated using a section of 30 mm GFRP, 200 mm rigid polystyrene foam and 30 mm GFRP. The displacement is shown in the following illustrations:

The horizontal displacement is mainly caused by the wind force applied in the x-direction. As a result the displacement is also in the positive x-direction. The vertical displacement is caused by a combination of gravity and snow load. Because the displacement was decisive in this case, the highest tensile force and compressive force in the material are only 65,35 MPa and -118,62 MPa. Which is much lower than the maximum compressive strength of 207 MPa and a tensile strength of 241 MPa. The distribution of forces are shown in the diagrams of the maximum and minimum principal stress. The maximum principal stress is representative for the tensile forces in the material and the minimum principal stress is representative for the compressive forces. The diagrams are shown below. The highest stresses are located in the central hinge of the structure.
Model: 4 meter slabs

In the 4 meter slabs finite element model the allowable vertical displacement is 0.34 meters. For the horizontal displacement this is a value of 0.10 meters. The model shows a vertical displacement of 0.09 meters, which is just within the limit. The horizontal displacement is 0.11 meters and thus it is within the limit.

The horizontal deflection is caused by the wind force applied in the x-direction. The vertical displacement is caused by the combination of gravity, live load and snow load.

Because the deflection was decisive, the stresses are within the limits as well. For this model the occurring compressive force is -116,39 MPa and the tensile force is 64,48 MPa. This is much lower than the maximum compressive strength of 207 MPa and a tensile strength of 241 MPa. The diagram of the maximum principal stress is representative for the tensile stress and the minimum principal stress diagram is representative for the compressive stress. In this case the highest stresses are also located at the central hinge of the structure.
The allowable compressive and tensile stresses in the material are -207 MPa and 241 MPa. The stresses occurring in the material are within the limit. The occurring tensile stress, shown in the occurring principal stress diagram, is 64.48 MPa. The maximum compressive stress, shown in the minimum principal stress diagram, is -116.39 MPa. The maximum stresses occur in the corner section of the model.

Model: 5 meter slabs
The 5 meter model has an allowable horizontal deflection of 0.09 meters and a vertical allowable deflection of 0.34 meters. The occurring horizontal deflection in the model is 0.09 meters and the vertical deflection is 0.14 meters. Thus the horizontal displacement was decisive for the dimensioning of the section. The dimensions used for the section are 17 mm GFRP, 200 mm rigid polystyrene foam and 17 mm GFRP. The diagrams of the displacement are shown below.

The allowable compressive and tensile stresses in the material are -207 MPa and 241 MPa. The stresses occurring in the material are within the limit. The occurring tensile stress, shown in the occurring principal stress diagram, is 64.48 MPa. The maximum compressive stress, shown in the minimum principal stress diagram, is -116.39 MPa. The maximum stresses occur in the corner section of the model.

Model: 5 meter slabs, middle position
As was expected the middle position is structurally stronger in comparison to the model of the large position. The horizontal displacement in this model is only 0.02 meters and the vertical displacement is only 0.04 meters. The allowed horizontal displacement is 0.05 meters and the allowed maximum vertical deflection is 0.34 meters. In this model the same section is used, but it is not necessary to fix the structure in 6 points instead of 4. With only 4 hinged
connections to the ground, the displacement is already within the limits. The diagrams are shown below.

The maximum tensile stress has a value of 40,10 MPa. This stress occurs in the corner section opposite of the wall loaded with wind forces. See the maximum principal stress diagram. The stress is lower than 241 MPa, which is the maximum allowable stress in the GFRP material. The maximum compressive stress occurring in the material is -89,92 MPa (see minimum principal stress diagram), which is lower than the allowable -207 MPa. This compression occurs in the corner section of the model on the side where wind force has been applied. Compared to the large position model, has a slightly higher value, while the compressive stress has been reduced.

Model: 5 meter slabs, small position

In the small position the horizontal displacement is 0,01 meters. The allowed horizontal deflection is 0,05 meters. The occurring vertical deflection is 0,01 meters. The maximum allowed vertical deflection is 0,34 meters. Thus the deflections are within the limit. However the deflections have partially a larger value compared to the middle position and smaller than the large position. The deflections are shown in the diagrams below.
stress occurs at the same location as the maximum stress. The compressive forces are larger than the forces in the model of the middle position. This is consistent with the results of the deflection. The tensile stress is represented in the maximum principal stress diagram and the compressive stress is represented in the minimum principal stress diagram.

The maximum tensile stress occurring in the GFRP material is 23.58 MPa, which is within the tensile stress limit of the material, which is 207 MPa. This stress occurs on the corner section, which is loaded by wind force. The maximum occurring compressive stress is -51.69 MPa, which is below the limit of 241 MPa. The maximum compressive
5.3 Chosen concept design

Based on the structural and acoustical analysis, the variant with 5 meter slabs appears to be the most convenient for both building properties. This concept shape will be developed into a final design. In this paragraph the following aspects of the concept design will be discussed: shape, materialisations, hinge principal, acoustic transformation.

5.3.1 Shape

As mentioned above, the final design has a folding pattern where the vertical lines in the pattern have a distance of 5 meter. See figure 5.3.1. The smallest position of the hall has been used to determine the length of the roof slabs. The roof slabs have a length which causes the roof to have a small slope, to prevent water accumulation. The roof has a slope of 3,5% in the smallest position. In the middle and large position the percentage of the slope is much larger.

The changing shape of the building and the changing angle between the roof and the walls, also means the side walls also changes its shape, while all of the edges maintain their original length. The ideal solution would be to solve this with the folding concept, used for the global shape of the building. This concept was tested, but did not prove to be successful. Other solutions could be using soft isolating material, to create a flexible wall or a construction similar to fish scales, which are connected in a way which gives the wall the possibility of changing shape. The chosen concept for the side walls combines the overlap technique of fish scales and the triangular shape of folding patterns. Each triangular shape is connected to one of the edges of the wall. When the constructions moves the large panels slide passed each other so they can fixate in a different position. The panels are ordered in such a way, so each panel is overlapped by the panel above it. A technique similar to fish scales and roof tiles. The different side wall shapes are shown in figure 5.3.2.
5.3.2 Materialisation

The structural analysis has been completed based on a sandwich construction of GFRP (glass fiber reinforced plastic) and rigid polystyrene foam. The structural analysis showed a thickness of 17 mm GFRP is needed for the concept design with 5 meter slabs when a 200 mm layer of rigid polystyrene foam is applied in between. This would be a solution to integrate the thermal insulation demands and the structural demands for facade package. However rigid polystyrene foam has a low value for sound resistance. The sound insulation is also an important property for the building because of its acoustical functions. The sound resistance is expressed by the Rw-value. The peak values of the sound pressure level will be about 110 dB. A value of 50 dB outdoor would be acceptable. Thus a value of Rw-value should around 60 dB.

Thermal insulation also depends on the section of the facade and roof package. Expected for the year 2015 is a Rc which has to have a minimum value 6,0 m²K/W for roofing in the Netherlands (Bouwwereld, 2013). At this moment the minimum Rc-value is 3,5 m²K/W (Bouwbesluit online, 2012b).

The Rc and Rw-value for the section used for the structural analysis has been calculated together with multiple variants which could improve the Rw-value. Many of these variants where tested, of which 7 are shown in figure 5.3.3. The Rw-value can be calculated using the ‘Meerlagenmodel’, which is a computer program developed by Lau Nijs. This model is discussed in the articles ‘Een rekenmodel voor geluidsisolatie van meerlaagse constructies’ and ‘De luchtgeluidsisolatie van spouwconstructies berekend met een meerlaags rekenmodel’ (Nijs, 2001). With this model it is possible to calculate the sound resistance values for the different octave bands. The Rw-value can be calculated using a reference curve shown in figure 5.3.4. The Reference curve is being moved down with steps of 1 dB until the difference between the sections curve and the reference curve have a sum of 10 dB or lower. The value of the 500 Hz is used to describe the Rw-value. The inputs for every section in the ‘Meerlagenmodel’ can be seen in appendix 11.2. The Rw-value and the Rc-value are shown in the table below.

<table>
<thead>
<tr>
<th>Facade package</th>
<th>Rw-value</th>
<th>Rc-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section 1</td>
<td>32 dB</td>
<td>5,8 m²K/W</td>
</tr>
<tr>
<td>Section 2</td>
<td>50 dB</td>
<td>6,5 m²K/W</td>
</tr>
<tr>
<td>Section 3</td>
<td>46 dB</td>
<td>5,7 m²K/W</td>
</tr>
<tr>
<td>Section 4</td>
<td>49 dB</td>
<td>5,7 m²K/W</td>
</tr>
<tr>
<td>Section 5</td>
<td>46 dB</td>
<td>5,7 m²K/W</td>
</tr>
<tr>
<td>Section 6</td>
<td>37 dB</td>
<td>7,2 m²K/W</td>
</tr>
<tr>
<td>Section 7</td>
<td>97 dB</td>
<td>6,1 m²K/W</td>
</tr>
</tbody>
</table>

The section used in the structural analysis (section 1) has a high Rc-value, however the Rw-value is 32 dB. A higher sound resistance
is desirable. The diagram in figure 5.3.4 shows a valley at 500 Hz, which is one of the main causes for the low value.

In section 2 a layer of soft mineral wool is added. The addition of insulation material increases the Rc-value. The sections 3, 4 and 5 have the same layer of mineral wool, but it replaces part of the rigid polystyrene foam. The location of the mineral wool in the sandwich panel influences the Rw-value.

When placed within the sandwich panel, but on the inside of the wall, the Rw-value is higher: 49 dB. When the mineral wool is placed in the middle of the panel or within the panel on the outside of the wall, the package has an Rw-value of 46 dB. The Rc-value is constant for these packages, because the same amount of material is used for each section. These sections have a sound resistance peak at 500 Hz. Section 6 has 2 layers of a high density material developed for buildings where sound insulation is needed. Two layers of this rubber material is added, but the analysis shows that this is not nearly enough sound insulation, so it can only be used in combination with other solutions. Section 7 uses a different material as a core for the composite panel: hard mineral rock wool. This material has a lower thermal insulation in comparison to the rigid polystyrene foam, but a better sound resistance. The thickness was determined by the thermal insulation. A flow resistance of 60700 for this material was determined using a program named Zorba (a program developed by Marshall Day Acoustics). The flow resistance is among others dependent on the density of the rock wool (110 kg/m³). These values can be found in the tables in appendix 11.2.

Based on this analysis section 7 is the best choice for this structure. Figure 5.3.4 shows that there is no valley in the sound resistance of section 7. Especially at the higher frequencies the section has a high sound resistance.
5.3.3 Hinge principal

The concept of paper folding is usually done with thin paper. Which means all the valley and mountain folds are located in one plane. In the case of a building structure the facade package has a certain thickness. In this case the package has a thickness of 296 mm. In order to make it possible for the construction to move all the hinges in the structure have to be in one plane. The hinges can be located at multiple locations: inside, middle, outside, see figure 5.3.5. The location of the plane influences the visual appearance of the building. If the folding plane is located on the outside the result is a smooth outside facade but it looks less smooth on the inside. This is reversed when the folding plane is located on the inside. The middle of the package as a folding plane would be a good compromise. The visual appearance has been tested for each position of the multifunctional hall. The result is shown in figure 5.3.6. Locating the folding plane in the middle of the facade package decreases the amount of moulds needed for the production of the glass fiber reinforced plastic panels, because the folding plane in the centre of the facade package creates a symmetry line in the sandwich panels.

Besides the location of the hinged connection, the hinges themselves are also an important part of the design, because they determine if the moving construction can be build. The hinges have to be watertight, thermal bridges should be prevented and the hinge should prevent sound leakages. Also the hinge should be easy to maintain. For example accumulation of leafs and dirt at the location of the hinge should be prevented. A regular piano hinge would be the first thing that comes to mind, but does not take into account any of the properties mentioned above. A different solution would be to create a fabric hinge. The hinge is shown in figure

![Figure 5.3.5 Location of the folding plane](image)

![Figure 5.3.6 Visual appearance of the folding plane located in the middle. Top: 150 meter, Middle: 75 meter, Bottom: 40 meter.](image)

![Figure 5.3.7 Top: fabric hinge, Middle: hinge by D.H. Vosmaer, Bottom: piano hinge with extra insulation.](image)
5.3.7. This hinge uses a Kevlar fabric to create a hinge between two sandwich panels. The hinge can be created in a way that it is water- and airtight (Gruber et al., 2007). If the building would have 2 positions, the thermal insulation and sound insulation could be continuously, but in the case of 3 positions additional insulation would be needed in the middle position of the building.

D. H. Vosmaer has developed a hinge which also uses a fabric connection. This connection would also have thermal bridges and sound leakages. But the benefit of the hinge she developed is the easy mounting of the hinges. The holder of the hinge can be simply pressed onto the sandwich panel after which the hinges can be pushed into place (Vosmaer, 2006). The hinge is watertight but additional insulation needs to be added.

A third option would be to integrate a piano hinge like detail in the sandwich panel, and simply adding a flexible fabric on top of the hinge with soft insulation material which is able to move along with the bending movement. A major disadvantage of this hinge is the integration of the hinge in the sandwich panel which complicates the production of the panel.

The best option would be to simplify the production of the sandwich panel as has been done in the hinge by D. H. Vosmaer and add a flexible layer of insulation, which also prevents accumulation of dirt and leaves.

5.3.4 Acoustic transformation

The smallest size of the hall is used for the acoustical music events and speech related functions. The acoustical demands for these two functions differ. Therefore the amount of absorption or the acoustical volume of the room has to change. The acoustic qualities of the room have been optimized for the acoustic music event, because they are more demanding. To reduce the reverberation time for the speech function, the volume should be reduced, however the roof is fixed and a smaller floor surface is also undesirable. Therefore the logical solution is to change the amount of absorption in the room.

When assuming the reverberation time in the acoustical music room is 2.0 seconds, the amount of absorbing surface can be calculated, using the formula:

\[ T = \frac{K \cdot V}{S \cdot \bar{a}} \]

V has a constant value of 13699 m³. K is a constant: 0.16. The surface multiplied with the absorption coefficient is called the absorption surface. For the acoustic music hall this should be 1141 m². The surface of the audience has a minimum of 966 m². It should also be taken into account that the walls and floors will not have an absorption coefficient with a value of 0. Thus it is likely that no additional absorption material is needed. For the speech function the reverberation time has to be approximately 0.8 seconds. This means there has to be an absorbing surface of 2854 m². So 1713m² of absorbing surface has to be added.

The additional absorption can be added by changing the interior of the room. The room has be optimized to create envelopment. For the speech function it would be more preferable to have more early sound (in the first 50 ms). This can be done by adding reflecting surfaces above the sound source.
as shown in fig. 5.3.8. The backside of the surface can contain an absorbing material. This surface will create more direct lateral reflections and can be removed when the room is used for an acoustical music function. A similar principal can be applied on the back wall. The wall can be constructed out of multiple panels with a reflecting side and an absorbing side. When the reverberation time has to be lowered the panels can be flipped so the sound absorbing material is located on the inside. A third example of adding sound absorption is by splitting the tribune into parts, each with a reflecting side and a sound absorbing side. In the acoustic music room the absorbing sides are placed against each other and in the speech room the reflection sides are placed against each other so the sound absorbing sides are on the outside of the tribune. These examples are illustrated in figure 5.3.8 and figure 5.3.9.
6. Final design

6.1 The design in general

6.1.1 Situation plan

The plans are shown below. They illustrate the three positions that are used for the exposition hall and the position of the hall. The hall is positioned on the location of the previous hall, which was replaced. Therefore no parking places were removed. In this situation plan the hall has a transparent (glass) connection to the corridor of the WTC-expo. When developing a design for climate installations this connection might not be transparent and contain an installation room. This way the installations can be placed on a fixed location and do not need to be placed on a visible location like the roof, which leaves a clean view from the city centre (located on the east of the building). When the building reduces the floor surface the open space can be used for an outdoor exposition, which increases the possibilities for expositions.
6.1.2 Project drawings

The final hall has three formations used for three different causes. All of the formations have a side wall with a width of 85 meters (see figure 6.1.7-9). The length of the hall is variable and can change from 40 meters to 75 meters to 150 meters (see figure 6.1.4-6). The small hall is used for acoustical music functions and speech functions. The middle position is used for large concerts with amplified music. The largest hall can be used for all kind of expositions. The 4 meters high doors and a width of minimal 6 meters ensure large objects can enter the exposition hall. The height of the hall differs as well. The exposition hall has an height of 26 meters, while the acoustical hall only has a height of 15 meters and the concert hall used for amplified music performances has an height of 15.5 meters. This is caused by the changing angle between wall and roof. In every position the roof has a slope to prevent water accumulation on the roof. This slope is the smallest in the acoustic hall (40 meter position). The structure consists out of 16 similar ribs. When flat on the floor every rib has a width of 10 meters, by folding the structure, the width of the ribs change. In the exposition hall the ribs have a width of 9.4 meters. This reduces to 4.7 meters for the middle hall and 2.5 meters in the smallest position.

Side wall structure

The side walls of the building change shape. Therefore a moving structure is also needed for this part of the building. The structure is constructed out of triangular slabs, consisting out of a glass fibre reinforce plastic shell and a rock wool core (similar to the structural slabs). The slabs are connected to the main structure using fabric hinges. Between each overlaying slab a rubber strip is applied for air and water tightening. Rails are integrated into the different slabs at multiple points, so the triangular slabs will stay in contact with each other. The bottom slab, which contains the doors is connected to supports on rails, because one of the side walls has to move with respect to the floor surface. In between the slab and the floor surface, a rubber strip is also applied to assure water tightness. A small slope of the floor has to prevent water from accumulating and passing this barrier. The other edges of the structure have been water tightened and insulated using a flexible insulation layer. The combination of triangular slabs creates an image which refers to the folding technique used in the main structure of the building.

Fire safety and emergency exits

The side views shown in figure 6.1.7, 6.1.8 and 6.1.9 show a difference in door openings. This is caused by the construction of sliding panels on the side wall. In the smallest position (figure 6.1.7) there are two fire escapes on each side wall of the building. Together this means there are 24 meters of opening when the doors are opened.
According to the Dutch ‘Bouwbesluit’ 135 persons can escape per meter opening in the facade. This means, in regard to fire safety, the maximum capacity of the building would be 3,240 people, which is more than can fit in the room. When the hall is used for concerts (figure 6.1.8) there is a total of 78 meters of doors in the side walls, which gives a maximum capacity of 10,530 people. This is double the capacity described in the list of requirements (5,355 people). The exposition hall (figure 6.1.9) has a total of 18 meters door per side wall, which means the maximum capacity would be 4,860 persons. The doors have an height of 4 meters, so if necessary lower doors can be added or doors can open inward so they aren’t blocked by the sliding wall panels. However the exposition hall has a floor surface of 12,750 square meters and an escape route with the maximum length of 75 meters, So fire compartments would be needed. The doors are made out of the same materials as the structure (Glass Fibre Reinforced Plastic and rock wool insulation). When the doors are closed, the panels of the wall can slide over the doors.

6.1.3 Building process
The building process consists out of three main stages: production, transportation and building phase. See figure 6.1.11.

Production
The first stage is the production. In this phase all of the different components of
the building have to be produced. These components are the structural slabs, side wall slabs, composite hinges, rails, supports and hinges. All of the structural panels are triangular panels. They are made out of a shell of glass fiber reinforced plastic with a core of hard rock wool, the same applies to the side wall panels. These panels can be created using vacuum assisted resin transfer moulding (VARTM), see figure 6.1.10. This is a low cost production method (Ashby, 2014). In this production technique for every unique panel a mould has to be created. For the structural triangular panels this means 8 moulds are needed, each mould will be used 32 times. For the side walls a total of 6 moulds is needed to create all the panels. First a releasing coat is applied on the mould. A desirable colour can be added to the coating to create the desired effect. The bottom of the mould in covered with a layer of glass fibre fabric. Using a milling technique pieces of hard rock wool can be shaped so they fit in the mould like puzzle pieces. The insulation material is covered with another layer of glass fibre fabric. The mould is closed with a lid. By using a pump a vacuum is created and resin is sucked into the mould, creating the glass fiber reinforced plastic and the connection to the rock wool insulation material. Preferably the panels would be constructed out of one element. Another solution would be to use glass fiber resin and resin to connect different elements at the building site. This production can be carried out in a large hall. For example in a shipyard or at the storage of a manufacturer.

Transport

The GFRP panels differ in size. Structural panels of the walls have an maximum width of 5 meters and a length of 15 meters. The wall panels have a maximum width of 5 meters and a length of 40,5 meters. The side wall panels have a maximum width of 15 meters and a height of 40 meters. A normal truck or semi-trailer in the Netherlands has a maximum length of 12/13,6 meters, an height of 4 meters and a width of 2,55 meters (Hoozemans, 2013). When transporting the panels over land special transport is needed, or the panels have to be constructed out of multiple elements. For the specific location in Leeuwarden a cargo boat could be used for transportation. Directly to the south of the building site lays the ‘Harlingervaart’ which is connected to ‘Waddenzee’. The channel is large enough for cargo ships to pass through.

Building phase

During the production and transportation of the buildings components the building site can be prepared, meaning demolition of the existing hall. The next step is hammering the foundation piles into the ground, pouring in the concrete foundation beams, placing the prefab floor elements, the floor insulation, the floor finishing and the rails. (Phase 1) The next phase is the construction of half a rib, flat on the floor. The different panels are connected with composite fabric hinges and the supports are slid onto the rails. (Phase 2) The same is done for the other half of the rib. The two separate elements are connected with a hinge in between. (Phase 3) The rib is supported in the middle (at the hinge) and pushed outward into the supports. (Phase 4) Phase 2, 3 and 4 are repeated. Each rib is connected to the one next to it using a composite fabric hinge. (Phase 5) When this is repeated 16 times the main structure is finished. (Phase 6) Next the side walls can be put into place. These panels are fixed to the main structure using a fabric hinge. Each panel has to be slid into place because the panels are connected with guiding rails. (Phase 7) The last phase is placing the doors in the side walls and the external insulation slabs. This completes the building and makes it watertight. (Phase 8)
Production Transport Building phase

Phase 1
Foundation, floor and rails.

Phase 2
Mounting half a rib on the floor and fixing the mounting shoes.

Phase 3
Second half of the rib is mounted and connected with a hinge.

Phase 4
Placing the rib onto the supports.

Phase 5
Connecting ribs with composite hinges.

Phase 6
Finishing the main structure.

Phase 7
Placing the side walls.

Phase 8
Placing the external insulation slabs and door.

Fig. 6.1.11 Diagram illustration the building process
6.2 Structural design

An important part of the design is the structure. The concept of a folding pattern results in a surface that has been divided into triangles, which together form a load-bearing structure. In this paragraph the functioning and the load factors will be explained.

6.2.1 Forces and schemes

When looking at a simplified scheme of the structure it becomes clear the structure is a three-hinged span, with one hinge at each support and one hinge at the centre. For the force schemes this results in a bending moment with a value of 0 kNm at the hinges. Figure 6.2.1 shows one rib of the structure in the largest position of the hall. In this situation the hall has an height of approximately 26 meter. The structure has the shape of a pinched roof, which means the angle between the roof and the wall is larger than 90 degrees. In a hall with walls perpendicular to the floor applies a reducing factor for the bending moment: 1/h. This is the length of the column divided by the total height at the ridge of the building. For this building the bending moment in the wall will still be reduced. The formula for the horizontal report reaction of a three-hinged span also involves the total height of the structure: F=(q*l^2)/(8/h). So a higher height at the ridge of the building also reduces the horizontal support reaction.

The acoustic hall does not have the benefit of a roof with the shape of a pinched roof, see figure 6.2.2. But this structure has a different benefit. While the rib has a smaller width compared to the exhibition hall, it does use the same amount of material. The folding pattern is compressed causing roof and wall to have a higher profile. The profile changes along the roof and the wall, but has the smallest height at the mid-sections and a larger height at the corner sections. The moment of inertia can be calculated using the following formula, that shows the relation between the height of the structure and the moment of inertia: (1/12)*bh^3. So the height of the profile has a bigger influence on the moment of inertia than the width of the profile.

The structure has to withstand a variation of conditions. In this case the walls and roof are self-supporting and there are no other building elements. The forces on the building are: dead load, wind force, snow force and live-loads. In this case the live load would only be repairs to the roof. In case of a heavy weather the repairs would not take place, so the live load is left out the calculations. The dead load is its own weight multiplied by a load factor 1.2. Wind force is applied to

![Fig. 6.2.1 Wire-frame of a rib in the 150 meter model (exhibition hall)
one side of the structure. In this district in the Netherlands and in an urban environment this is a force of 1,24 kN/m². For the other two models this is a force of 0,86 kN/m². This value has to be multiplied with a load factor of 1,3. The last load is the snow load. This is a value of 0,7 kN/m², which has to be multiplied with a form factor. This factor is 0,8 for flat roof and roofs with an angle up to 30 degree. So for the first model the snow load is 0,7*0,8 = 0,56 kN/m². In the model of the acoustic hall, snow can accumulate in between the ribs. For this calculation a form factor of 2,0 is used, which results in a load of 1,4 kN/m². This load will be concentrated in the valleys of the roof.

6.2.2 Materialisation and dimensions

The material properties are also of importance for the structural design. The slabs are created out of a shell of 17 mm GFRP (glass fibre reinforced plastic). This material has the following properties which were used in the calculations.
Density: 1800 kg/m³
Young’s modulus: 25 GPa
Poisson ratio: 0,32
Max. tensile stress: 220 MPa
Max. compressive strength: 180 MPa

The core of the panels is filled with hard rock wool, with a thickness of 260 mm. The thickness of the core was chosen because of the necessary thermal insulation. This material has different properties, which are listed below. Some of the properties are related to the direction of the material.
Density: 110 kg/m³
Young’s modulus X: 0,5 MPa
Young’s modulus Y: 11 MPa
Young’s modulus Z: 45 MPa (Čuk, 2013)
Poisson ratio: 0

Further functioning of the structure can be found in the structural analysis in chapter 7.

6.2.3 Detailing

Because of the moving structure there are a lot of interesting junctions. Four of these junctions have been detailed. The location of these details is shown in figure 6.2.4. The details will be discussed in this paragraph. The images of the details are shown on the following pages. While the concept in paragraph 5.3.3 describes that the folding plane will be in the middle of the facade package, in the details it became clear that the folding plane has to be on the outside.
of the facade package. This is caused by the external flexible insulation slab, which cannot be placed on the sloped part of the panel, because it would block the movement of the structure when it is being compressed. Placing it outside the slope is possible, but this would make the external insulation slabs highly visible, while in these details the external insulation slabs accentuate the folding lines (see paragraph 6.4).

**Detail 1**
This detail (see page 75) is a corner detail located at one of the supports. It shows the connection of the structure to the support and the foundation. A concrete foundation is placed on top of the foundation piles, which are needed because of the soft soil in the area. In the concrete foundation is poured into polystyrene insulating lost casing and a cut out has been made, which functions as a gutter. On top of the foundation a concrete floor with 80 mm of lost insulating polystyrene casing is placed, with a layer of hard rock wool on top. The top layer of the floor is a Polyurethane poured floor. This has been chosen to minimize thermal leakages. The material of the poured floor has to be thick, so it can be placed in a small slope, to prevent water from accumulating on the floor. The supports are placed on a rails. The rails have two types of holes. Most of the openings are drainage holes, that are large enough for leaves to fall through. This has been done because of maintenance reasons: this way the gutter can be hosed and cleared from any dirt. The other holes are to fix the supports in place. The supports can glide over the rails, which allows the folding structure to be compressed. The structure can be fixed in several positions in between the three positions described in this report. On top of the support is a plastic layer to minimize the thermal leakage. On top of the gliding support a hinge is mounted which can rotate in direction perpendicular to the rails. On top of the rails two shoes are mounted, connected by a 'piano hinge'. In these shoes the composite panels can be placed. On top of the gliding support also a profile for the external flexible insulation layer is placed. This profile can hinge in one direction, so it stays on the floor surface. The profile also has a small extrusion which functions as a gutter and leads the water toward the gutter, without the water landing on the floor. A ridge can be added to the profile to function...
as a gutter that transports the water from the valley folds directly to the main gutter. Underneath the profile, rubber strips are placed for water tightening. The composite panels are also connected with each other with a composite fabric hinge (fig. 6.2.3), similar to the hinge described by Vosmear in her thesis (Vosmaer, 2006). The hinge uses the PURE material glued to composite elements as a longitudinal hinge. The hinge is separated into two pieces. One piece is mounted on the composite panel. The other is slid into the cut outs that are present in the first part of the hinge. This way the hinge can be mounted with the panels already in place.

On the composite panels there is also a part of a profile fixed. When the external insulation slab is placed, the top of the profile can be fixed on top. The external insulation slab exists out of soft and flexible mineral wool, with a layer of rubber on both sides to make the material water resistant. By removing the top panel of the fixing profile the external insulation can easily be replaced.

Detail 2
The second detail is the connection of the main structure and the side wall, which can slide over the floor. The detail is shown on page 77. The floor, foundation and rails are similar to the first detail. The support also has a hinge with a shoe mounted on top in which the composite panel can be fixed. The shoe is connected to a 'piano hinge'. The other side of the hinge is connected with a L-profile to a composite panel of the side wall. This composite panel has to be able to move and rotate along with the main structure. Another L-profile is mounted on the support, this is used to mount the bottom part of the side wall. This part is also a composite panel which moves along with the structure and therefore it is mounted on the gliding supports. The wall does not have to rotate. Underneath the wall there is a rubber profile to create a water-tight seal. The side wall panels also have a rubber profile and rails, that connects the panels to each other. This prevents emergence of openings when the panels slide over each other and take in a different position. The same profile that has been fixed on the structural composite panels has also been fixed on the composite side panels, so the external flexible insulations slabs coated in a rubber layer can be fixed. The side panels and the structural composite panel are connected with the composite hinge developed by Vosmaer.

Detail 3
The third detail is the joint located at the ridge of the structure. This detail is shown on page 79. At this joint four of the structural composite panels meet each other. On each side of the hinge composite panels are connected with the composite fabric hinge. The corners of the panels are mounted in shoes. Two of these shoes are connected with a 'piano hinge'. The hinges are placed in the same line as the composite fabric hinge. The two sets of shoes are connected by another hinge. On the outside of the composite panels the profiles and the external flexible insulation slabs are placed. These slabs consist out of different parts, which can be glued together using an adhesive tape.

Detail 4
The third detail is at located at the valley-fold of the structure, see page 81. In this detail four of the composite panels come together, at this location the composite hinge by Vosmaer is also used, but because the two composite panels in the middle are too small to fix this hinge to, the fabric will be glued directly onto the panel. On the outside of the composite panels again the external insulation slabs are placed. At the bottom side of the panel telescopic tubes are placed as an extra security for the structure to maintain its shape. The tubes will mainly take in tensile stresses and in some cases small compressive forces.
Detail 1  Exploded view

- Composite hinge developed by D. Vosmaer
- Plastic profile (part of the profile used to fix the external insulation slabs)
- Plastic profile (part of the profile used to fix the external insulation slabs)
- GFRP plastic shell (17 mm), Hard rockwool core (260 mm)
- Profile to fix the external insulation slabs (profile can rotate in one direction)
- Plastic layer to prevent thermal bridges (5 mm)
- Pin to fix the support in place
- Polyurethane (PU) poured floor (applied under a small slope to prevent water accumulation)
- Rockwool insulation (45 mm)
- Concrete floor slab (100 mm)
- Polystyrene insulating lost casing (EPS) (80 mm)
- Concrete foundation (with a cutout serving as a gutter) (1000 x 700 mm)
- Soil

- External insulation slabs (45 mm glass wool sealed by 2 mm flexible rubber layer on both sides)
- Steel shoe (connected to the support with hinges used to fix the slabs to the support)
- Stainless steel rails (with cutouts for water drainage and fixation of the hinges)
- Stainless steel support (400 x 700 x 145 mm) on bearings
- Brick pavement

Soil
**Sections**

**Side view 1:20**

- Pavement
- Polysyrene insulating lost casing (EPS) (80 mm)
- Concrete foundation
- External insulation slab (2mm rubber + 45 mm mineral wool + 2mm rubber)
- Steel mounting shoe
- Polysyrene insulating lost casing (EPS) (80 mm)
- Polysyrene insulation board (EPS) (45 mm)
- Concrete floor (100 mm)

**Top view 1:20**

- Rails
- Drainage holes
- Composite panels (17 mm GFRP + 260 mm hard rock wool + 17 mm GFRP)
- Longitudinal composite slab (25mm rubber + 45 mm mineral wool + 2mm rubber)
Brick pavement

Concrete foundation (with a cutout serving as a gutter) (1000 x 700 mm)

Polystyrene insulating lost casing (EPS) (80 mm)

Concrete floor slab (100 mm)

Rockwool insulation (45 mm)

Polyurethane (PU) poured floor (applied under a small slope to prevent water accumulation)

Stainless steel support (400 x 700 x 145 mm) on bearings

Plastic layer to prevent thermal bridges (5 mm)

Polyurethane (PU) poured floor (applied under a small slope to prevent water accumulation)

Rockwool insulation (45 mm)

Polyurethane (PU) poured floor (applied under a small slope to prevent water accumulation)

Composite hinge developed by D. Vosmaer

Plastic profile (part of the profile used to fix the external insulation slabs)

Plastic profile (part of the profile used to fix the external insulation slabs)

GFRP plastic shell (17 mm), Hard rockwool core (260 mm)

Profile to fix the external insulation slabs (profile can rotate in one direction)

Plastic layer to prevent thermal bridges (5 mm)

Pin to fix the support in place

Polyurethane (PU) poured floor (applied under a small slope to prevent water accumulation)

Rockwool insulation (45 mm)

Polyurethane (PU) poured floor (applied under a small slope to prevent water accumulation)

GFRP plastic shell (17 mm), Hard rockwool core (260 mm)

Profile to fix the external insulation slabs (profile can rotate in one direction)

Soil

External insulation slabs (45 mm glass wool sealed by a 2 mm flexible rubber layer on both sides)

GFRP shell (17 mm), hard rockwool (400 / 200 mm), with a plastic profile (part of the profile used to fix the external insulation slabs)

Steel shoe (connected to the support with hinges used to fix the slabs to the support)

L-profile (to mount the sidewalls to the structure)

Stainless steel support (400 x 700 x 145 mm) on bearings

Stainless steel rails (with cutouts for water drainage and fixation of the hinges)

Brick pavement

Stainless steel support (400 x 700 x 145 mm) on bearings

Stainless steel rails (with cutouts for water drainage and fixation of the hinges)

Brick pavement
External insulation slab (2mm rubber + 45mm mineral wool + 2mm rubber)

Stead mounting shoe

Composite side wall panel (17mm GFRP + 200mm hard rock wool + 17mm GFRP)

Polypropylene insulation (EPS) (45mm)

Concrete floor (100mm)

Concrete foundation

Poured PU floor

Polystyrene insulating lost casing (EPS) (80mm)

Back view 1:20

Side view 1:20
Plastic profile to fix the external insulation slabs

GFRP plastic shell (17 mm), Hard rockwool core (260 mm)

Steel hinge (d = 200 mm)

External insulation slabs (45 mm glass wool sealed by a 2 mm flexible rubber layer on both sides)

Steel shoe (mounted on the GFRP panels and connected to other shoes with hinges) (1000 x 250 mm)

Profile to fix the external insulation slabs (profile can rotate in one direction)

Composite hinge developed by D. Vosmaer

GFRP plastic shell (17 mm), Hard rockwool core (260 mm)

Plastic profile to fix the external insulation slabs

Plastic profile (part of the profile used to fix the external insulation slabs)
Concrete foundation

External insulation slab (2mm rubber + 45 mm mineral wool + 2mm rubber)

Composite panels (17 mm GFRP + 260 mm hard rock wool + 17 mm GFRP)

Longitudinal composite fabric hinge

Steel mounting shoe

External insulation slab (2mm rubber + 45 mm mineral wool + 2mm rubber)

Composite panels (17 mm GFRP + 260 mm hard rock wool + 17 mm GFRP)

Steel mounting shoe
Telescopic arms to fix the angle of the GFRP panels (d = 40 mm)

Hinged connection

Plastic profile (part of the profile used to fix the external insulation slabs)

GFRP plastic shell (17 mm), Hard rockwool core (260 mm)

External insulation slabs (45 mm glass wool sealed by a 2 mm flexible rubber layer on both sides)
6.3 Acoustical design

The acoustical design is focussed on the smallest position of the hall (40 meter position), because this position is meant for the most demanding functions when it comes to acoustics. The hall, when it is in the smallest position, can be used for acoustical music functions and for speech functions. The acoustics in the other two positions of the hall would also be interesting to research. The middle position (75 meter position) is meant for concerts. Concerts usually have amplified music. The wanted envelopment can be achieved by placing speakers in the right places. Reverberation is often electronically generated. This way the acoustical properties can be easily adjusted to the preferences of the performers. So in order to create the right acoustical properties a lot of absorbing surface should be added to the hall. The exposition hall (150 meter position) is less demanding when it comes to acoustics, but people will still have to be able to have a conversation and understand each other. Because of the time limit for the design there was chosen to focus on the acoustical music hall and the transformation to the speech hall.

6.3.1 Acoustical function

The acoustical music hall can be used for live music performances such as orchestras, opera and other acoustical performances. This type of music has specific demands when it comes to reverberation and clarity, as has been described in the program of requirements. These values have been achieved without adding extra diffuser panels or absorption panels. This contributes to the concept of integrating acoustics with the structural components and shapes. The folded wall and roof contributes to the diffusion of sound, which has a positive effect on the envelopment. The performers, for example an orchestra, have to hear each other during the performance. The folded surface of the outer wall prevents a lot of the lateral reflections to other instrument players. Therefore the stage is located at the internal wall. This wall and the two side walls allow more lateral reflections to the other instrument players.

The hall has a total capacity of 1801 seats, spread over 31 rows. Every second row the seats are shifted 30 cm, so the next person has a view in between of the two persons in front of him or her. This is shown in figure 6.3.2. The seats themselves are designed in a way so the contribution of an empty seat to the overall absorption in the hall is similar to an occupied seat. This way the hall can be tested and customized without the audience being present. Every two rows the tribune rises 20 cm. These dimensions are based on the values mentioned in Architects Data (Neufert, 2000). The chairs have a width of 60 cm and use 90 cm of depth together with the path in front of the chair. The stage has a width of 32 meters and depth
of 7 meters. The total surface is 224 square meters. The stage has an height of 80 cm. These dimensions are large enough to have an orchestra of 100 musicians perform or for a theatre performance (Beranek, 2004).

The audience is the main absorber in the room and has a total surface of 1.093 square meters. The walls and the roof are made out of GFRP panels. The absorption of the GFRP panels is negligible. The panels have a hard rock wool core, which has a high Rw-value to prevent noise nuisance to the nearby neighbourhood. The internal wall is made out of panels similar to the Sonico 85 wall panel, see figure 6.3.5. The panels contain an absorbing core, which results in a Rw-value of 58 dB (Espero bv, 2014). The absorption coefficient of the perforated panel is not mentioned by Espero, therefore a default value for perforated insulating panels was used (Cavanaugh, 2010). The absorption coefficients are as follows: 125 Hz: 0.55; 250 Hz: 0.89; 500 Hz: 0.73; 1000 Hz: 0.99; 2000 Hz: 0.99; 4000 Hz: 0.99.

The panels can rotate and thus the side facing inward to the hall can change. In the acoustic hall this is a hard wooden finish. The other site of the panels is perforated so they function as absorbers. By rotating the panels 90 degrees they function as doors to the foyer. The central axis of each panel can be fixed to an anchor point in the floor, that can be revealed by removing a plate in the floor. The top part of the panels axis can be connected to the hinge on the top of the structure. Between the roof slabs triangular panels are used to fill the openings, while the other 3 panels on the axis are rectangular. The system uses magnets to connect the panels and create a closed wall. By attaching the panels to the floor, the main part of the dead-load of the panels is being transferred to the floor structure. See figure 6.3.6. The floor is made out of concrete and the stage is finished with a wooden floor. With this materialisation in combination with the shape and the volume of the room the desired clarity and reverberation was reached.
6.3.2 *Speech function*

The same hall, with the same shape can also be used for speech functions, such as lectures or theatre. These functions require a lower reverberation time and more early sound, so the voice of the performer is more clear. In this design the volume of the room cannot change. Therefore more absorption must be added to the hall. This is done by adding panels to the side of the stage, next to the entrances. Also the complete inner wall, behind the stage, can be flipped over, so the absorbing side is facing inward. The last addition to the room is a reflector above the stage, see figure 6.3.3 and figure 6.3.4. The angle of the reflector is chosen so the complete audience will receive reflections, this contributes to the clarity. The other side of the reflector functions as an absorber. Using these measurements 1.153 square meters of surface with an high absorption coefficient was added to the hall. The halls acoustic properties are optimized for speech functions. By flipping some of the back wall panels a variation in reverberation time between 0.8 and 2.3 seconds can be created, depending on the preference of the performer.
6.4 Impressions
Because the design has a complicated shape, impressions can help give a better idea of what the final design looks like and how it can function. The impressions show the exterior and the interior in different positions and for different functions that are described above.
Fig. 6.4.3  Exterior speech and acoustic hall

Fig. 6.4.4  Exterior concert hall

Fig. 6.4.5  Exterior exhibition hall
Fig. 6.4.6  Interior empty exhibition hall

Fig. 6.4.6  Interior empty concert hall used for amplified music
7. Analysis

7.1 Structural analysis

The materials that were initially used are glass fiber reinforced plastic (GFRP) for the shell of the structural panels and rigid polystyrene foam as insulation material which is fixed to the GFRP panels. Because of the sound insulating properties of rigid polystyrene foam, there was chosen to use a different insulating material: hard rock wool. This material has better sound insulating properties and thus the thickness of the insulation layer was defined by the thermal insulation. The layer of hard rock wool has a thickness of 260 mm. The material has other mechanical properties than rigid polystyrene foam. For example the density of the material is twice as high. Also there are small changes in the dimensions of the triangular panels. The change of material and the change in thickness of the section creates the need to do a final structural analysis. In this analysis all three positions of the hall (exposition-, concert- and acoustic hall) have been analysed. Forces have been applied so the structures can withstand the ultimate limit state. The wind load has been applied in the opposite direction of the x-axis. This has been tested by the following components: vertical deformation, horizontal deformation, compressive stress and tensile stress. In the analysis a 17 mm shell of GFRP was used.

7.1.1 Deformation

The allowable horizontal deformation depends on the height of the structure and thus it differs for all three of the positions. This value can be calculated by dividing the height of the structure by 300 (h/300). The deflection which has to be within this limit is the additional deflection. Therefore the difference between the deflection by its own weight and by its own weight, wind load and snow load has been analysed. For the exposition hall the allowable deflection is 0,09 meters, which is equal to the occurring additional deflection. In order to achieve this an extra support had to be added underneath the corner, which would otherwise not touch the ground. The other two positions of the hall, as has been seen in the previous analysis, are more stable and stronger. The concert hall has an additional horizontal deflection of 0,03 meters. Because the hall has a lower height in comparison to the exposition hall the allowable deflection is 0,05 meters. The acoustical hall has an additional horizontal deflection of 0,01 meters where 0,05 meters is still allowable. The result of this component of the analysis supports the assumption that when the structure is in a more compressed state, the hall becomes more stable and stronger. The horizontal deflection is mainly caused by the wind force. However when the height of the structure is reduced the wind force on the building will also reduce. This also influenced the results of the analysis. The largest deflection of the exposition hall occurs in the mid sections of the roof spans, which is the location where the folded panels have the lowest height and thus a lower moment of inertia in comparison to the sections at the corner. In the other two positions the deformation is more spread along the structure and the largest in the corner sections. The results can be seen in diagram 7.1.1.

The allowable vertical deflection for the hall is equal for all of the positions of the hall, because it depends on the span of the structure (0,004*l). The span of the structure is 85 meters, resulting in an allowable deflection of 0,34 meters. The additional vertical deflection of the hall has to be within this limit. For the exposition hall this additional vertical deformation is 0,28 meters. When the hall is compressed to the dimensions of the concert hall the deformation is slightly larger: 0,29 meters. When the hall is in its smallest position (acoustic hall) the deformation is 0,11 meters. While the largest additional vertical deformation was expected to be found at the exposition hall, there is a simple explanation why it the largest additional vertical deformation is actually at the concert hall. The exposition hall has a roof with a small angle, meaning it has a lower form factor for the snow load compared to the other two positions of the hall. So the other halls have a larger load on the roof, which results in an additional vertical deflection of 0,29 meters for the concert hall. In exposition hall the largest deflection occurs again at the weakest part of the section, while in the
other two positions the deformation is more spread along the structure and the largest in the corner sections. See figure 7.1.2.

7.1.2 Stresses
The stresses have been analysed for the GFRP material. The maximum compressive strength of the material is 180 MPa. Figure 7.1.2 shows the minimum principal stress. The lowest values in these figure are representative for the compressive stress. The highest compressive stress can be found along the longitudinal hinges and at the hinge in the middle of the structure. For the acoustic hall the largest compressive force can be found at the same locations, with a maximum value of 89 MPa. All of these maximum compressive stresses are

In the concert hall this stress is larger: 146 MPa. The highest compressive stress can be found along the longitudinal hinges and at the hinge in the middle of the structure.
well within the limit of the compressive strength of GFRP (180 MPa). The increasing compressive stress at the concert hall can again be explained by the higher snow load on the roof.

The maximum tensile strength of the material is 220 MPa. The maximum tensile stresses are represented in the figure of the maximum principal stress (fig. 7.1.4). For the exposition hall the maximum tensile stress is 62 MPa. Again the stress in the concert hall is slightly larger as a result of the increasing snow load. It has a value of 99 MPa. In the acoustic hall the maximum occurring tensile stress is smaller: 57 MPa. All of these stresses are well within the limit of 220 MPa. The largest stresses for each of the positions of the hall can be found at the folds between the roof slabs and the wall slabs.

Based on this analysis the structure is still functional, when the extra support is added to the structure when it is in the position for exposition.

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**Fig. 7.1.3** Minimum principal stress. (Left: exposition hall; Middle: concert hall; Right: acoustic music hall)

**Fig. 7.1.4** Maximum principal stress. (Left: exposition hall; Middle: concert hall; Right: acoustic music hall)
7.2 Acoustical analysis
Both functions of the smallest hall position were analysed. By varying the amount of flipped Sonico panels an intermediate between these two extremes can be created, resulting in a large range of possibilities. The design has been modified and reanalysed until it was optimal for the wanted functions.

7.2.1 Absorption coefficients
In order to get a realistic result out of the CATT-acoustics analysis, the correct absorption coefficients (ABS in CATT-acoustics) have to be used. In CATT-acoustics they can be filled in as percentages. Each material has a different absorption, the used values for this analysis are based on own calculations for the GFRP and diagrams of Barron and Beranek. The values are true for the following frequencies: 125 Hz, 250 Hz, 500 Hz, 1,000 Hz, 2,000 Hz and 4,000 Hz. The used values for the acoustic hall are listed below:

For the speech functions the following values were used:

For the music functions the following values were used:

![Fig. 7.2.1 Clarity C80-value in the acoustic hall](image)
![Fig. 7.2.2 Reverberation time in the acoustic hall](image)
![Fig. 7.2.3 Loudness G in the acoustic hall](image)
7.2.2 Acoustic music hall analysis

The aim of the acoustic hall was an objective clarity with a value between -3.0 dB and 0.0 dB. The objective clarity in the final design has an average value of -0.8 dB, which is within the wanted range. There are three stripes in the diagram where the clarity is slightly over the value of 0.0 dB. The stripes shown in the hall are most likely caused by the unusual shape of the building and the direction of the lateral reflections as a result. These stripes are unusual to be found in a rectangular hall with similar dimensions, this can be seen in the analysis of the rectangular hall (fig. 7.2.7). The spread of clarity has a large range, however when in the rectangular hall this is even larger. The rectangular hall does have a clearer peak in its histogram of the objective clarity. A slightly higher value can also be found near the sound source. See figure 7.2.1.

The reverberation time has an average value of 2.28 seconds. This value should be between the 2.0 seconds and the 2.3 seconds. The reverberation time is lower on the location where the objective clarity is lower as well. This is a logic result, as objective clarity is relation between early sound (first 80 ms) and late sound (after 80 ms). A lower reverberation time is also less late energy, which can cause an higher objective clarity. See figure 7.2.2. Although this was the...
desired value, it is rather high because the amount of 3000 seats was not achievable and thus an amount of 1801 seats was used. The spread of reverberation is slightly smaller than occurs in the rectangular hall (see figure 7.2.2 and 7.2.8) and has a lower average value.

The loudness of the hall (G) should be between 1,5 dB and 5,5 dB. The average value of the hall is 5,09, which is within the limit. Figure 7.2.3 shows slightly higher values near the sound source and at the same locations where there is a lower reverberation time and an higher objective clarity. The loudness in the acoustic hall is slightly lower than the loudness in a rectangular hall with similar dimensions shown in figure 7.2.9.

7.2.3 Speech function hall
The speech function has a different demand for the objective clarity. Here the C50-value is used to show the relation between early and late arriving energy. The value should be higher than 1,5 dB, see figure 7.2.4. The average of the objective clarity (C50) is 2,01 dB, which meets the requirements. Higher values can again be found near the sound source and in three parallel stripes. There are also location in the hall where the clarity is lower than 1,5 dB. This is caused by the large dimensions of the hall and also results in a low loudness. In halls with a similar dimensions it is not uncommon to amplify the sound.

Fig. 7.2.7 Clarity C80-value in the rectangular acoustic hall

Fig. 7.2.8 Reverberation time in the rectangular acoustic hall

Fig. 7.2.9 Loudness G in the rectangular acoustic hall
A desirable reverberation time for a hall with a speech function is lower than 0.8 seconds. The current value is 0.78 seconds, which is just below the limit. See figure 7.2.5. When the receiver is further apart from the sound source, the reverberation time becomes slightly higher.

The average loudness in the speech hall has a value of 4.75 dB, see figure 7.2.6. This is lower than the value in the acoustical hall. There is no aim for the loudness of a speech related function, so this value is acceptable as it is, however there are also locations with a lower value which is the result of the large dimensions. The loudness is higher near the sound source. The diagram also shows similar stripes as are shown in the other diagrams.

When these results are compared to a rectangular hall with similar dimensions and a similar interior design, the differences are minor. This could be the result of the interior design. The reflector is designed to improve the clarity and the absorbent material is placed in location so most of the lateral reflections are absorbed. Therefore less lateral reflection use the folded surface, meaning the structure is less of an influence.
7.3 Functionality

In order to have a successful project or design it should meet the requirements defined in the program of requirements (paragraph 2.2) and the preconditions (paragraph 2.3). In this paragraph these requirements and preconditions will be compared with the final design.

7.3.1 Program of requirements

All of the mentioned functions (exhibitions, amplified music events and speech related performances) are integrated in the new hall. Also the connection to the WTC passage has been created. When the hall is in its smallest position it can be split into two halls. But in order to comply completely with the functions of the original hall, the hall should also be able to be split into two halls in the other positions. With a little further development this should be possible.

The dimensions show some deviations from the dimensions in the program of requirements, because of the folded pattern of the walls and roof. However the dimensions in the program of requirements were used as a guidance and thus the final dimensions of the hall are useful for the functions described above. The height for the exhibition hall is indeed larger than 14 meters. For the concert hall (used for amplified music) the height is between 11 and 15 meters high, which is a little lower than the aim was in the program of requirements. The acoustical hall and music hall have a room height between 10 and 15 meters, which is lower than the requirement for the acoustic hall and higher than the requirement for the speech hall. Also there are 1801 seats in the hall, while 3000 seats was set as a goal for the hall. The dimensions are a result of the acoustical optimisation. The used heights in combination with the shape are more useful for these functions. More seats could be added by using balconies, which is common in theatres with similar dimensions. But because of the movement of the structure and the temporary interior, this would be difficult to incorporate.

The building physical requirements in paragraph 2.2 where less specific. The detailing is focused on water tightening, thermal insulation and sound insulation. The insulations of the building have been solved, but there were no calculations made to see to what extend there are thermal and sound leakages along the folding lines. It is to be expected that there are leakages as the panels become thinner towards the edge and the additional external insulation has a smaller thickness (45 mm). Ventilation, lighting, and heating have not been designed, because the focus of the research question was on the acoustical and structural design. The variable acoustics were partially established. The requirements in table 2.1 where established for the acoustic music function and the speech function. All the intermediates of these requirements can also be created as has been explained in paragraph 7.2. The concert hall was not examined and developed because the acoustical properties are less demanding for amplified music. However by adding sound absorbing materials the room should be useful for concerts.

The guidelines for construction and design were used during the whole project, especially the integration of the acoustical shape and the construction. The sustainability was less decisive in the designing process than it could have been.

7.3.2 Preconditions

The preconditions focused on the location of the design and its surroundings. These preconditions were used to determine the dimensions of the floor plan and the location of the connection to the WTC passage. The further the design developed the more the focus was put on the acoustics and structure and the preconditions became less important. This did not influence the functionality negatively, as the design as it is now could also be used on locations other than Leeuwarden.
7.4 Strength, weakness and opportunity

The concept has been developed into a design with potential, but not into a finished design. After an analysis of the final design it becomes clear some improvements could be made to the design and what the strengths and weaknesses are.

7.4.1 Strengths

The main strengths of the design derive from the research question. The aim during the development of the design was to increase the multifunctionality of an exhibition hall. The design succeeded in this by creating a building with a flexible floorplan that can change its amount of floor surface and by optimizing the structure for music and speech related functions. The structure has a width of 85 meters, but the length can change in length anywhere between 40 meters and 150 meters.

The change in floor surface is accompanied by a changing volume. The large variant of the exhibition hall is not often needed. When the building is vacant or less surface is needed the building will be set to a smaller position. This means the amount of air that has to be conditioned (ventilated, cooled or heated) is minimized. This is desirable from a sustainable point of view.

Another strength that derives from the aim of the project is the integration of structure and acoustics. The shape used for the diffusion of sound is also a structural strong shape. The possibility to integrate these shapes contributed to the integration of the main structure with acoustics and building physical demands. By using composite panels with insulating internal material this was all combined and no extra material was needed to create a design usable for the acoustic performances. This means the amount of material is limited, which is also desirable from a sustainable point of view.

Besides its structural and functional benefits, the design also has acoustical benefits. The shape of the smallest hall is designed in a way so no additional absorption had to be added to the hall, other than the audience, and no adjustments where needed to the structural material (for example perforations). This is only true for the for the acoustical hall and not for the speech hall.

The internal wall, consisting out of Sonico 120 panels by Espero with perforations on one side and a hard finish on the other side, can change its composition. By switching some panels, rather than all the panels, a large variety in reverberation time can be achieved. The reverberation can vary between 0,8 seconds and 2,3 seconds. This also contributes to the functionality.

The last strength of the design is the aesthetically pleasing design. Aesthetics are a subjective aspect of the design. The goal for this aspect was to create an interesting design that is more pleasing than a rectangular black box with corrugated sheets, fits the functions and could be a recognizable icon at the entrance road to Leeuwarden. In these aspect the design succeeded and in my opinion it is a aesthetically pleasing design.

7.4.2 Weaknesses

Besides strengths, the shape of the structure also has weaknesses. While the possibility of reducing the floorplan and volume of the building is beneficial for the climate installations, the folded structure does have a large outer surface. The optimum proportion between outer surface and volume would be a sphere. With every fold, extra surface was added while the volume remained the same. For the large hall the relation between outer surface and volume does not seem to be extraordinary. When the building becomes more compressed, the amount of outer surface remains the same. This means there is a large surface to lose heat, which is a disadvantage for the climate.

Another weakness can be found in the construction of the building. The details have a lot of fragile elements, because of the movement they have to provide. The movement also causes problems with water tightening and air tightening. In further research 1:1 scale models could be made to test the details and see what problems occur and if there are elements that are too fragile.
This research would make the design more convincing.

The movement of the structure complicates the interior design of the acoustical and speech hall, but also of the larger hall. In the original plan it was the intention to optionally split the hall in 2 parts, because this is also possible in the existing hall. The unusual angles in the roof and the walls make it more difficult to install a temporary wall. For the acoustic and speech hall a conceptual solution for the interior wall is designed. Here the main disadvantage is the application of balconies. Because of the absence of balconies the amount of seats has been reduced from 3000 seats to 1801.

The moving structure also means fire exits can only be located on the two flat outer walls. This could be a problem in the concert hall and the exhibition hall, because of their large dimensions. Extra measurements would be needed to meet the demands.

In the acoustical analysis three stripes occurred, which are likely to be a result of the angles in the roof. In the analysis of the rectangular hall this pattern did not occur. The angles in the structure result in a good envelopment, but in a rectangular room the reverberation time, clarity and loudness are usually more equal on the audience plane, although the analysis showed large differences for this shape as well. With further research a solution could be found to spread the sound more equal. With a 1:10 scale model these solutions could be tested and be used to support the results of the computer analysis made with CATT-acoustics. Adding reflectors underneath some of the gaps could be a solution to get a more equal spread, another solution could be introducing more angles in the structure to increase the diffusion of sound even more.

Another acoustical weakness of the design is the transformation between the speech hall and the acoustical hall. The acoustical hall was successfully designed without any additional materials. Originally this was also the goal for the speech related function. Gradually, it was found to be not possible, therefore additional measurements where used to improve the acoustics. These additions (curtains, reflector with two sides) make it more complex to transform the hall, although it is still doable. It would be interesting to see how this design could be simplified.

7.4.3 Opportunities
In this design the focus was on structural design and acoustical design. Aspects of climate design other than acoustics have not been designed. Because of the variation in volume a climate control station is needed which can adapt to the changing ventilation, heating and cooling demands. Because of the music functions the system would also need to be as silent as possible. Fixing ventilation shafts to the roof might be difficult because of the movement of the roof. It would be interesting to see what solutions are possible. One could imagine flexible shafts hanging from the roof, or an underground structure with fixed spots on de floor where air is blown into the room.

As has been mentioned in the previous paragraph it would be interesting to see how well the details function and how the water and air tightening can be improved, thermal leakages can be reduced and to see to what extent the detailed elements are too fragile. At this moment the dimensions of the different components in the details are based on estimations. The structural functioning of these details can also be analysed.

The costs of the production, the building process and the maintenance haven’t been analysed as well as the CO2 footprint. A cost analysis could show if the development of a building with varying dimensions can be beneficial and if it is a more sustainable solution in comparison to a more traditional design of a multifunctional exhibition hall. One could imagine the costs and CO2 footprint of climate control when using only a small portion of a large hall are substantially larger than maintaining the same climate conditions in a small hall, so the potential sustainability of this solution is there.
8. Conclusion

At the start of the research the following question was defined: “What are the characteristics of a multifunctional exhibition hall of which the structural design is integrated with the variable acoustical design and of which the acoustic properties are used as decisive factors in the visual appearance of the design?” The goal of the question was to improve the functionality of this type of exhibition complexes and decrease the vacancy rate as well as to create a design that is more sustainable then the current rectangular halls with corrugated sheets.

During the research it became apparent that the simple rectangular or an hexagonal shape was most ideal when acoustical quality and visual quality for the audience are combined. For the exhibition function this would be a rectangular shape. Based on this shape for the floorplan analysis’s led to a three-hinged structure, with folded panels to improve the diffusion of sound.

To increase the multifunctionality of a building, without creating separate rooms for each function, the building has to be flexible. This can be done by changing the interior design, but in this case the most important difference between the different functions (exhibition, concert, acoustic music, speech) is the needed floor surface. To meet these requirement without creating separating walls, a folding pattern was used that allows the structure to be compressed.

A research in folding patterns has shown a variety of possibilities, that where tested for acoustical properties and structural properties. The analysis has shown that the direction of sound and the main direction of the folds have to be aligned in order to get a good acoustical result. Structural analysis has shown the strength of a folded structure. When the structure becomes more compressed, it becomes stronger as a result of the increasing moment of inertia. The results proved it is possible to combine the structural and acoustical shapes.

The final acoustical analysis show the difference between a rectangular hall, the speech hall and the acoustic hall. A variation in reverberation time between 0,8 seconds and 2,3 seconds was achieved, without the need to add layers of material to the main structure.

Based on the findings in this report an answer can be given to the research question, stated that this is not the only possible answer to the question. The first characteristics would be the functions. In this specific situation this would be exhibitions, amplified concert, acoustic concert and speech functions. This was based on the current functions in the WTC Expo in Leewarden. When acoustics are used as leading aspect in a design it depends on the function, what the shape of the building would be. In this case the focus was on the acoustic music hall. A folded pattern diffuses sound and thus it is a good characteristic in this case. If the speech hall was the main function, the design would most likely have had a different shape as diffusion of sound is less wanted. Another characteristic is the moveability of the structure, which is the result of multifunctionality without creating separate or vacant rooms.

The main goal of the project was to create an integral design where acoustics and structure coincide. This has been achieved for the acoustic music hall. The speech hall needs some minor additions (curtains and reflector) and is therefore slightly less successful. For the other compositions of the building the acoustics have not been tested and therefore is can not be said if the goal was successfully reached. The main disadvantage of the movable main structure to the acoustic design is the absence of balconies, which resulted in 1801 seats instead of the wanted 3000 seats, but overall the design was successful.
9. Reflection

This project was developed over a period of eight months. At the end of this period it is interesting to see to what extent the project and the used methods have contributed to the goal that was formulated at the start of the process. The goal of the project was to create an integral building design by integrating structural design with acoustical design.

In order to be able to combine structural and acoustical shapes literature research was needed to obtain the extra needed knowledge on acoustical design. This research was used to develop a concept with a favourable shape for structural and acoustical purposes. These concept shapes were further tested using analysis programs for structure and acoustics. The results were analysed to make substantiated choices in the development of the design. This way research was done by designing a multifunctional exhibition hall. During the process design and research were inseparably connected to each other and resulted in a substantiated design. The research focussed on the acoustical part, although the structural element was of equal importance. It resulted in a report in which the acoustics are dominant. If I would perform the project again I would do research on the structural element as well, even though this is more familiar for me, as it would provide a more complete report.

The chosen theme for the graduation project was an integral building design with a focus on structural design. When the assignment became more defined, the focus of the design was on the acoustical aspects as well as the structural aspects. This led to an interesting design and process. At first the goal was to create an integral building design by which is meant that a structural, climate and facade design was created at the end of the process. At the end of the process an integral building design was delivered with a different approach. In the final product an integral design means there is thought about the production, transportation, building process and the final building design and detailing.

In order to make decisions about the building requirements and the preconditions an existing location in the Netherlands was chosen. However this design could be used on more locations. The main benefit is the reduction of volume, which means there is less air which needs to be conditioned when the hall is not used or only a part of the total floor area is needed. This could be a sustainable solution to reduce the climate demands for a similar hall. Another benefit is the elimination of the need for adding extra material to reach optimal acoustical properties. And the optimisation for acoustical functions means the usage rate of the hall can be increased. These three benefits could reduce costs of an exhibition hall, however an analysis of costs has not been made at this time.

Overall the used approach was successful and resulted in an interesting and successful design in terms of structural and acoustical design. In order to appeal to a wider social context solutions for climate design should be included as well as an analysis of building costs and possible solutions to reduce these costs. Because only literature studies and computer analysis were used to substantiate the design it is not completely reliable. More complicated calculated analysis and tests with mock-ups would make it more reliable. Also some of the used values are assumptions. Next time I would approach an acoustic lab to do some physical research to get more feeling with the subject.
Because the focus and restrictions of the research project were defined by myself, I experienced the graduation process as an opportunity to gain more knowledge on my areas of interest. Therefore it was also a very educational and enjoyable process that did not fail to hold my interest. It was very educational to be able to go into more depth with a research-based design. Therefore it lived up to my expectations.
10. Bibliography


11. Catt-acoustics analysis results

In Catt-acoustics two variants of the same folding pattern were tested. The first variant has slabs with 3 meter width and the second is constructed out of slabs with 4 meter width. Both variants are tested in two directions and with the receiver and source aligned or not aligned. Meaning there is a total of 8 analysis results, which are shown below. In this analysis the lateral reflections that reach the receiver in the first 80 ms are shown.

11.1 Variant with 3 meter slabs

- There are only a few reflections.
- The sound waves are reflected by the ceiling, back wall and one side wall.
- The receiver hears sounds mainly from the left.
- There is little envelopment.

**Fig. 11.1.1** View of the used model

*Fig. 11.1.2* Image source model, isometric view

*Fig. 11.1.3* Image source model, side view

*Fig. 11.1.4* Image source model, reflectogram
11.1.2 Variant with 3 meter slabs aligned

- There is an average amount of reflections.
- The sound waves are reflected by the roof, back wall and side walls.
- Receiver hears sound from the front, the side and multiple angles from above.
- There is a good envelopment.

Fig. 11.1.5 View of the used model
Fig. 11.1.6 Image source model, isometric view
Fig. 11.1.7 Image source model, side view
Fig. 11.1.8 Image source model, reflectogram
11.1.3 Variant with 3 meter slabs rotated

- There are many reflections.
- Most of the lateral reflections are caused by the ceiling and only a few are reflected by the back, front and side wall.
- The receiver will hear most sound reflection from the back.
- There is little envelopment.

Fig. 11.1.9 View of the used model

Fig. 11.1.10 Image source model, isometric view

Fig. 11.1.11 Image source model, side view

Fig. 11.1.12 Image source model, reflectogram

Volume: 19616m³ (approx.)
11.1.4 Variant with 3 meter slabs rotated aligned

- There are many reflections
- Most of the reflections use the ceiling and only a few use the front, back and side walls.
- Receiver hears sound from the front and the back, but all the lateral reflections occur one plane.
- There is a terrible envelopment.
11.1.5 Variant with 4 meter slabs

- There is an average amount of reflections.
- Most reflections are caused by the roof and a few of the lateral reflections are caused by the front, back and side wall.
- Because the roof reflections have a large variety in angle, the receiver hears sound from many angles.
- There is a good envelopment.
11.1.6 Variant with 4 meter slabs aligned
- There is an average amount of reflections.
- The lateral reflections are caused by the ceiling, side walls and back wall.
- The receiver hears sound from many different directions.
- There is a good envelopment.
11.1.7 Variant with 4 meter slabs rotated

- There are many reflections.
- The lateral reflections are caused mainly by the roof, but also by the back, front and side wall.
- The receiver hears sound from the front, back and left side.
- There is an average envelopment.
11.1.8 Variant with 4 meter slabs rotated aligned

- There are many reflections.
- Many of the lateral reflections are caused by the roof and a few by the back and front wall, but all the reflections are located in one plane.
- The receiver hears sound mainly from the front.
- There is little envelopment.
### 11.2 Input ‘Meerlagenmodel’

In this table the values used in the ‘Meerlagenmodel’ are shown. The results are shown and discussed in chapter 5.3.2.

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