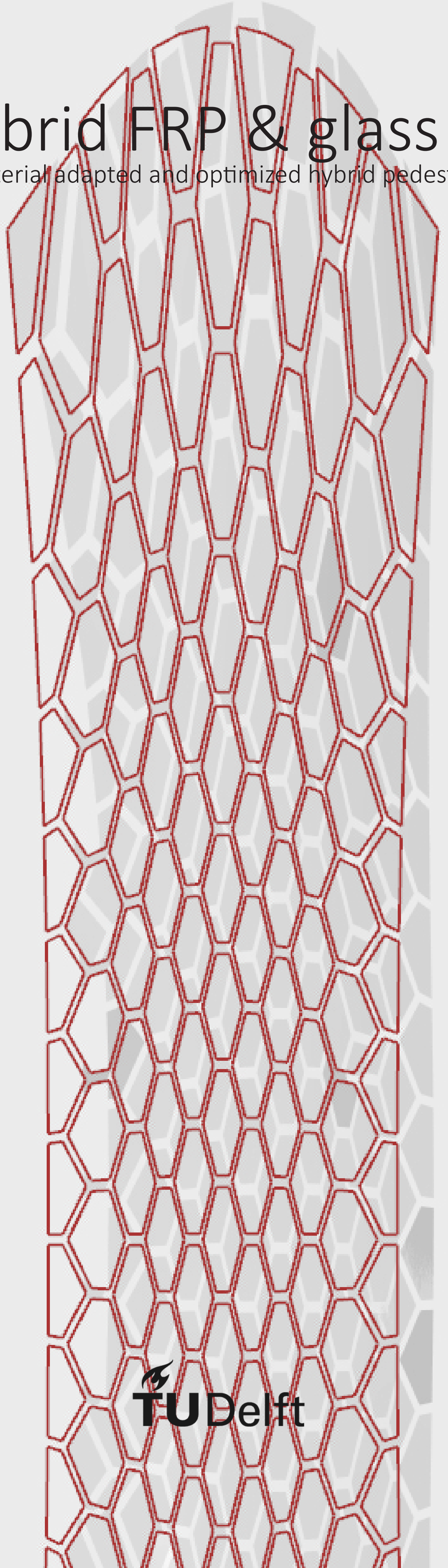
The hybrid FRP & glass bridge

Research for a material adapted and optimized hybrid pedestrian bridge design



TU Delft

The hybrid plate shell bridge

Research for a material adapted design of a FRP & structural glass hybrid pedestrian bridge

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1 Research outline

Fig. 1.1 - Material adapted FRP bridge design: the Dragon's Bridge [Source:http://www.plastics.gl/construction/enter-the-dragon/]

1.1 - Problem definition

The (mis) use of FRP and glass in bridge structures
Both Fibre Reinforced Polymers (FRP) and reinforced structural glass are relatively new materials that are gaining popularity in the building industry. Nowadays 20% of the plastics produced and 25% of the glass production is used in the building industry. [Fradelou, 2013] Besides the standard FRP window frames, FRP facade elements and glass windows, there are also load-bearing elements - like beams - produced from both materials. These load-bearing elements are increasingly applied in structures.

Especially in bridge design an increase in the use of these load-bearing elements can be witnessed. Both FRP and structural glass bridges are increasingly designed in hybrid form or as an all-FRP or all-glass design. The city of Rotterdam is an example for this development: about 90 all-FRP or hybrid bridges have been completed here since 2009, while it also contains one of the first all-glass bridges in the world (figure 1.2). [FiberCore] [Kraaijvanger, 2009]

Fig. 1.2 - One of the first all glass pedestrian bridges in Rotterdam [Kraaijvanger, 2009] [Louter, 2016]

Part of the popularity of glass and FRP in bridge designs can be explained by their advantageous properties. FRP as a “new” building material is lightweight, durable, has high corrosion resistance, high fatigue resistance and is easy to transport and install. [Keller, 2003] Glass has high compressive strength and high stiffness - when glass is used and loaded in the right way it can be as strong as high strength concrete. [Veer, 2016] The most important feature of glass is its aesthetically interesting property of pure transparency, which gives people the opportunity to enjoy the view from a glass bridge from literally all sides.

However, the real drive for the popularity of both materials is expanded knowledge. FRP bridge designs have developed from traditional bridge concepts - where conventional materials are simply substituted by FRP - to material adapted concepts, where the properties of FRP are really taken into account. This resulted in a development from structurally non-efficient and over-dimensioned bridges to very efficient and safe structures (figure 1.3).
Glass mainly benefits from the recent development in safety concepts. New safety concepts, like the reinforcement and lamination of glass, have partially solved the problem of the brittleness of glass. This resulted in stronger and safer glass structures and therefore the possibility to give the material a load-bearing function.

The combination of FRP and glass
The expansion of knowledge did not yet stop. New research projects are developed to further test and

improve the use of both materials in structures. Such research often concerns the combination of glass or FRP with other materials in hybrid designs to enhance the efficiency and behaviour of the structure. The goal of these hybrids is to optimally use the material's strengths while its weaknesses are accounted for by an other material.

Fig. 1.3 - The development of FRP bridges: from mimicking steel structures to material adapted concepts. [Source: fiberline.dk] [Smits, 2016]

FRP is in many occasions combined with materials like steel, concrete and aluminium, while structural glass is often combined with a steel primary load-bearing structure (figure 1.4). [Wan, 2014] More recently FRP has also been combined with glass in several hybrid beam designs, showing the potential of a combination of these materials on a small scale (figure 1.5).

Fig. 1.4 - Pedestrian bridge in China with steel main structure and glass secondary structure [Source:http://edition.cnn.com/travel/article/china-zhangjiajie-glass-bridge-closed/index.html]

Fig. 1.5 - Hybrid glass & FRP beam (more information in chapter 5 - Hybrid systems) [Louter, 2015]

Strengthened by the recent developments in conceptual FRP-glass hybrid structures (figure 1.5) and lead by both materials' rising popularity in bridge design and the differences and similarities in material properties the question raises if these two materials can be combined to create an optimized bridge design.
A hybrid FRP-glass beam shows the advantage of their combination on a smaller scale. However, when considering the popularity of both materials in bridge design, it is interesting to research if these advantages continue to apply or possibly are extended on a larger scale structure - the pedestrian bridge.

According to the authors' knowledge no hybrid bridges with a load-bearing structure of FRP and structural glass have been built or designed yet, to illustrate the relevance of this research. To research this subject could offer new possibilities in the structural design sector and contribute to the knowledge about these materials.

1.2 - Aim of research

The aim of this research is to research the material properties of glass and FRP to find the structural advantages of both materials and subsequently use these advantages in the best possible way to create an optimized transparent hybrid pedestrian bridge design.
This will be a new and challenging collaboration between two materials with different (and sometimes similar) advantages and disadvantages in a material adapted concept:

> *"In material-adapted concepts the basic idea is not to give preference to any material, but to use it where its advantages can be best utilised" [Keller, 2003]*

This means that the advantages and disadvantages (or strengths and weaknesses) of both materials should be researched. This should result in a bridge design where the strengths of both materials are used optimally, while the weaknesses of each material are captured or solved by the other material.

- There is one very specific type of bridge that is most popular in both FRP and structural glass design: the pedestrian bridge. This research will therefore focus on the pedestrian bridge type, also due to the large array of possible bridge types.

- This research will focus on a medium long span of about 30 meters. This span length has not yet been reached in any bridge design where glass is the main load-bearing structure.

- This research will primarily focus on the structural efficiency of the design. The main focus will therefore not be on sustainability, meaning that for example bio-based fibres will be chosen when they prove to have better mechanical properties than conventional fibre types. When there is no difference in structural efficiency the choice can be made considering other factors like the sustainability, costs, aesthetics, etc.

1.3 - Research questions

1.3.1 - Main research question

The aim of research leads to the following main research question:

"Can a hybrid pedestrian bridge with a load-bearing structure of FRP and reinforced structural glass be designed while making optimal use of the material properties of both materials?"

1.3.2 - Sub-questions

This main question will be answered by using sub-questions. These sub-questions are answered one by one and will lead to a complete and integrated design of the hybrid bridge.
The first sub-question focuses on the location of the hybrid bridge. This choice will influence the remaining research as it has the largest effect on boundary conditions:

1. *What is the most suitable location for a hybrid pedestrian FRP and structural glass bridge considering the aim of research and material characteristics?*

When the location has been chosen it is important to define a complete program of requirements for this bridge. The second sub-question is therefore:

2. *What are the boundary conditions for this bridge design considering the location and function of the bridge?*

First of all the general material properties of both FRP and glass have to be studied to understand the material. This can lead to a certain approach of the design task. Therefore the first two research questions are:

3. *What are the (mechanical) properties of fibre reinforced polymers?*

4. *What are the (mechanical) properties of reinforced structural glass?*

Secondly the structural use in bridges and hybrid systems of these materials has to be studied, leading to an analysis of precedents. The following two research questions are therefore:

5. *What hybrid systems have been built and what are their structural characteristics?*

6. *What precedents (structural glass and FRP) have been built and what are their structural characteristics?*

The theoretical study will lead to several design guidelines, which can then be used to create preliminary variants for a hybrid FRP and structural glass bridge:

7. *What is the optimal structural concept for a hybrid FRP and structural glass bridge?*

This structural concept has to be elaborated on leading to the next sub-questions:

8. *What is the most efficient structural shape and size for this bridge design?*

9. *What is the most efficient connection between FRP and structural glass?*

1.4 - Methodology

The design by research done in this thesis can be divided in nine different steps. This is visualized in figure 1.6.

1. MATERIAL RESEARCH
The first step in designing the bridge consists of research into the material properties of FRP and structural glass. The knowledge of these properties will be translated to design guidelines. These guidelines can be used to create a hybrid design where the structural advantages of both materials are put to best use.

2. ANALYSIS PRECEDENTS
Bridges in FRP and glass are popular: therefore many examples of these bridges can be found to analyse. The quality and more practical advantages and disadvantages of these designs will be derived from this research and will be design guidelines for the preliminary design variants.

3. ANALYSIS HYBRID DESIGNS
The third step includes the analysis of already existing (state of the art) hybrid designs of FRP and structural glass. These examples will result in several ways both materials can be combined: what are their strongest points and what are the weaknesses that are the reason to combine them with another material.
The findings will be presented as design guidelines to form the preliminary design variants.

4. PRELIMINARY VARIANTS
The fourth step is to define multiple variants, each with a different structural method for combining glass and FRP. The best material adapted concept is then chosen based on criteria (which in turn are based on the previous research). This concept is elaborated on.

5. CONCEPT DESIGN
The chosen preliminary variant is elaborated on. Possible further theoretical research will be conducted in this phase.

6. FORM-FINDING
The elaboration of the concept design also includes a form-finding process. The globally ideal shape and geometry will follow from this process.

7. OPTIMIZATION
A FEM-analysis is then conducted on the design concept. This results in a modification of the design concept and a new FEM-analysis (and possibly a new form-finding process). This is repeated until an optimized design is reached.
Also observation and hand-calculation will be done to evaluate the concepts and reach an optimized design.

8. FINAL DESIGN
After optimization the design is further elaborated - drawings are made presentable and models are created and/or finished. The final optimized design should be able to answer the research question of this thesis.

9. REFLECTION
In the reflection conclusions will be drawn. The design process and the final results will be reflected upon.

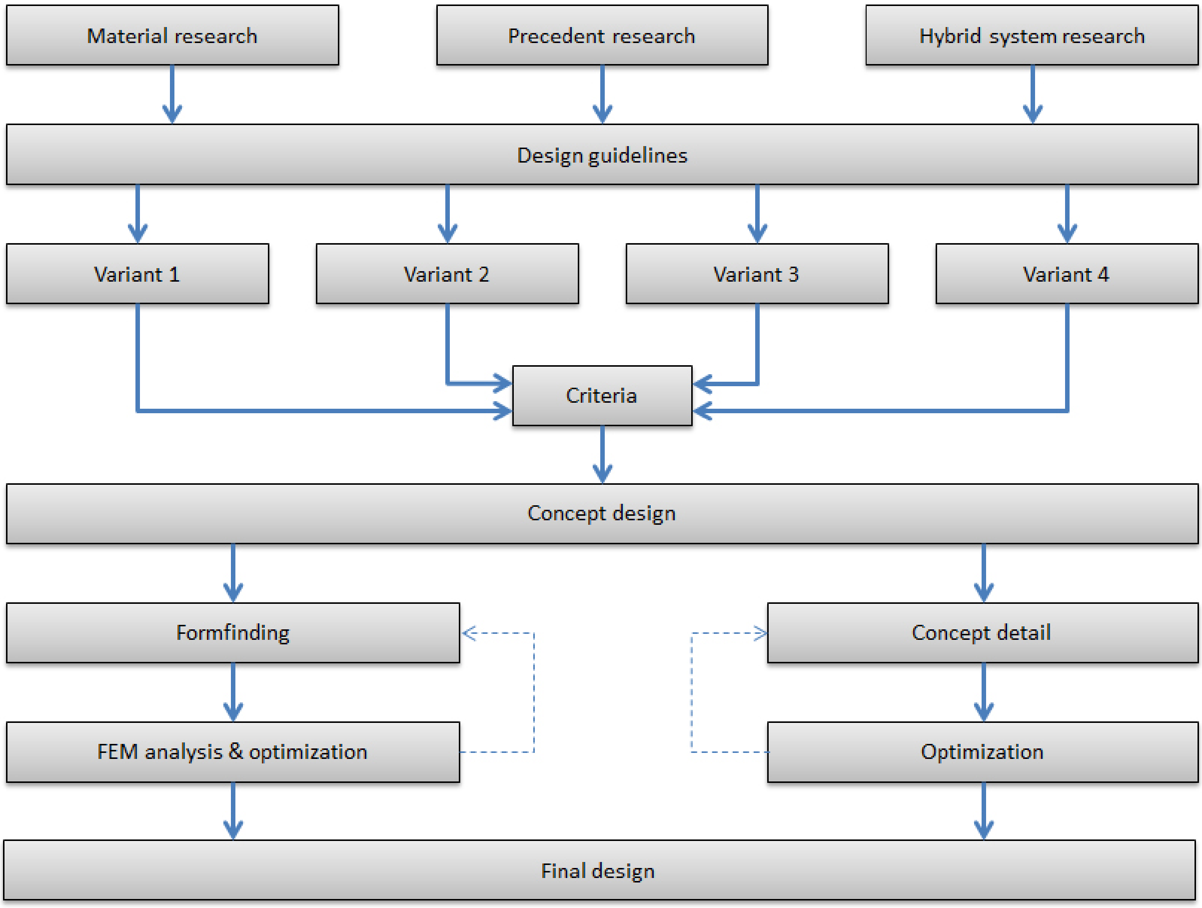
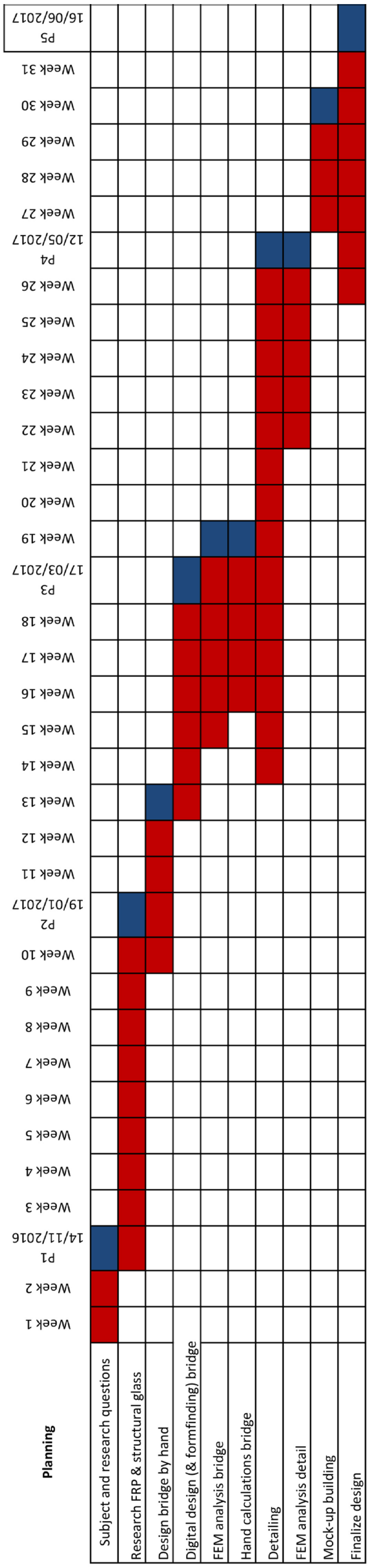


Fig. 1.6 - Visualization of the steps in the design process.

1.5 - Relevance

This design explores the usage and possibilities of two relatively new materials: Fibre reinforced Polymers and structural glass. These materials have not yet been combined in a structure, due to lacking knowledge and the ease to use other conventional materials. However there is a lot of research being done concerning both materials and there is also research done where both materials are combined on a small scale. This thesis takes this research one step further and incorporates both materials in a material adapted bridge design, providing new knowledge of how to actually apply these materials together in a structural design.

1.6 - Planning


Planning
Subject and research questions
Research FRP & structural glass
Design bridge by hand
Digital design (& formfinding) bridge
FEM analysis bridge
Hand calculations bridge
Detailing
FEM analysis detail
Mock-up building
Finalize design
Week 1
Week 2
P1
14/11/2016
Week 3
Week 4
Week 5
Week 6
Week 7
Week 8
Week 9
Week 10
P2
19/01/2017
Week 11
Week 12
Week 13
Week 14
Week 15
Week 16
Week 17
Week 18
P3
17/03/2017
Week 19
Week 20
Week 21
Week 22
Week 23
Week 24
Week 25
Week 26
P4
12/05/2017
Week 27
Week 28
Week 29
Week 30
Week 31
P5
16/06/2017

1.7 - Location of bridge

For the definition of a program of requirements it is necessary to choose the location of the hybrid FRP and glass bridge. The following research question will be answered in this chapter:

> *"What is the most suitable location for a hybrid FRP and structural glass bridge considering the aim of research and material characteristics?"*

This results in two requirements for the location considering the aim of research. The location should:

- Require a pedestrian bridge
- Require a bridge with a medium long span length (30m)

Both materials have some very specific characteristics, which will reflect in the bridge design. Only the material characteristics that will undoubtedly reflect in the final design will be considered as requirements for the location. The location or actors exploiting the location should:

- Require a (partially) transparent bridge
- Require durable materials (as glass and FRP are both durable)
- Be open to innovative concepts and material use

1.7.1 - Proposed location

The proposed location of the hybrid FRP & structural glass bridge is in Delft on the terrain of "the Green Village". The bridge is located on the north-side of the location as an entrance to the area (figure 1.7 - in the red circle).
Several innovative concepts designs are under construction on this terrain, which are caught in the masterplan of this area (figure 1.13 & 1.14). On the west side of the location a glass masonry bridge is going to be built (see chapter 4 - precedent research for more information about this bridge). This bridge will become the main entrance to the Green Village.
The Green Village wants to "create a green future together". According to the architects the Green Village is considered a self-sufficient and sustainable area in which all water, waste, and energy flows will be measured and monitored. The area is designed as a lively and open community where students, academic staff, and professionals can enrol in courses, perform research, and test their own products. In addition, the area will function as a hotspot with a lively public space, cinema, restaurant, shop, and large entertainment venue. The master plan is built on four pillars: the lively street, flexible framework, variation in form and image, and functions. [Karres+Brands, 2015] According to the urban planners of the Green Village the visitor should experience how his or her living and working environment will look like in 10 to 15 years. [Buro Lubbers, 2015]

1.7.2 - Possibilities of location

The proposed location should suffice in the requirements stated in chapter 1.7. These requirements are treated in order. The location should:

Require a pedestrian bridge
At first sight a new pedestrian bridge for the Green Village is not necessary due to the existing main entrance - the glass masonry bridge. However, the glass masonry bridge is not accessible for people in wheelchairs due to the height difference of the glass masonry bridge (700mm up over a length of 14 meters). The new bridge can therefore make the area wheelchair accessible.
Secondly, the new bridge perfectly connects to the existing infrastructure of the area. A somewhat unused,

but wide sidewalk coming from the Mekelpark can become the new connection of the Green Village with the Mekelpark. (See figure 1.8) The bridge will be exactly in line with the main street of the Green village. It will therefore be a more direct entrance to the area.

Thirdly, due to the experimental nature of the glass masonry bridge it might get closed for maintenance or research purposes. An alternative entrance for the Green Village is then necessary - the hybrid FRP & glass bridge can be this alternative entrance.

Require a bridge with a medium long span length (30m)
On the proposed location (figure 1.7) A bridge with a length of 33,8 meters is required. This is a bridge with a medium long span of about 30 meters.

Require a partially transparent bridge
The bridge will function as the main entrance to the Green Village. An entrance has to be an eye-catcher to raise the curiosity of visitors. The transparency of glass can be used to fulfil that purpose.

Require durable materials
Glass is a very durable and sustainable material as it has a high corrosion resistance while its raw materials are renewable. FRP is a very durable material due to its corrosion resistance. This resistance can be very useful in the wet Dutch climate.
The Green Village focuses on sustainable materials. Both glass and FRP have certain advantages over conventional structural materials concerning sustainability. Glass is a renewable and durable material, while FRP is very durable. This makes the use of these materials in the Green Village appropriate.

Be open to innovative concepts and material use
The Green Village is looking for innovative designs, which means designs that are ahead of their time. A hybrid FRP and glass bridge has never been built before and is therefore an innovative concept.
The bridge can also introduce an alternative approach of using structural glass compared to the glass masonry bridge. This can introduce an interesting comparison between both innovative bridges.

1.7.3 - Demands of location

This location suits with the requirements as stated in paragraph 1.7.1. However, the location itself has some additional requirements. The “Green Village” demands a bridge with the following criteria:

- A span length of 33,8 meters (figure 1.16 & 1.17).
- A maximum possible width of 10 meters, due to the plans for a floating pavilion in the masterplan (figure 1.14 & 1.17).
- The plans of building a pavilion in the water and the suggestion of a floating platform indicate the possible use of the water. This can result in traffic under the bridge - this should be taken into account in the design in terms of safety (protecting the edges of the glass) and vertical clearance of the bridge. (Figure 1.11, 1.14 & 1.15)
- A bridge design that takes incidentally dense pedestrian traffic into account, for example when the Green Village closes and every visitor has to leave.

Fig. 1.8 - View on the proposed location of the bridge

Fig. 1.9 - View on the proposed location of the bridge

Fig. 1.10 - View on the proposed location of the bridge

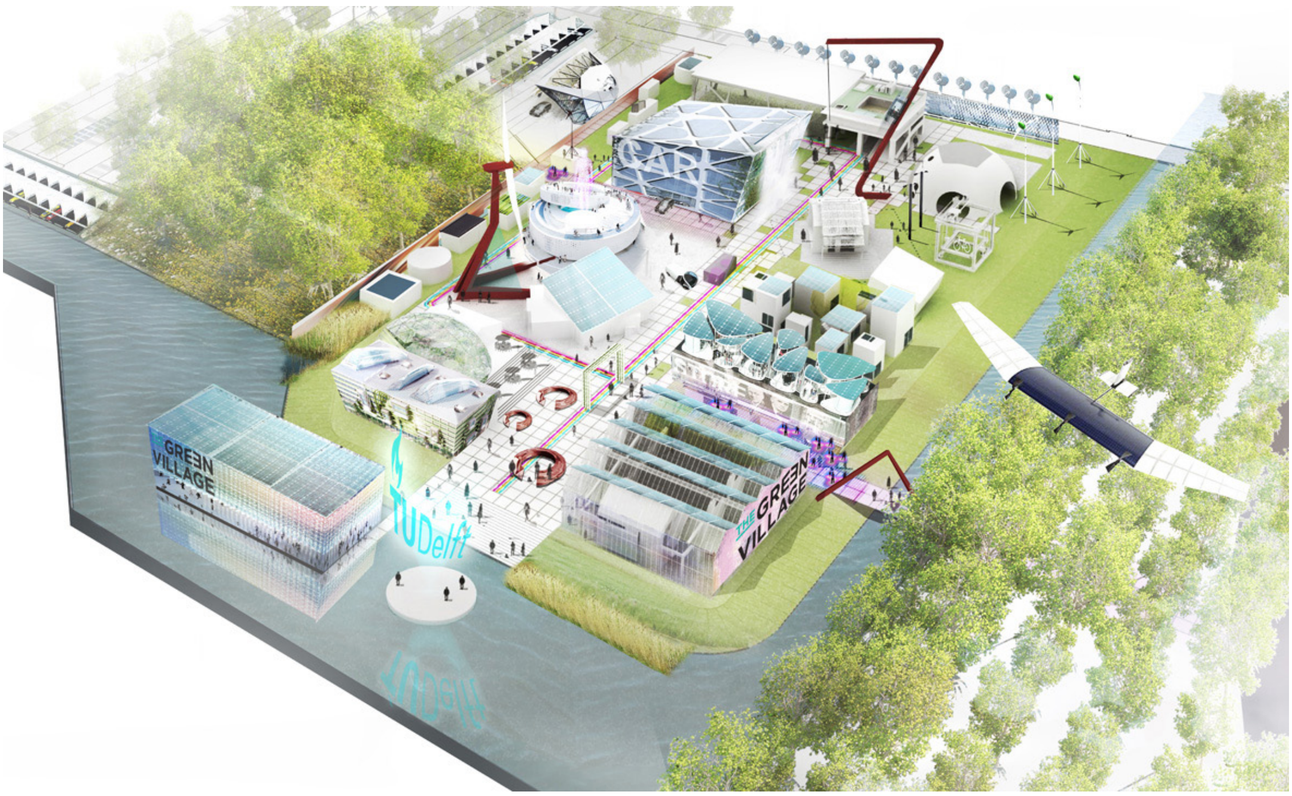


Fig. 1.11 - Birdview impression of the plans for the Green Village of the architects [Karres+Brands]

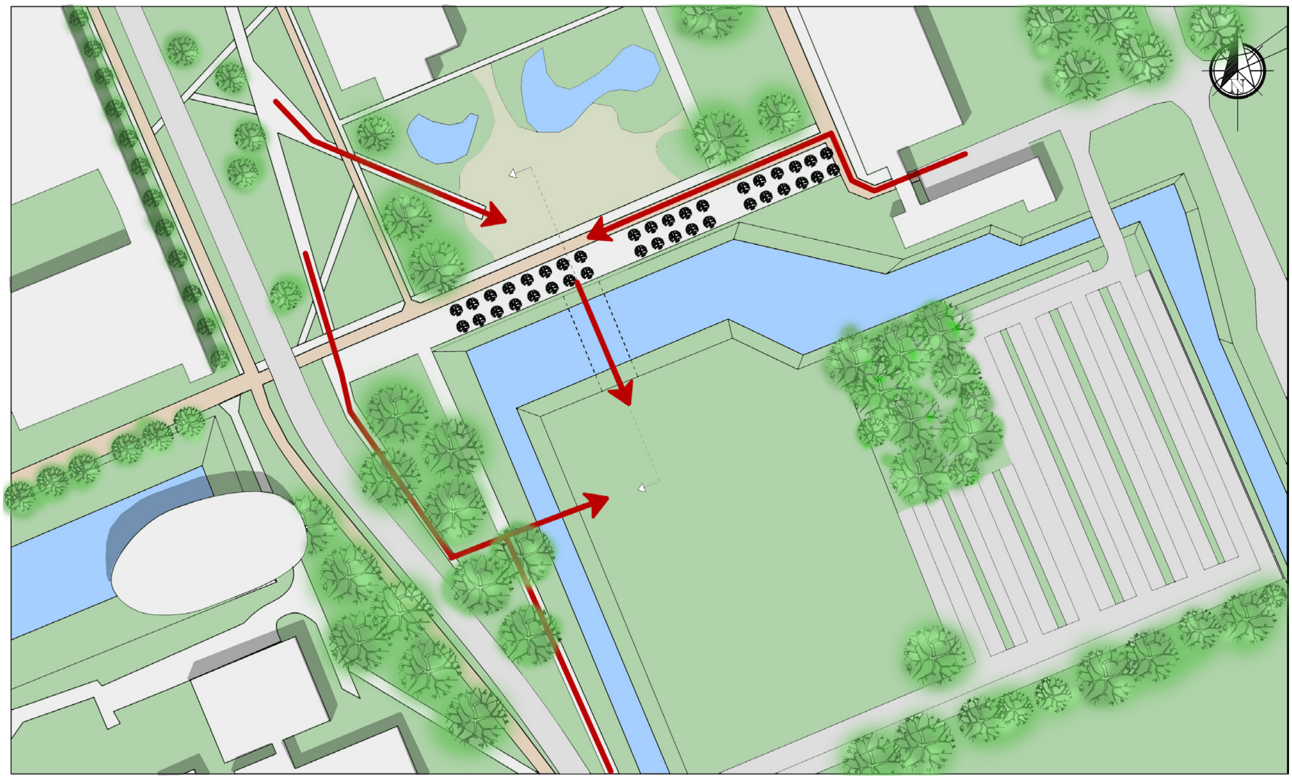


Fig. 1.12 - Map showing the entry routes to the Green Village. Both the main entrance and the new hybrid bridge serve different traffic routes

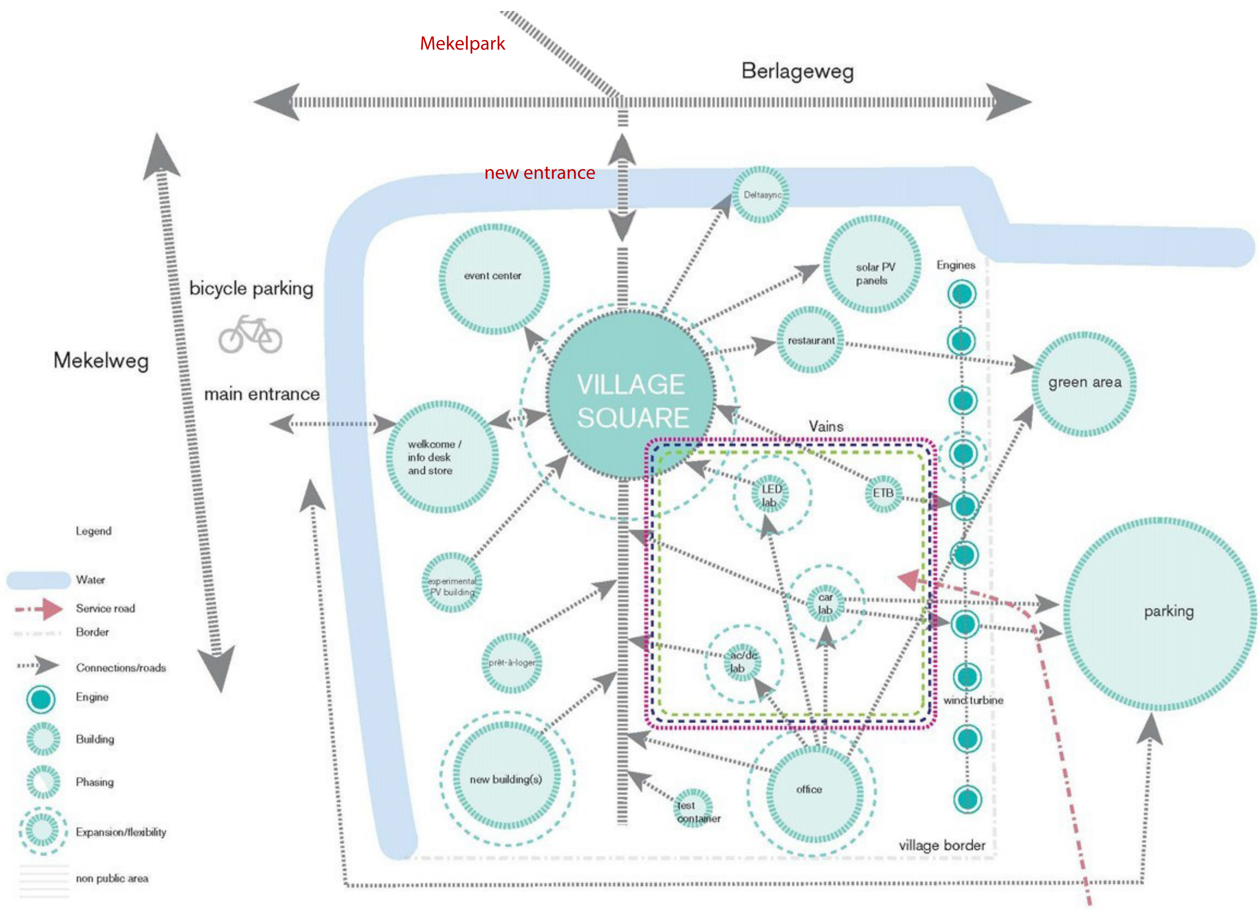


Fig. 1.13 - Schematic masterplan showing the functions and most important infrastructure. [Source: http://www.karresenbrands.nl/project/green-village]

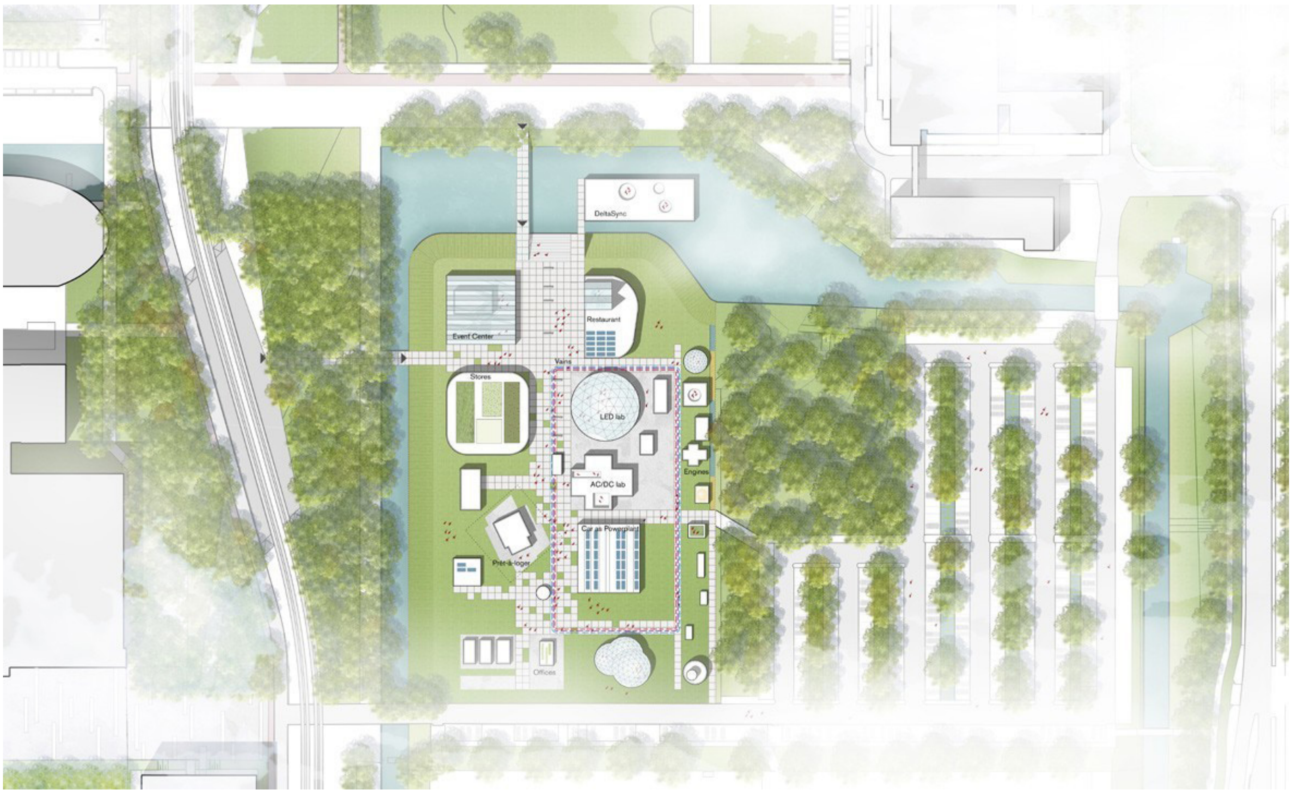


Fig. 1.14 - Map showing the location of the new bridge compared to the proposed functions in the area [Source: http://www.karresenbrands.nl/project/green-village]

Fig. 1.15 - Impression of Green Village showing the proposed functions on the location of the new hybrid bridge {Source: http://www.karresenbrands.nl/project/green-village]

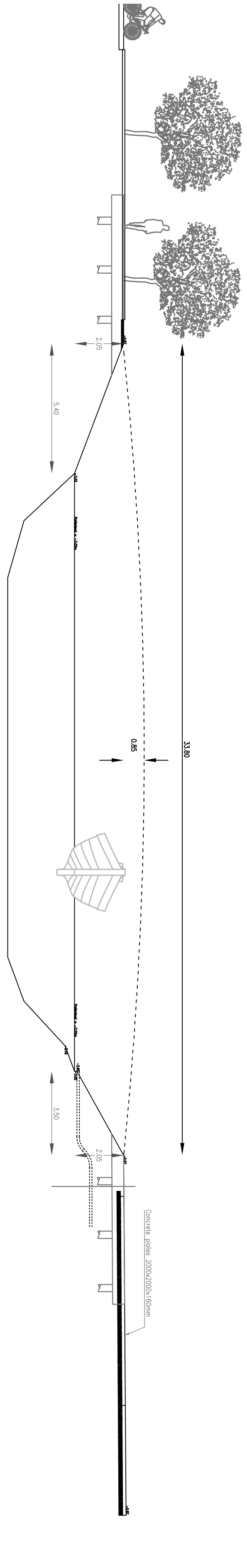


Fig. 1.16 - Section with maximum dimensions of bridge

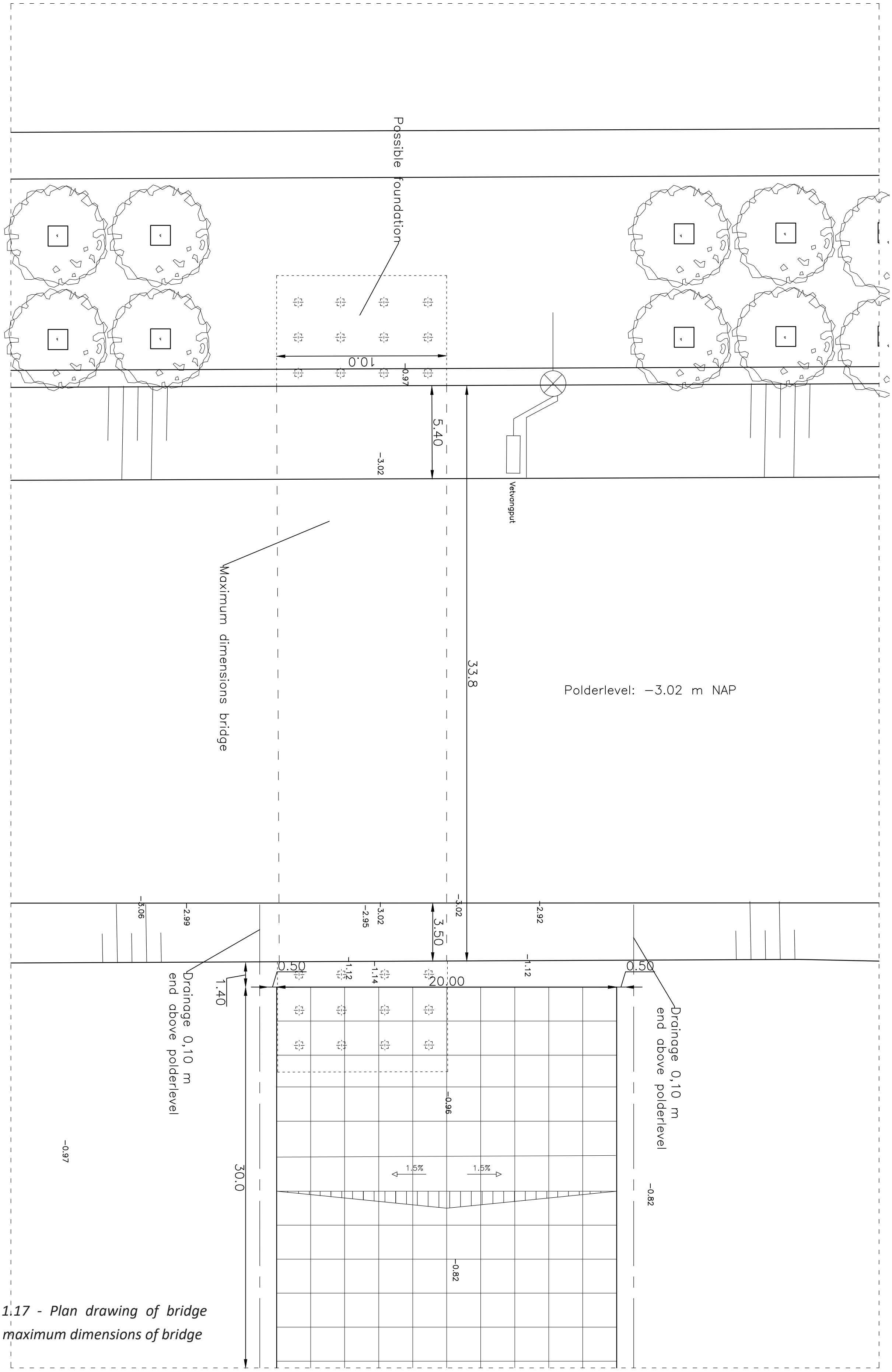


Fig. 1.17 - Plan drawing of bridge with maximum dimensions of bridge

1.8 - Program of requirements

The aim of research, the location and the material characteristics all have their influence on the program of requirements. The research question of this chapter is therefore:

What are the requirements for this bridge design considering the aim of research, location and material characteristics?

The aim of research makes a statement about the function, the type of structure and structural efficiency. The bridge should:
- Be a pedestrian bridge and should follow the loading requirements of a standard pedestrian bridge with incidental dense traffic loads according to NEN-EN 1991-2+C1/NB (the Dutch norm for traffic bridges) (see loading requirements).
- Be a hybrid construction of structural glass and fibre reinforced polymers (FRP). The definition of a hybrid system is explained in the chapter 5.

The location requires a bridge of certain dimensions and level of sustainability. The bridge should:
- Be wheelchair accessible and therefore have a maximal inclination, a minimal width of 2,2m and a maximal height of 1m (see wheelchair accessibility).
- Take recreational use of the water into account. The vertical clearance of the bridge should therefore be of a certain minimal height (see vertical clearance)
- Be sustainable and durable considering the LifeCycle Analysis (LCA) (see sustainability requirements).

The material characteristics defines some safety requirements. The bridge should:
- Be safe. This means several safety concepts should be applied to the bridge (see safety requirements).

1.8.1 - Loading requirements

This will become a pedestrian bridge and will therefore have to carry people. It should follow the loading requirements stated in NEN-EN 1991-2+C1/NB (the Dutch norm for traffic bridges).

1.8.1.1 - STATICAL MODELS FOR VERTICAL LOADS

According to NEN-EN 1991-2+C1/NB there are three different load models to be analysed for this type of bridges:
- An uniformly distributed load representing the static effects of a dense crowd.
- A concentrated load representing the effect of a maintenance load.
- One or more standard vehicles when maintenance or emergency vehicles are expected to cross the footbridge.

UNIFORMLY DISTRIBUTED LOAD

The uniformly distributed load simulates the effect of the crowd on the bridge.
The recommended value for this uniformly distributed load, depending on the loaded length L, is:

$$2{,}5\ \mathrm{kN/m^2} \leq q_{fk} = 2{,}0 + \frac{120}{L+30} \leq 5{,}0\ \mathrm{kN/m^2}$$

CONCENTRATED LOAD

1. A concentrated load Q_{fwk} - representing a maintenance load - of 10 kN should be considered on a square surface of 10 cm.
2. When both local and general effects can be distinguished during a test, the concentrated load should

only be applied for the local effects. The concentrated load should not be combined with a variable non-traffic load.

3. When a service vehicle is taken into account this concentrated load can be disregarded.

SERVICE VEHICLES
Service vehicles like maintenance, emergencies or other services must be considered as accidental when no permanent obstacle prevents these vehicles from driving onto the bridge deck. The vehicle and forces shown in figure 1.18 should be considered.

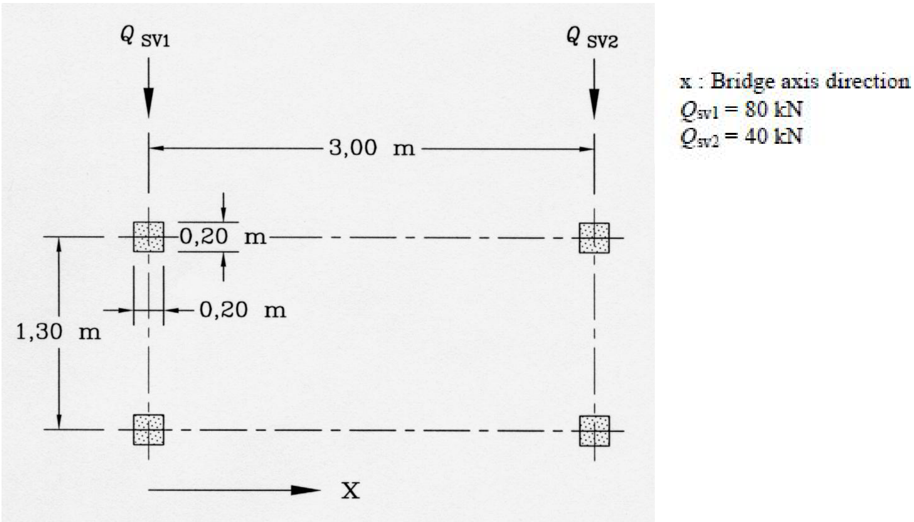


Fig. 1.18 - Service vehicle with corresponding loads on bridge deck [NEN-1991]

1.8.1.2 - STATICAL MODELS FOR HORIZONTAL LOADS
The characteristic value of a horizontal force Q_{flk} which acts along the bridge deck on pavement level should be equal to the greater of these two values [NEN-1991]:

1. 10% of the total load corresponding to the uniformly distributed load
2. 60% of the total weight of the service vehicle (mentioned earlier)

This force should act on a square surface of sides 10 cm.
This horizontal force is assumed to act simultaneously with the vertical load and not with the concentrated load Q_{fwk}.

Vertical traffic loads and horizontal traffic loads should be combined in the following load groups:

Load type		Vertical forces		Horizontal forces
Load system		Uniformly distributed load	Service vehicle	
Groups of loads	gr1	q_{fk}	0	Q_{flk}
	gr2	0	Q_{serv}	Q_{flk}

Traffic loads on footbridges do not act simultaneously with significant wind- or snow-loads.

1.8.1.3 - DYNAMIC MODELS FOR PEDESTRIAN LOAD

Vibrations and deformations due to traffic can influence the serviceability level of footbridges, especially on a lightweight FRP bridge.

Vibrations to take into account are horizontal vibrations, vertical vibrations and torsional vibrations - either alone or coupled with vertical or horizontal vibrations.

The design situation that should be studies should include:

- A group of about 8 to 15 persons that is walking simultaneous on the bridge.
- The accidental presence of a stream of pedestrians (more than 15 persons) that is simultaneously on the bridge.
- Occasional events, which requires specific studies.

The first dynamic model of pedestrian loads for a footbridge is as follows:

A concentrated force (F_n), representing the excitation by a limited group of pedestrians, which should be systematically used for the verification of the comfort criteria.

In this model F_n should be placed in the most adverse position on the bridge deck.

It consists of a pulsating force (N) with a vertical and horizontal component which should be considered separately:

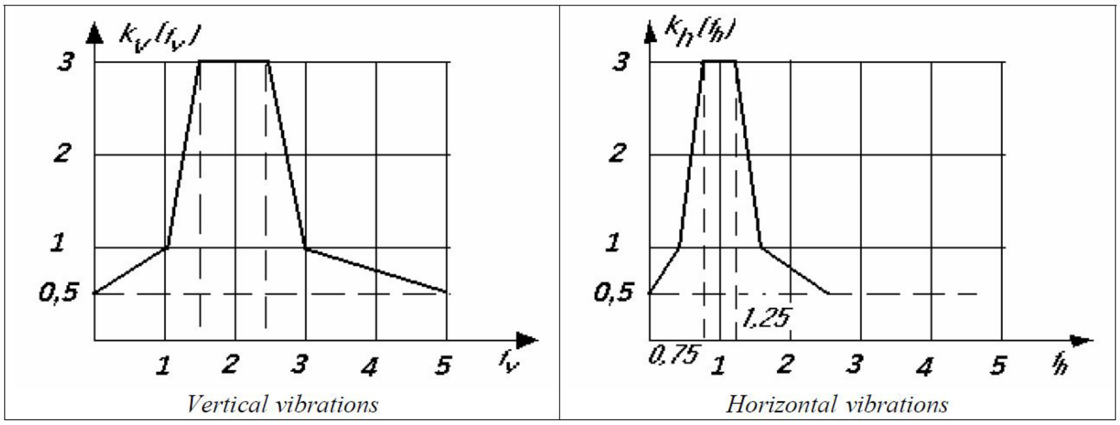
$$F_{n,v} = 280\, k_v\, (f_v)\, \sin(2\pi f_v t)$$

$$F_{n,h} = 70\, k_h\, (f_h)\, \sin(2\pi f_h t)$$

f_v is the natural vertical frequency of the bridge closest to 2 Hz and f_h is the natural horizontal frequency of the bridge closest to 1 Hz.

t is the time in seconds

k_v (f_v) and k_h (f_h) are coefficients, depending on the frequency. These are given in the figure below.



F_n should be associated with a static mass equal to 800kg applied at the same location.

The second dynamic model of pedestrian loads for a footbridge is as follows:

An uniformly distributed load (F_s), representing the excitation by a continuous stream of pedestrians, which should be used also where specified, separately from F_n.

F_s should be placed on the entire bridge deck. It consists of a uniformly distributed pulsating load (N/m^2) with a vertical and a horizontal component, which should be considered separately:

$F_{s,v} = 15\ k_v\ (f_v)\ \sin(2\pi f_v t)$

$F_{s,h} = 4\ k_h\ (f_h)\ \sin(2\pi f_h t)$

F_s should be associated with a static mass equal to 400kg/m^2 applied at the same location.

To ensure pedestrian comfort, the maximum acceleration of any part of the deck should not exceed 0,7 m/s^2 for vertical vibrations and 0,15 m/s^2 for horizontal vibrations. These comfort criteria have to be assessed when the natural vertical frequency is less than 5Hz and the horizontal and torsional frequencies are less than 2,5Hz. [Sanpaolesi et al., 2005]

1.8.2 - Bridge parapet

The parapet of the bridge should be designed conform NEN: NPR-CEN/TR 16949:2016 en. [NEN, 2016]

1.8.2.1 - Horizontal uniformly distributed load (q_{hk})

The characteristic value of the horizontal uniformly distributed traffic load qhk to be applied to the top rail, can be determined in the range between 1,0 kN/m (1,0 kN/m for footways used by maintenance personnel only) and 2,8 kN/m according to the following Formula:

$q_{hk} = 0,5\ (1,0 + b)$ kN/m, $1,0$ kN/m $\leq q_{hk} \leq 2,8$ kN/m

Where:
b is the width (m) of the elevated footway or footpath subject to pedestrian traffic.

1.8.2.2 - Concentrated horizontal traffic point load (Q_{hk})

A pedestrian parapet rail should withstand a concentrated horizontal point load Q_{hk} applied to any point of the rail. The minimum value for Q_{hk} is 1,0 kN.

1.8.2.3 - Vertical uniformly distributed traffic loads (q_{vk})

All horizontal and inclined elements up to 60° of a pedestrian parapet should withstand a vertical uniformly distributed traffic load q_{vk}. The minimum recommended value for q_{vk} is 1,0 kN/m.

1.8.2.4 - Concentrated vertical point traffic load (Q_{vk})

A concentrated vertical point load Q_{vk} should be applied to any point of the horizontal and inclined elements of a pedestrian parapet. The minimum value for Q_{vk} can be 1,0 kN.

1.8.2.5 - Wind actions (F_w)

The pedestrian parapet should be designed to withstand a wind action F_w. The recommended minimum value for F_w is 0,8 kN/m^2.

1.8.2.6 - Snow load (S)

Where the design of a pedestrian parapet allows for snow load(s) S, the value of S should be declared.
The minimum value for S. can be 1,0 kN/m2. When no snow load is declared, the value(s) for S should be declared as nil. [NEN, 2016]

1.8.2 - Safety requirements

Safety is very important for FRP and especially for structural glass design. Both materials show brittle material behaviour. When these materials are combined in a bridge design there will be several safety related topics that are of importance:

1.8.2.1 - GLASS SAFETY FACTOR

When constructing with glass a safety factor of about 5 to 7 is generally used. However, due to the extra knowledge about glass and the use of reinforcement and better connections to reduce failure it is sufficient to use a safety factor of 2. [Veer, 2016]

1.8.2.2 - GLASS PSYCHOLOGY

Psychology is also an important factor when constructing in glass. People perceive glass as a dangerous, brittle and fragile material, due to its transparent nature. They find it hard to believe that a transparent bridge is going to carry their weight. [Nijsse, 2003] Therefore, it is sometimes necessary to use translucent glass on certain parts of a fully transparent bridge to enhance the feeling of safety. Psychology should therefore be addressed on the final bridge design.

1.8.2.3 - GLASS SLIPPING

Glass can be slippery when it is wet, due to its smooth surface. When the bridge deck is made from glass a special treatment to make the glass rougher will be necessary to prevent people from slipping. [Nijsse, 2003]

There are several methods to do this:

- Melting grains of sand or small pieces of broken glass into the glass
- Acid-etched anti-slip glass
- Anti-slip coating
- Contour glass
- Glueing clear rubber
- Sandblasted anti-slip glass

1.8.2.4 - GLASS EDGES

The edges of glass are vulnerable to hard impacts, which can cause the glass to break. These edges have to be protected in order to prevent breaking when traffic passes under the bridge.

1.8.2.5 - FRP FIRE SAFETY

When FRP materials are exposed to high temperatures (300-500 C) their organic matrix decomposes, releasing heat, smoke, soot and toxic volatiles. Even when heating to moderate temperatures (100-200 C), the FRP material will soften, creep and distort. [Correia, 2015] FRP should therefore be protected from fire. Measures to improve the fire resistance of FRP are:

- By additives: fire retardants can be added to the polymer matrix to obtain self-extinguishing properties or to slow the flame spread.
- By the right use of polymer matrix: phenol is used when there are requirements for high fire resistance, temperature resistance, low smoke generation, and flame retardation when subjected to fire. [Correia, 2015]
- By coating: for example an intumescent coating. Intumescent coatings are a sort of paint that expands to many times their original thickness when exposed to high temperatures (of a fire). It then protects the underlying material from the heat of the fire. [Williams et al., 2006]

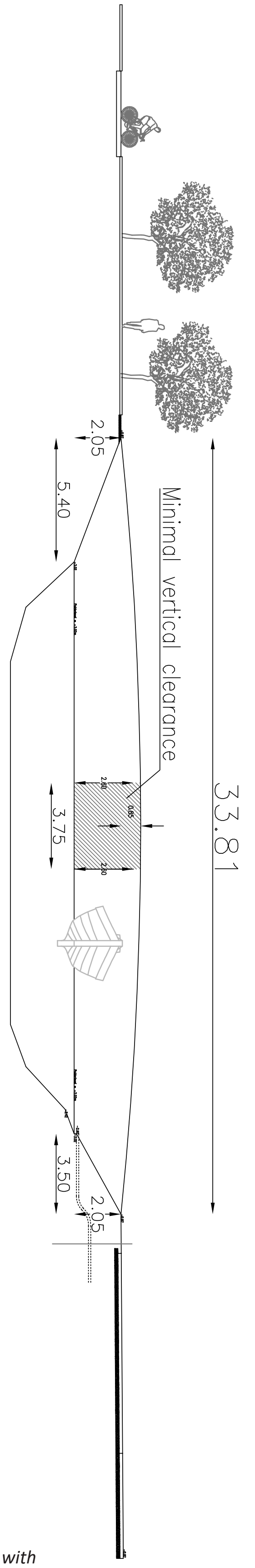


Fig. 1.19 - Shape of the new bridge design with measurements according to boundary conditions

1.8.3 - Sustainability requirements

Because the location of the bridge is in the Green Village this bridge should have a focus on sustainability. The main focus will be to build a structurally optimized hybrid bridge design, but some attention will be given to the sustainability of the used materials. For example: if it is possible to reach the same structural efficiency in a more sustainable type of FRP, this type of FRP will be used.
The way to assess the sustainability is by using the Life-Cycle Analysis (LCA): the manufacturing process, the service life and the end of life cycle (see chapter 2 - sustainability).

1.8.4 - Wheelchair accessibility

According to the Dutch building regulations (2012) a ramp should have a width of at least 1,1 meters, a height of no more than 1 meter and a maximum inclination of:

A. 1:12 when the height difference is no more than 0,25m;
B. 1:16 when the height difference is larger than 0,25m, but less than 0,5m;
C. 1:20 when the height difference is larger than 0,5m.

This means that the bridge will rise 850mm at the centre of the bridge: maximum inclination of 1:20 and a length of 34 / 2 = 17m, so 17 / 20 = 0,85m. The minimum width should be 2,20 (2 x 1,1m).

1.8.5 - Vertical clearance bridge

Due to the possible use of recreational boats it is necessary to define a minimal vertical clearance for this bridge. According to the Dutch waterway guidelines from Rijkswaterstaat (2011) there are several categories: A, B, C, D for small recreational boats without sail (figure 1.20). The boats that will sail under the proposed bridge will have a maximum length below 12,0 meters and a maximum width below 3,75 meters. The water these boats will sail in can be classified as an access water. Therefore a height of 2,60 meters above water level will be sufficient.
This results in a proposed bridge shape as shown in figure 1.20.

M-route		length	width	depth	height of boat	height of bridge
connecting water	A	15,0	4,25 - 4,5	1,50	3,40	3,75
access water	B	15,0	4,25 - 4,5	1,50	2,75	3,00
	C	14,0	4,25	1,40	2,75	3,00
	D	12,0	3,75	1,10	2,40	2,60

Fig. 1.20 - Table with categories and dimensions of recreational traffic and corresponding bridge heights [Rijkswaterstaat, 2011]

2 | General material research: Fibre Reinforced Polymers

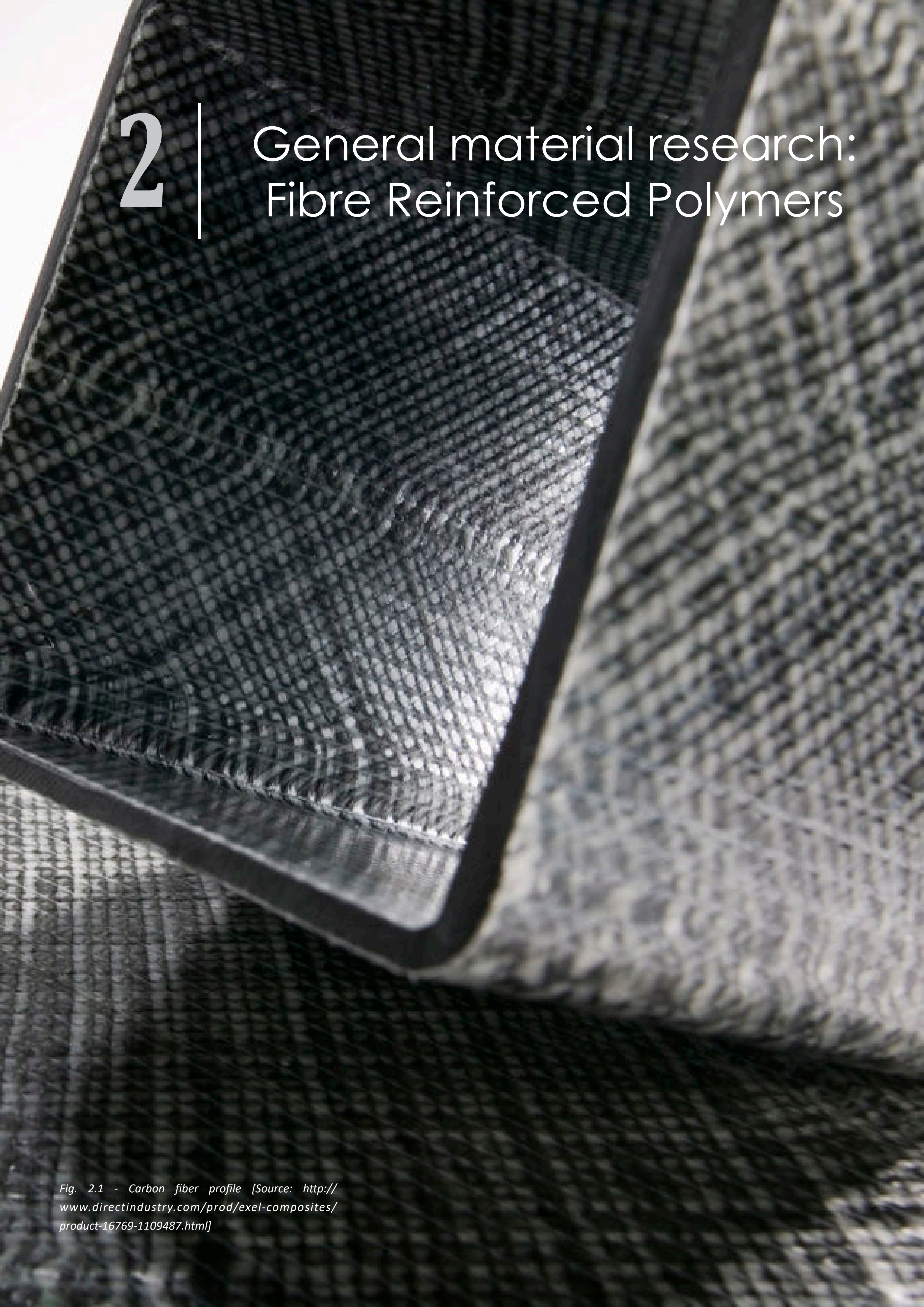


Fig. 2.1 - Carbon fiber profile [Source: http://www.directindustry.com/prod/exel-composites/product-16769-1109487.html]

2.1 - Introduction

To find design guidelines for a material adapted design with FRP it is necessary to research the state of the art of using Fibre Reinforced Polymer materials as a structural material: fibre types, polymer matrix types, sustainability, production methods and assembly methods are researched in this chapter, following the research question of this chapter:

What are the (mechanical) properties of fibre reinforced polymers?

The results are summarized in a conclusion. This conclusion will be compared with the conclusion of the material research into structural glass, resulting in several design guidelines (chapter 3).

2.2 - What is FRP?

Fibre Reinforced Polymers is in fact a composite material that is reinforced with fibres in a matrix of polymers (resin).

A composite material is defined as a combination of two or more materials, which when combined constitute a new material that symbiotically merges the best properties of the original materials. [Correia, 2015] Or in other words:

"A composite is a material structure that consists of at least two macroscopically identifiable materials that work together to achieve a better result." [Nijssen, 2015]

The fibres in the composite are responsible for the mechanical performance of the material, providing most of the strength and stiffness. This effect can be compared to the steel reinforcement in concrete. [Correia, 2015]
The polymer matrix acts as the glue of the composite material, guaranteeing the load transfer between the fibres and also between the applied loads and the composite itself. It surrounds and supports the fibres by keeping them in their relative position. There are often also some additives in the matrix, beside the resin. These additives may reduce production costs, improve the manufacturing process or improve specific properties of the product. [Correia, 2015]

2.3 - History of FRP as construction material

To use fibres to strengthen a material is a principle that goes back thousands of years. In ancient times people used mud to build their houses, which was reinforced with straw to prevent cracking while the mud would dry.

The use of fibres as a strengthening principle was first patented in the 1930's by Slayter and Thomas. The first real structural application however occurred in the 1940's when FRP was used for structural aerospace parts, radomes and later also boat skulls. In that time the military became interested in lighter and stronger materials, which lead to experimentation with FRP's.

However, it wasn't until the 1950's before the first use of FRP in the construction industry took place. The demographic and cultural changes in America and the need for housing in war-struck Europe were the perfect opportunity for the introduction of FRP in the housing industry. There were about 70 prototype houses built in the period 1950 - 1970, all of which were not at all architecturally traditional.

Cost reduction of FRP in the 1980's and the 1990's and the growing need for renovation of structures - especially highways - lead to a rise in product development and more comprehensive knowledge of the fundamental properties of composites. From now on safety factors were reduced to realistic levels, the numerous advantages of FRP's as compared to conventional materials such as concrete and steel were known.
Examples of products that were developed in the 1980's and early 1990's are: bars and pre-stress cables for internal concrete reinforcement; strips, laminates and wraps for external reinforcement of concrete structural elements; pre-stress cables for suspended bridges; structural profiles and cellular panels. [Correia, 2015]

One of the first applications of these FRP products can be found in bridge structures where FRP sheets or strips are used to retrofit and strengthen structural concrete elements. These externally bonded FRP composites have been used for increasing flexural and shear capacity of the concrete elements like girders, beams and slabs. [Potyrala, 2011]

Another application of FRP to strengthen or retrofit an existing structure is by replacing the steel reinforcement, which can be corroded due to aggressive environmental conditions. These replacements can be done in the form of FRP re-bars or tendons.

Fig. 2.1 - The Dome Home from Domes International - a FRP shelter, military cabin and residential building [Composites Building Systems inc.]

Besides the development of many FRP products to reinforce and retrofit FRP bridges and other structures, the 1980's and 1990's was also the time when the first bridges were made from FRP. At first hybrid bridges were designed. Hybrid bridges are understood as structures created by combining elements made of traditional materials - like girders - with elements made of FRP composites. [Potyrala, 2011]
The first all-FRP bridge is the Miyun bridge in Beijng, China, which was built in 1982 and consists of six hand-laminated sandwich girders.
Nowadays about 20% of the total amount of plastics that is produced is used in the construction industry. This is due to the developments in polymer resins, fibre reinforcements and production techniques. [Fradelou, 2013]

2.4 - General material properties

The properties of Fibre Reinforced Polymers depends mainly on the properties of the polymer resin, the additives, the orientation of the fibres, the properties of the fibres and the volume ratio of all these components. [Potyrala, 2011] This high moldability of the FRP material results in several general material properties that every composite material has in a certain range:

- FRP materials are anisotropic
  This depends on the fibre reinforcement. They can become quasi-isotropic, depending on the composition of the FRP material.
- They have low density
  The density of FRP materials often differs between 1,2 and 1,8 g/cm^3 (in comparison: steel is 7,8 g/cm^3 and glass is 2,5 g/cm^3). This gives the FRP material a high specific stiffness and high specific strength and brings some extra advantages: the material is easy to handle and assemble, easy to transport and has reduced dead-loads. [Nijssen, 2015]
- They have high corrosion and oxidation resistance, resulting in high durability
  This reduces the maintenance costs for FRP structures.
- They have a lot of freedom of form or moldability
  This results in a wide array of structural possibilities and integration of functions.
- The material is easy to colour
- FRP materials are brittle
  The ultimate strength and breaking strength are therefore the same.
- The material has high initial costs
  The total costs are often less high, due to the durability of the material.
- Colour and gloss preservation is not always predictable
- There is still limited knowledge about structural behaviour, connections and detailing in FRP.
- FRP is sensitive to temperature
  This results in low fire resistance.
- Finishing is not yet well developed.
- Recycling is not yet well developed.
- The material is sensitive to UV-light.

[Potyrala, 2011] [Nijssen, 2015]

Then there are material properties that can differ depending on the composition of the FRP material:

- Translucency
  Glass Fibre Reinforced Polymers (GFRP) can be translucent.
- The Young's modulus of the material can differ
  It can differ per used fibre type and the direction of these fibres. Generally carbon fibres are the stiffest, while glass fibres have a relatively high E-modulus in the transversal direction of the fibres. Aramid fibres have a high E-modulus in the longitudinal direction of the fibres and are very weak in the transversal direction.

Some of the most important general material properties have been plotted in comparison with conventional structural materials. For this comparison the two most common types of FRP have been considered: GFRP and CFRP. These two types of FRP materials can also be composed in different ways - for this comparison unidirectional FRP with a fibre rate of 40-60% has been chosen (figure 2.2).

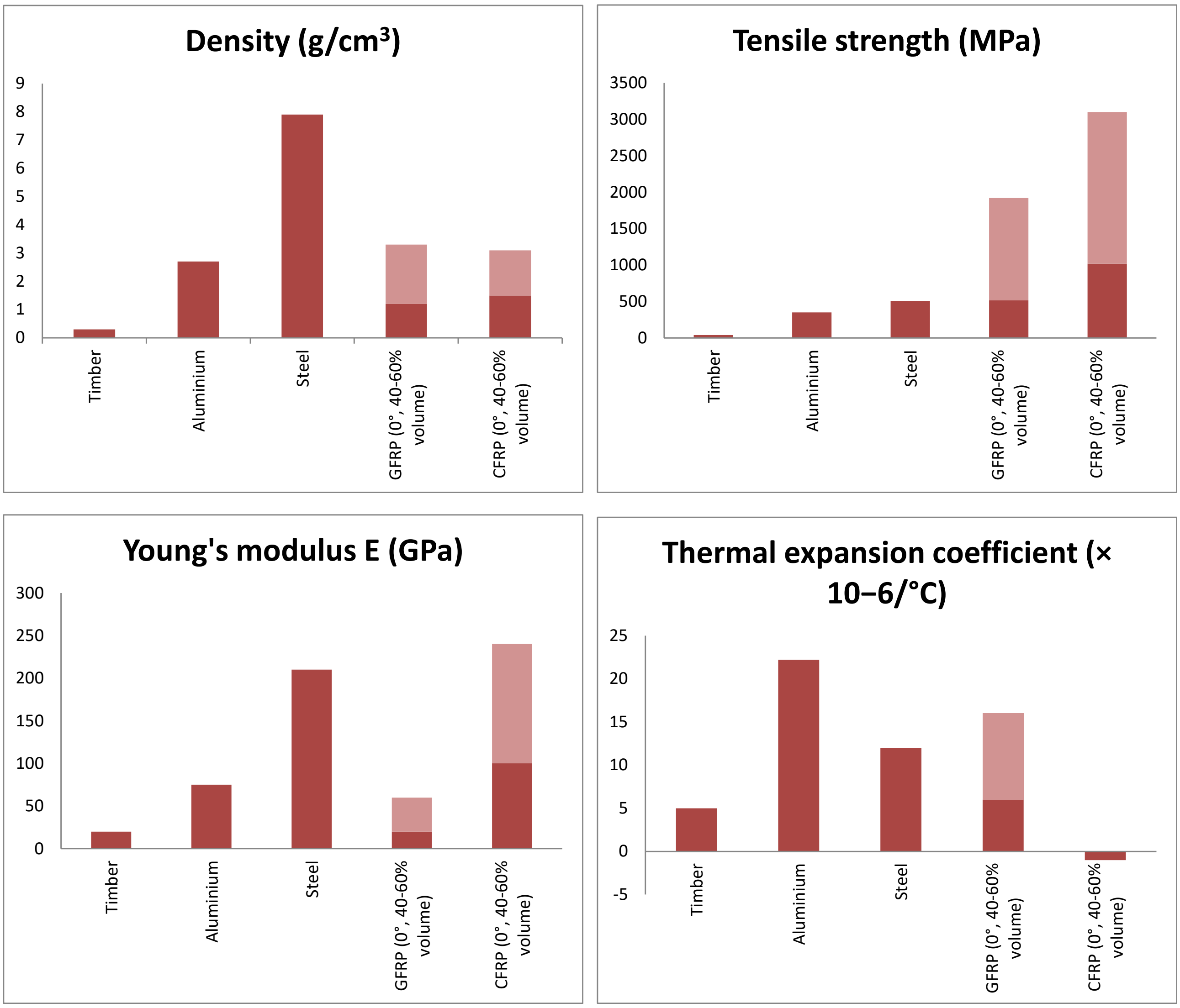


Fig. 2.2 - Tables with general comparison between GFRP and CFRP and traditional building materials

Typical properties	Fibres					
	Glass		Aramid		Carbon	
	E-glass	S-glass	Kevlar 29	Kevlar 49	High strength	High modulus
Density (kg/m³)	2600	2500	1440	1440	1800	1900
Young's modulus (GPa)	72	87	100	124	230	370
Tensile strength (MPa)	1,72	2,53	2,27	2,27	2,48	1,79

Figure 2.3 - Table with the typical properties of several fibre types [Potyrala, 2011]

2.5 - Fibres

The fibres that will be used in any kind of FRP material have generally the largest influence on the properties of the material. They generally determine the strength and stiffness of the composite material. A polymer to which directional fibres have been added is much stronger in the fibre direction than the polymer without fibres. Perpendicular to the fibre direction, the strength and stiffness is lower, because the fibres act as a stress concentrator. In most cases however, the fibres are placed in different directions to create a (quasi-) isotropic material. [Nijssen, 2015]
The most commonly used types of fibres are glass-, carbon- and aramid-fibres and will therefore be focused on. Also, several natural fibres are more recently being produced for commercial use. [Correia, 2015]

2.5.1 - Glass fibres

Glass fibres (figure 2.4) are produced by heating silicon oxide with various additives until it melts. This molten material is poured into small channels with holes in the bottom of approximately 2 mm diameter. The molten material passes these holes and is wound on a coil at high speed. Due to this speed the molten material is stretched and becomes much thinner. When the molten fibres leave the extrusion sleeves they are sprinkled with water, which makes them solidify at high speed. [Nijssen, 2015)

Glass fibres have the advantage that they are relatively low-cost, have high strength and are relatively sustainable. They are used in pultruded profiles, bars and skins of sandwich panels. The disadvantages of GFRP are the low elasticity modulus, reduced long-term strength (stress rupture) and susceptibility to moisture and alkaline environments. [Potyrala, 2011]

There are various types of glass used for the glass fibres, each with different material properties. Each type is designated by a letter. The most common type is E-glass. Other types include S-glass, which has increased strength and stiffness, C-glass, which is more chemically resistant and finally D-glass, which has a low dielectric constant. [Nijssen, 2015] The correct type of glass for the bridge design should be chosen based on the function of the FRP material. Some typical properties of E-glass and S-glass have been summarized in figure 2.3.

2.5.2 - Carbon fibres

Carbon fibres are produced by first oxidating threads drawn from raw material with a high carbon content at approximately 200ºC. During this stage the fibres get their characteristic black colour. Then the fibres are carbonized at 800 - 1600ºC and various components are removed, such as nitrogen atoms. Finally the fibres are graphitized, where they are stretched so that the orientation of the carbon chains is parallel to the fibre direction. This makes the fibre material anisotropic. [Nijssen, 2015]

Fig. 2.4 - Right: close-up of glass fibres. Left: close-up of carbon fibres. [Source: https://commons.wikimedia.org/wiki/File:Carbon_fiber.jpg]

These fibres have the advantage that they have high tensile strength and elasticity modulus, low self-weight, high fatigue and creep resistance, excellent chemical resistance and they are often transversally isotropic and have much higher stiffness in the axial direction. The main disadvantages of Carbon Fibre Reinforced Polymers (CFRP) are the high cost and the large amount of energy needed for the production. [Nijssen, 2015]

2.5.3 - Aramid fibres

Aramid fibres are produced by extruding a solution of aromatic polyamide with a temperature between -50°C and -80°C through a hot cylinder of 200°C. The fibres are subsequently stretched and drawn to increase their strength and stiffness. During this process, aramid molecules become highly oriented in the longitudinal direction. This results in a very stiff fibre. [Potyrala, 2011]
Aramid fibres (AFRP) generally have a higher elasticity modulus (50% higher) and they are stronger than glass fibres. [Correia, 2015] They are available in low density/high strength form (Kevlar 29) or in a form suitable for reinforcement (Kevlar 49). The first is used in situations where high energy absorption is needed, like bulletproof vests, helmets and ropes (for cable stayed bridges). [Nijssen, 2015] The second type is used as reinforcement in polymers for aerospace, marine and automotive applications.

Fig. 2.5 - Close-up of chopped aramid fibres [Source: http://www.directindustry.com/pt/prod/teijin-aramid/roduct-18087-1097033html]

2.5.4 - Basalt and natural fibres

Basalt fibres have a production process that closely resembles glass fibres. Basalt is volcanic rock that is heated in a furnace, after which threads are drawn. No components have to be mixed before the processing of the material(unlike glass fibres). Basalt is however more difficult to melt and more abrasive than glass. This leads to higher costs when producing basalt fibres.

There are also many forms of natural fibres being tested and used. Examples are: flax, hemp, bamboo, jute and wood fibres. However, these fibres commonly have the disadvantage of being sensitive to moisture absorption and rotting. Another disadvantage of these plant fibres is that they are relatively short. Their strength and stiffness however can be of the same order as synthetic fibres. [Nijssen, 2015]

Fig. 2.6 - Hanging jute fibres - a natural fibre type - to dry [Source: https://en.wikipedia.org/wiki/Jute]

Fig. 2.7 - Bamboo fibres [Source: https://www.mtm.kuleuven.be]

2.6 - Rovings, laminates & textiles

There are many forms in which fibres can be used as a reinforcement of polymer materials. [Potyrala, 2011] The methods and terminology of processing these fibres is based on the textile industry. [Nijssen, 2015] An overview of the processing of fibres will be given in this paragraph.

2.6.1 - Rovings

Fibres can be used as a one-dimensional reinforcement of polymer composites in the form of fibre bundles or rovings. There are several types of rovings according to Potyrala (2011):

- Smooth roving: fibre filaments placed longitudinally in a free manner.
- Interlaced roving: a bundle of fibres arranged longitudinally with several fibres interlaced to mechanically connect neighbouring rovings.
- Tangled roving: bundle of fibre filaments arranged longitudinally, interlaced to better co-operate with neighbouring filaments in a roving.
- Stapled fibres: short fibre filaments made by cutting the smooth roving.
- Minced fibres: very short filaments made by milling and sifting stapled fibres.

Fig. 2.7 - Different types of rovings: a) smooth roving b) interlaced roving c) tangled roving [Potyrala, 2011]

2.6.2 - Textiles

Generally, to strengthen the FRP material in more than one direction, the rovings are first woven into a textile. These textile mats are for almost all production methods (except filament winding) most suitable to use. [Nijssen, 2015] [Potyrala, 2011]
The rovings can be oriented, biaxial or triaxial and stitched to each other or a thin support layer: this is called a woven fabric. The weave in a woven fabric can have different patterns, for example a plain weave, twill weave, satin weave and a basket weave. [Nijssen, 2015]
It is also possible to create a mat with randomly oriented rovings, which can be short or continuous. This

is called respectively a chopped strand mat and a continuous strand mat.

All these forms can be further combined to create textile fabrics with continuous oriented fibres, together with continuous or randomly oriented short fibres. [Nijssen, 2015] The exact composition depends on the desired material properties. A few types of woven fabrics are given in figure 2.9.

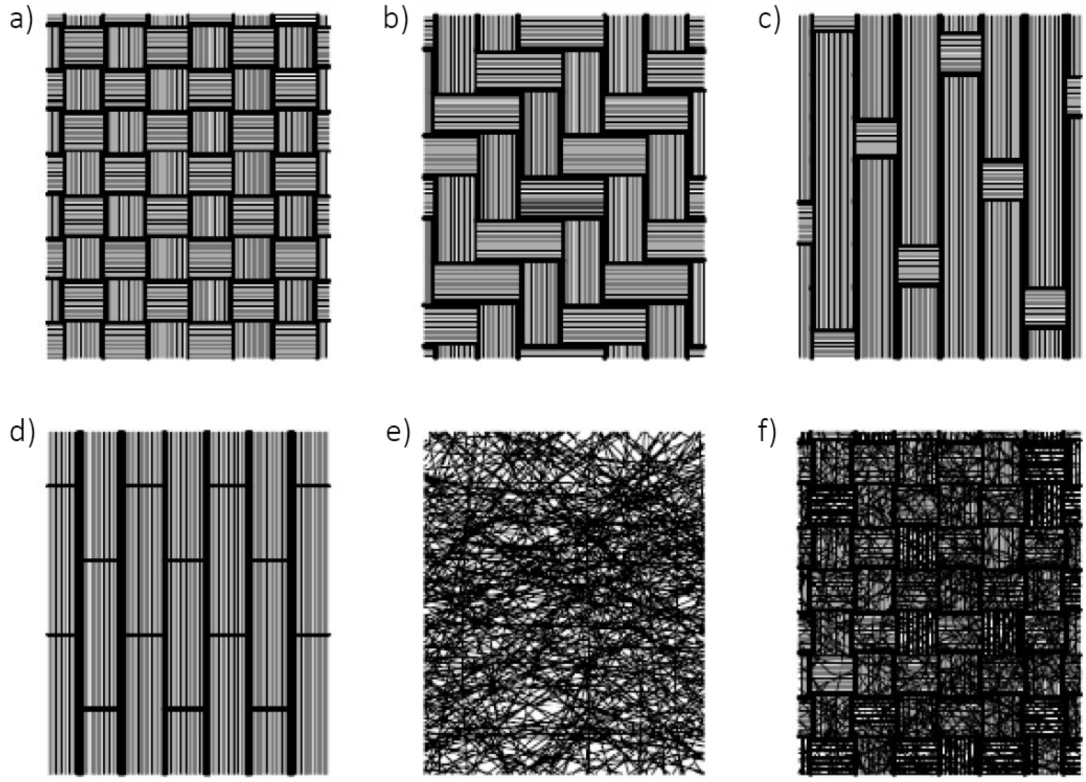


Fig. 2.9 - Several types of fabrics: a) plain weave b) oblique weave c) satin weave d) smooth unidirectional roving fabric e) unidirectional mat f) roving plain interlaced weave fabric [Potyrala, 2011]

2.6.2 - Laminates

When the previously mentioned fabrics are impregnated by a resin you speak of a lamina or a ply. A stack of plies or lamina's is called a laminate. There are many possibilities for the structure of a laminate. [Nijssen, 2015]

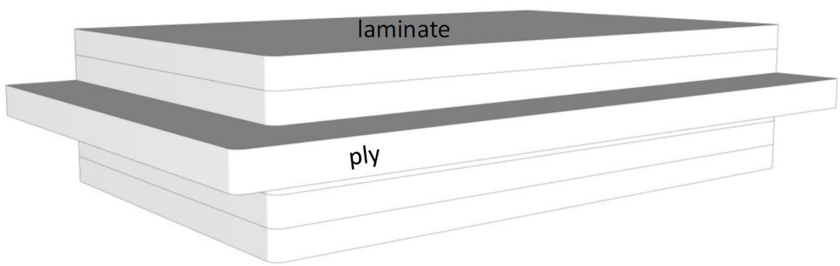


Fig. 2.10 - The definition of ply and laminate [Nijssen, 2015]

2.7 - Polymer matrix

While the fibres are the most important factor for the material properties of an FRP material, the polymer matrix in which the fibres are encapsulated, also plays an important role. The polymeric matrix has several functions:

- It serves as an adhesive to keep the fibres together. This results in a more even load distribution in the material: the polymer transfers loads from one fibre to the other through shear stresses and transversal normal stresses are resisted. This will prevent the material from buckling under a high compressive load. [Barbero, 2011]
- The polymer matrix also protects the fibres from the environment (moisture) just like concrete protects steel reinforcement. [Correia, 2015]

There are two main groups of polymeric matrices: the thermoplastics and the thermosets.

2.7.1 - Thermosets

Thermosets are polymers that are formed by an irreversible chemical reaction to cure them (resin curing). They do not melt upon heating, but disintegrate. They have a low viscosity which makes them easy to impregnate fibres with. They also cost less than thermoplastic resins. [Hyer 1998]
Examples of thermosets used for FRP materials are: polyester, vinyl-ester, epoxy and phenolic.

2.7.2 - Thermoplastics

Thermoplastics are polymers that become moldable when they warm up and reach a certain temperature; when they are cooled down they turn solid again - this process is reversible.
Most commonly used unreinforced polymers are thermoplastics. For FRP materials these thermoplastics are generally not very suitable for impregnation of the fibres due to their viscosity. To produce composite materials using thermoplastics, high pressures and temperatures are necessary. This results in high production costs. [Nijssen, 2015]
Examples of thermoplastics used for FRP materials are: polypropylene, polyamide, polyethylene and polybutylene.

2.7.3 - Most frequently used matrices

The most frequently used matrices are thermosets, due to the difficulties of handling thermoplastics. The single most frequently used matrix is polyester: this gives the composite good all-round properties. Furthermore, often used matrices are epoxy-matrices and phenolic matrices. They all have their advantages and disadvantages and specific areas of application.

2.7.3.1 - Polyesters

Polyesters can be thermosets, thermoplastic or an elastomer. Unsaturated polyester is the thermosetting polyester type and is most frequently combined with glass fiber. Unsaturated polyester can be divided into three main groups: orthopolyester, isopolyester and vinylester [Potyrala, 2011].

- Orthopolyester; polyesters are the cheapest matrices to produce - cheaper than epoxies and phenolic resins. [Nijssen, 2015]
- Isopolyester; this gives better impact resistance, greater flexibility, better resistance to temperatures and increases corrosion resistance compared to orthopolyester.
- Vinylester; this has even better corrosion resistance and thermal properties. The impact resistance

and fatigue resistance is also improved due to greater elongation properties. A disadvantage of vinylesters is that they can turn yellow (due to the aromatic ether compounds).

2.7.3.2 - Phenolics

Phenol; this type of matrix is used where fire resistance is very important, giving the matrix high temperature resistance, low smoke generation, and flame retardation. [Potyrala, 2011] However, a disadvantage is that they are brittle and that water is released during curing. [Nijssen, 2015]

2.7.3.3 - Epoxies

Epoxies have excellent mechanical, electrical and adhesive properties and good resistance to heat and corrosion. They also shrink less during curing than polyesters. [Nijssen, 2015] Epoxies are, however, more expensive than polyesters. [CES EduPack]

	Polyester	Phenolic	Epoxy
Density	1.04 - 1.4	1.24 - 1.32	1.11 - 1.4
Young's modulus	2.07 - 4.41	2.76 - 4.83	2.35 - 3.08
Shear modulus	0.744 - 1.59	0.996 - 1.74	0.84 - 1.1
Yield strength	33 - 40	27.6 - 49.7	36 - 71.7
Tensile strength	41.4 - 89.6	34.5 - 62.1	45 - 89.6
Compressive strength	36.3 - 44	30.4 - 54.6	39.6 - 78.8
Moldability*	3 - 4	3 - 5	4 - 5
Castability**	3 - 4	3 - 4	4 - 5

2.7.4 - Additives

> *"Additives are constituent components that may be added to the composite matrix to modify its properties and in general, enhance its performance." [Potyrala, 2011]*

Examples of additives can be catalysts, colourants and flame retardants. They can be divided into two main groups: the function-related additives and the process-related additives.
Function related additives increase the performance of a finished FRP element. An example is the colouring of a profile by adding pigment or enhancing the fire resistance of an element by adding fire retardants as a coating.
Process-related additives have an advantageous effect on the manufacturing process. An example is the low-profile additive which is used to avoid shrinkage during the curing of profiles. [Potyrala, 2011]

2.8 - Sustainability

The sustainability of FRP materials depends on the lifecycle of the material. In order: the manufacturing process, the service life and the end of life cycle. [Nijssen, 2015]

2.8.1 - Manufacturing process

FRP materials consist of fibres and a polymer matrix. The production of glass fibres, aramid fibres and carbon fibres requires a considerable amount of energy. In the case of carbon fibres, this amount of energy is largest. The energy needed to produce GFRP profiles is about 1/6th and 1/4th of the energy needed to produce steel and aluminium profiles, which is a big advantage in terms of sustainability.

A big disadvantage in terms of sustainability is the polymer matrix. The polymer matrix is in almost all cases made of petroleum or a by-product of the oil industry.

It is possible to make composites from natural fibre materials like flax, hemp, wood or bamboo. Most resins can very well be combined with these materials. However, the mechanical properties of these natural fibres are generally lower than those of synthetic fibres. The labour associated with picking the right reinforcing material from the biological resources can be very high. Also, an important disadvantage is the sensitivity to moisture during the manufacturing process. However, the relatively low density of these fibres often provides composites with a high specific strength and stiffness.
Polymer matrices are also available - to a lesser degree - on the basis of natural resources. Vegetable oil can be used to make polymers. The most important disadvantage here is the possible competition with food crops.
The type of production process also has an influence on the sustainability of the material. Production based on open moulds, for example, will deliver more emission of VOC's (volatile organic compounds) than a closed-mould. With closed-moulds, however, many aids are often used (e.g. vacuum film) that become waste after release of the product. [Nijssen, 2015]

2.8.2 - Service life

During the service life of FRP materials there are a few advantages over traditional materials like steel and concrete. FRP materials need less maintenance and are very durable even in chemically aggressive environments. The low thermal conductivity may provide energy savings when FRP is used in building applications. [Correia, 2015]

2.8.3 - End of lifecycle

At the end of the lifecycle FRP materials have a limitation. The thermosetting resin does not melt upon heating, but it disintegrates, therefore it can not be re-used. It can only be recycled and for example used as granulate for roads and other landfill applications.
FRP materials are also often made for a very specific purpose or application, due to which the practical possibilities of re-use are very limited.
Another problem in recycling the material is the fact that composites are often manufactured in combination with other materials. There are for example foam cores or metal inserts used, which makes it harder to recycle FRP materials.

The recycling of FRP materials can be divided in mechanical recycling - the material is crushed to smaller particles and then re-used as for example landfill - and thermal processing.

2.8.3.1 - MECHANICAL RECYCLING

Mechanical recycling processes include making powdered fillers and fibrous products. These processes are only suitable, however, for composite material that is relatively clean and uncontaminated.
The produced powder recyclates and powder have the potential for reuse back into the thermoset from which they originated. However, they do have a lower density, lower mechanical properties and are more difficult to process.
The fibrous recyclates have potential to be used as a reinforcement material, but they are not as good as the virgin reinforcement and there are problems with the bonding of the recyclate with polymers. The larger pieces of the recyclate prove to be failure initiation sites when recycled and reused. [Pickering, 2005]

2.8.3.2 - THERMAL PROCESSING

Thermosetting polymers, like all organic materials, have a calorific value and can be burned as a source of energy. The thermal recycling processes can tolerate more contaminated scrap material than the mechanical processes.

Several thermal recycling processes include:

- The fluidised bed process: produces a very clean fibre product, but not in the same form as an existing virgin fibre product. More development is needed to produce new cost effective products.
- Pyrolysis process: the recycled fibres from this recycling process have varying degrees of char on them, which limits the reuse options. It requires further processing to remove the char.
- Combustion with energy: this is plain burning of the material, which provides energy, because every organic material has a calorific value.

[Pickering, 2005]

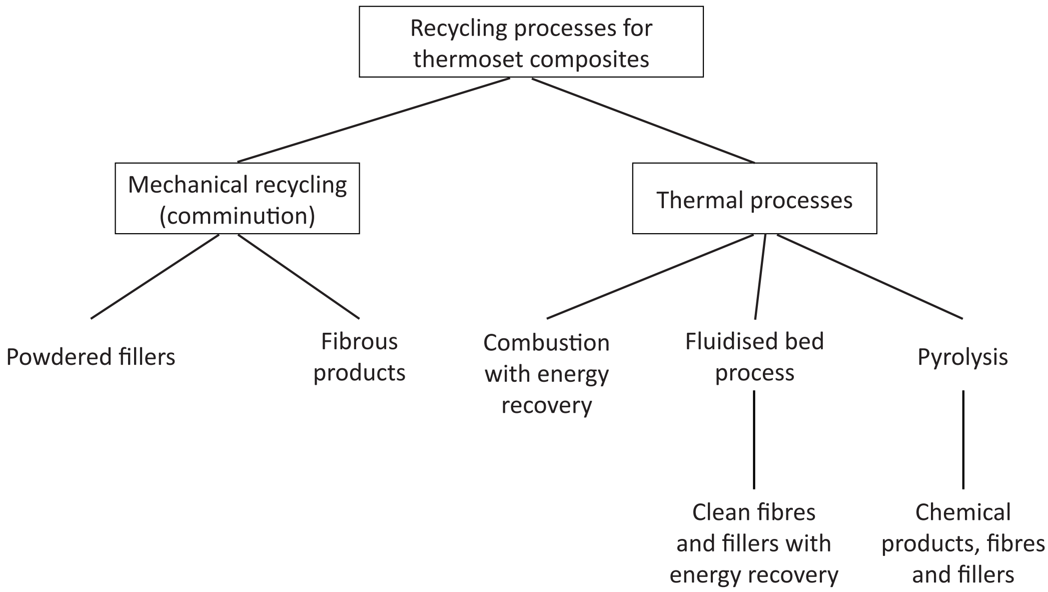


Fig. 2.11 - Scheme of ways to recycle FRP materials [Pickering, 2005]

2.9 - Production methods

FRP materials can be produced in several ways. There are two main production methods that can be distinguished: open moulding and closed moulding. During open moulding there is no second mould or vacuum film covering the first mould during the impregnation process. [Nijssen, 2015]

This distinction is somewhat arbitrary due to the possibility to make products with a combination of techniques.

2.9.1 - Open mould processes

Open-mould methods are generally the most labour intensive and manual methods, but also the cheapest, simplest and often most low-tech methods. The quality, consistency and control of the final product is reduced due to this.

2.9.1.1 - HAND LAY-UP

During hand lay-up fibre mats impregnated with resin are placed in a foam or FRP mould. These impregnated mats are subsequently connected to each other by adding resin between and on the mats with a metal laminating roller. This procedure can be repeated until the required thickness is reached.

Some limitations of hand lay-up are the inconsistent quality of the produced parts, the low fibre volume fraction and environmental and health concerns due to the emission of styrene. [Potyrala, 2011]

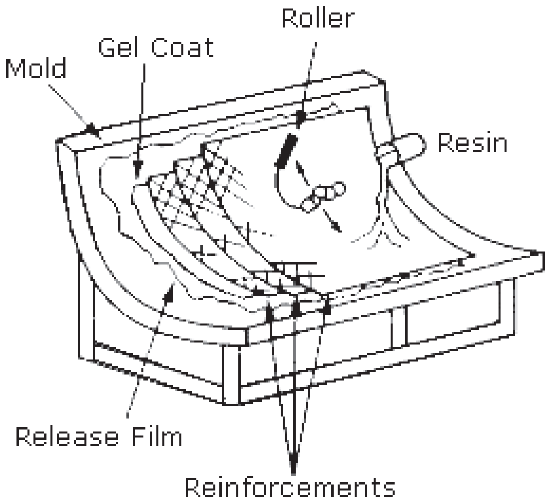


Fig. 2.12 - Hand lay-up and spray lay-up [Source: osha.gov]

2.9.1.2 - SPRAY LAY-UP

Spray lay-up is similar to hand lay-up, but cheaper and quicker. During the spray-up production process chopped fibres of about 10 - 40 mm and resin are sprayed on a mould surface using a spray pistol. This method is often used for larger surfaces where the fiber fraction should be high or to provide coating for construction appliances. It is very difficult to control the fibre volume fraction and the fibre thickness, so the process is very dependent on a highly skilled operator. [Potyrala, 2011]

2.9.1.3 - FILAMENT WINDING

This process involves winding filaments under tension over a rotating mandrel. Filament winding offers the possibility to orientate the fibres so it provides weight advantages. The workpiece is cured by removing the mandrel and placing it in an oven. This method is often used to produce pipes and other cylindrical shapes. It is low-cost due to the low-cost materials and tools that are used. [Potyrala, 2011]

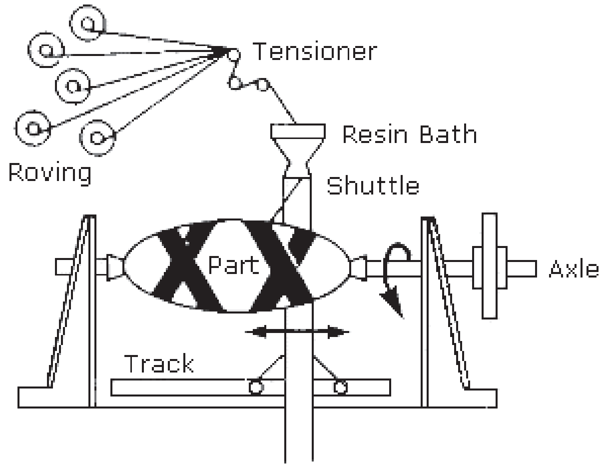


Fig. 2.13 - Filament winding [Source: osha.gov]

PULTRUSION
Pultrusion is a manufacturing method where the raw material (fibre bundles and fibre mats) is compressed by a series of hardened steel forming dies in the shape of the cross-section. The material is finally pulled through a resin bath and subsequently through a heated mould. The profile is cured at high temperatures (130ºC) and then sawn at certain lengths or wound onto a drum. The speed of travel through the die is determined by the viscosity, thickness and curing of the resin. [CES, 2017]

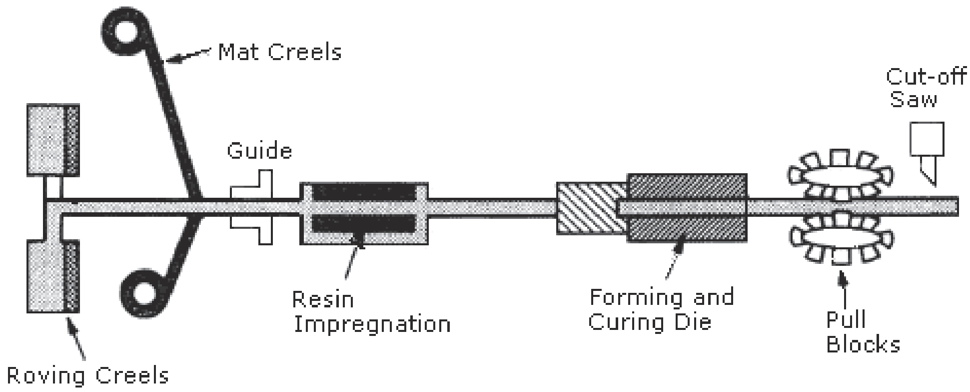


Fig. 2.14 - Pultrusion process [Source: osha.gov]

2.9.2 - Closed mould processes

Closed mould processes are generally more expensive machinal moulding processes. The precision, however, is larger than in open mould processes.

RESIN TRANSFER MOULDING (RTM)
During resin transfer moulding, fabrics are preformed to the mould shape and held together by a binder. These preforms can then easily be put in the mould. A second mould is put over the first and a mixture of low viscosity thermoset resin (mostly polyester), a catalyst, filler, etc. is injected into the mould cavity under pressure. Once all the fabric is impregnated the mould inlets are closed of and the material is left to cure. Both injection and curing can take place at ambient or elevated temperatures. [Potyrala, 2011] This

type of production process is mostly used for the manufacture of complex shapes without high tooling costs.

VACUUM MOULDING

A variation on resin transfer moulding is vacuum moulding. Vacuum moulding processes like Vacuum Assisted Resin Transfer Molding (VARTM) and Seeman's Composite Resin Infusion Moulding Process (SCRIMP) make use of atmospheric pressure to impregnate the workpiece. The mould is closed off airtight and air is then extracted using a vacuum pump. A vacuum film (a piece of plastic) can make the workpiece airtight when on the other side a mould supports the workpiece to avoid it being compressed in its plane. Vacuum moulding has a simple principle, is cheap and the quality is good, while large products and large series can be made. [Nijssen, 2015]

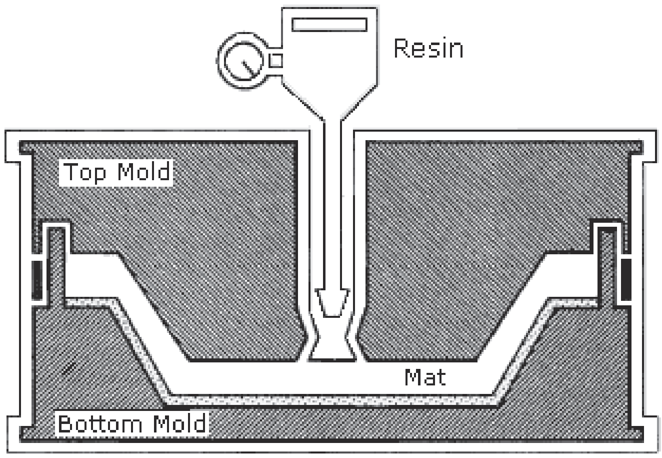


Fig. 2.15 - Resin transfer moulding [Source: osha.gov]

AUTOCLAVE MOULDING

An autoclave is in fact a large pressurized oven. Reinforcement is layed-up on the mould and the resin is applied by conventional hand or spray lay-up techniques. A flexible bag is placed on top of the glass fiber layer. The laminate and the mould are then placed inside the autoclave and pressures up to 40 bar compress the laminate, squeezing out air inclusions in the material to result in a dense product free from porosity. Like vacuum processes the excessive resin can be removed and air inclusions in the material may be reduced. [Nijssen, 2015]

Autoclave molding is mostly used for high strength aircraft and aerospace components - particularly for thicker parts or parts where a high fiber volume fraction is required. [CES, 2017]

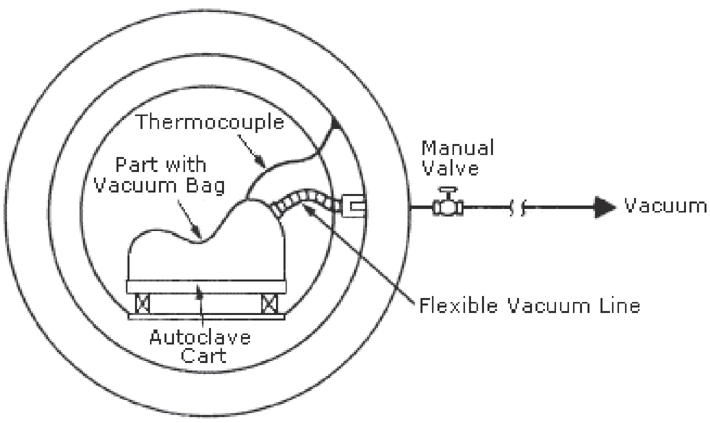


Fig. 2.16 - Autoclave moulding [Source: osha.gov]

2.10 - Assembly methods

There are many different ways to connect FRP elements to each other or to other materials. Connection methods developed from mimicking conventional connection methods to making more material adapted connections types - A process which is still in progress. An overview of the assembly methods used nowadays are given in this chapter.

2.10.1 - Mechanical

The mechanical joints in FRP are mainly based on the joints in steel. They are generally of the 'pin-loaded hole' joint type. However they have a big disadvantage over steel mechanical joints: every in-continuity in the FRP bonding elements like bolts will reduce the load-bearing capacity of the structure. This is due to the anisotropic, heterogeneous and brittle nature of FRP in contrast with the ductile behaviour of steel.

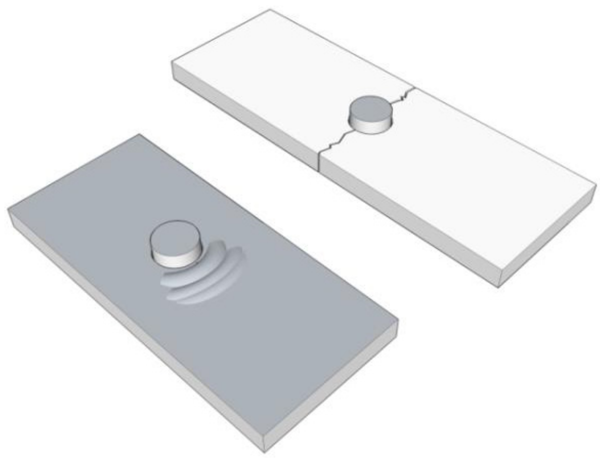


Fig. 2.17 - Fracture behaviour of a bolted joint in FRP [Nijssen, 2015]

Another disadvantage is the over-dimensioning of the FRP structural parts, because the differences in material properties between steel and FRP are not taken into account. [Correia, 2015]
The advantage of mechanical joints over bonded joints is the fact that there are a lot of design guides and rules available. [Potyrala, 2011]

2.10.2 - Bonded

Adhesive - bonded - joints are glued together with epoxy, acrylic and polyester glue types - the exact type of glue depends on the kind of polyester matrix that is used and the demands of the connection.
Bonded joints have some advantages over mechanical joints [Potyrala, 2011]:

- Glued connections distribute the forces and stresses more uniform.
- They are more rigid than bolted joints.
- They are less expensive and lighter and faster to apply.
- Thermal expansions can be compensated with the glue.
- Irregular surfaces can be easier bonded.
- There are very strong adhesives due to which the contact area can be made smaller.
- It is easy to make aesthetic joints.

Some disadvantages of bonded joints are:

- There are not a lot of design rules yet, so designing them is a challenge.
- Failure is sudden instead of gradually like a bolted joint.
- Adhesive joints depend on the humidity and other environmental factors due to which it is difficult to determine the durability of the connection.
- Connections are very hard to demount. [Potyrala, 2011]

2.10.3 - Welded

Welding seems to be a very adequate method to join FRP materials, because of economical and technical advantages. However, it is limited to FRP materials made of thermoplastic resins. These resins have several disadvantages compared to thermoset resins (see polymer matrix). This is why welding is very seldom used to assemble FRP parts. [Nijssen, 2015] For structural application in a bridge it is therefore not yet possible to use welded connections.

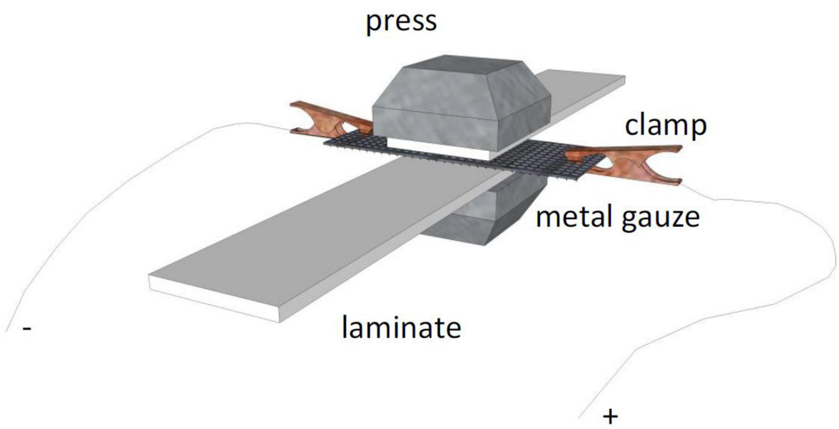


Fig. 2.18 - Welding of two FRP laminates [Nijssen, 2015]

2.10.4 - Interlocking

Interlocking connections are grooving and friction mechanisms that, in some cases, can be complemented with bolting and/or bonding. [Correia, 2015]
These construction systems are very quick to build, due to the simple connections between the components. However, the required precision is very high and little tolerances are allowed. These connections are also not very useful for the load-bearing structure of a bridge.
An example is the ACCS system designed by Maunsells Structural Plastic Ltd. The system uses a connector which slides into the groove of the panels. This system has been used to build bridge decks (of pedestrian bridges). [Correia, 2015]

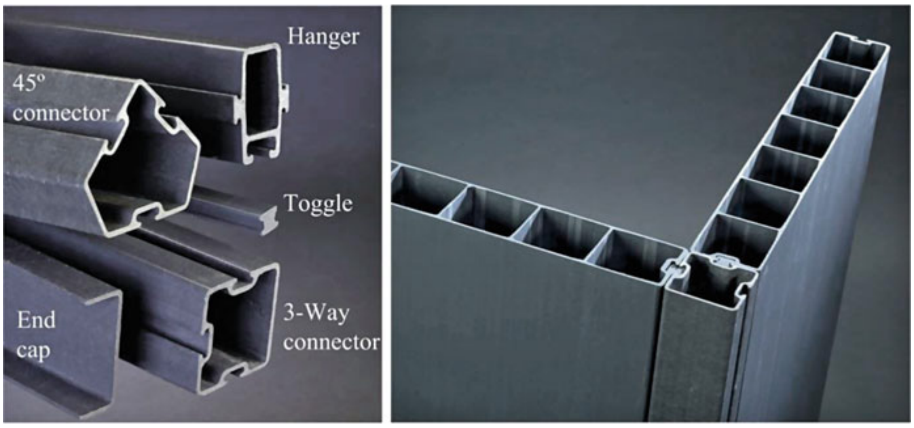


Fig. 2.19 - ACCS interlocking panels from Maunsells Structural Plastic Ltd.

2.10.5 - Inserts

For some joints, it can be useful to fix a piece of metal, wood or composite in one of the components to be connected. This is generally done to improve the distribution of the stresses introduced by a bolt or screw. Inserts are used with laminates, but are often particularly necessary in sandwich laminates. Such an insert is generally built into the laminate or sandwich during the production of the part to be connected or bonded later. [Nijssen, 2015]

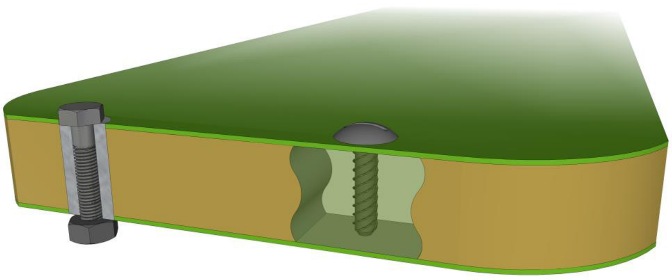


Fig. 2.20 - Sandwich panel with inserts to improve the distribution of stresses due to the screws. [Nijssen, 2015]

2.11 - Structural shapes in FRP bridge design

The first pultruded structural shapes made of mainly Glass Fibre Reinforced Polymers (GFRP) were based on and mimicked from metal beam design, having thin-walled open or tubular cross sections. [Correia, 2015] Some of these profiles are shown in the figure below:

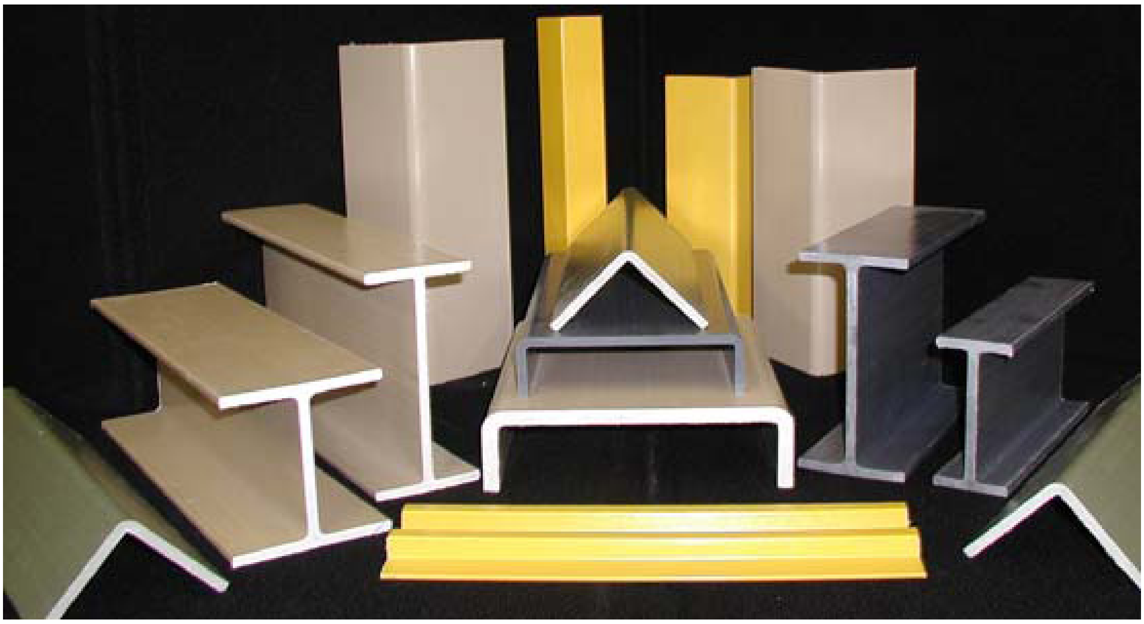


Fig. 2.21 - GFRP pultruded profiles - mimicked from steel beam design [Source: http://bellcomposite.en.made-in-china.com/]

They consist of alternating layers of rovings and mats with fibres oriented in various directions. The rovings give strength in the axial direction, while the mats give strength in the transverse direction and under shear loading.
The outer layer consists of a thin chopped strand mat, with short and randomly oriented fibres. This layer creates a smooth surface finish to protect against the environment.

These pultruded profiles are right now the mostly used element in FRP structures. However, they have several disadvantages generally caused by their sensitivity for compressive and impact loads. The profiles buckle before the material fails. [Correia, 2015]

2.11.1 - Pultruded bridge decks

The buckling failure of pultruded FRP profiles shows the need for material adapted profile designs. Several manufacturers have started developing material adapted pultruded profiles, mainly for bridge deck applications (figure 2.22). Almost all of these designs are multicellular pultruded panels connected through adhesive bonding or interlocking connections.
These panels are lighter and stronger than the traditional bridge decks, therefore saving in column and foundation works and enabling higher live loads on the bridge. [Correia, 2015] They also have different cross-section shapes compared to the GFRP pultruded profiles resulting in higher stiffness and higher compressive load resistance - so they are less likely to buckle.

There are several advantages in using FRP pultruded bridge decks compared to bridge decks made from traditional materials. FRP bridge decks have:

- Low density, so a low self-weight - resulting in less column and foundation works
- High strength to weight and stiffness to weight ratios.
- High fatigue strength
- Easy transportation to the construction site and easy application
- Low maintenance costs due to high corrosion resistance and long-term durability

There are however still some disadvantages in using FRP pultruded bridge decks:
- Fragile behaviour and vulnerable to hard impacts
- Fire behaviour; FRP is flammable and loses its mechanical properties at relatively low temperatures already, so it has to be protected.
- Initial costs; The initial costs are high, but based on life-cycle costs FRP allows for important savings when compared to traditional materials. [Correia, 2015]

A few examples of pultruded bridge decks are given in figure 2.22.

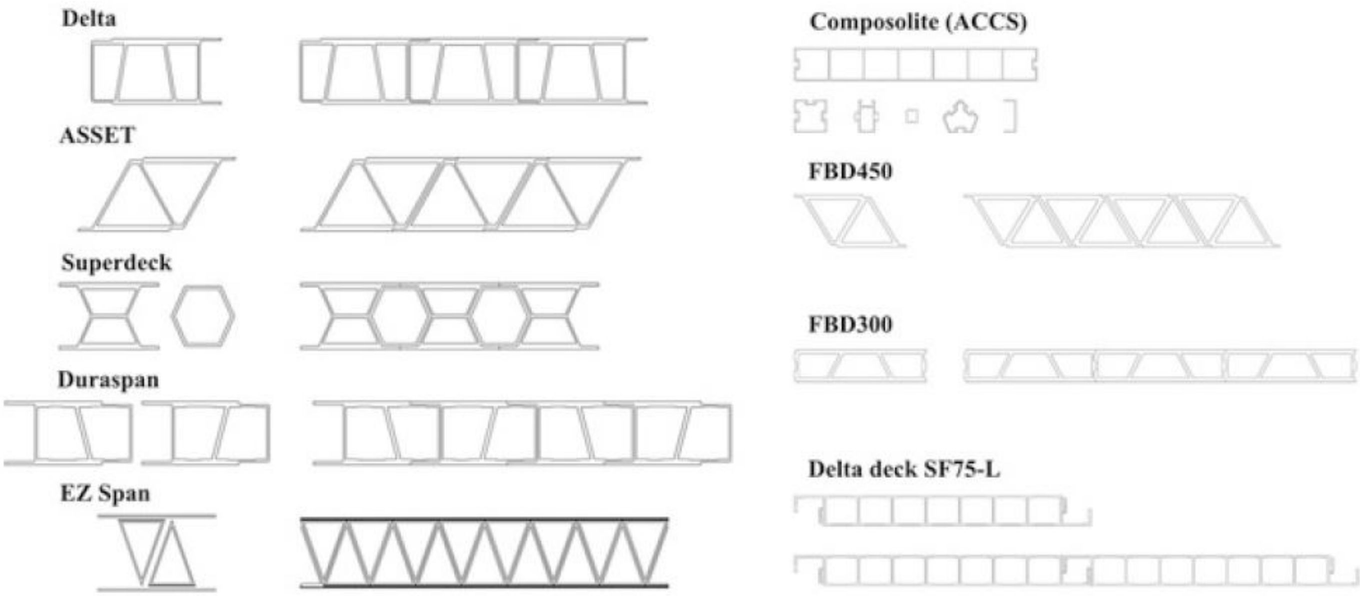


Fig. 2.22 - Examples of pultruded bridge decks made from GFRP of several manufacturers. [Correia, 2015]

2.11.2 - FiberCore bridge deck

A further development of the previously mentioned bridge deck can be found in the FiberCore bridge deck.
This bridge deck consists of a series of parallel positioned, non-loadbearing core elements wrapped in continuous woven fabrics. The reinforcement runs continuously from the elements' horizontal face planes through the webs and the facings of adjacent core elements. [Smits, 2014] Previous sandwich panels did not have this continuous reinforcement which makes them vulnerable to hard impacts and cracking in the weaker directions of the reinforcement.
The foam in the core of the sandwich deck elements does not fulfil a structural role - it is used as form-

work during the production process. (Figure 2.23)

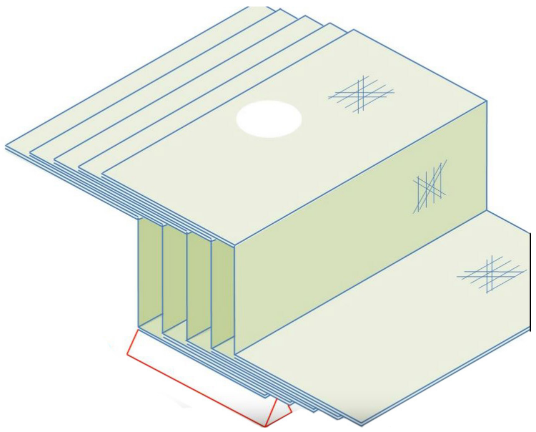


Fig. 2.24 - Flanges connected by web, flanges interconnected [FiberCore, 2016]

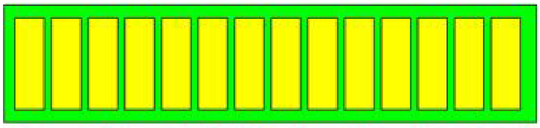


Fig. 2.23 - Schematic section of FiberCore Inside bridge deck (FiberCore, 2016)

2.11.3 - Monocoque structures

Monocoques are structures with a load-bearing exterior shell, comparable to shellfish [Smits, 2016]. The outer skin carries both tensile and compressive forces. These bridges are therefore very efficient with the use of material and make slender forms achievable.
A semi-monocoque carries tensile forces in the skin, but the compressive forces are carried by ribs or frames inside the skin.
An example of a monocoque structure is given in figure 3. The lightweight monocoque roof is carried by glass. The roof consists of a GFRP monolithic layer on the outside and foam-blocks placed between GFRP webs on the inside.

2.11.4 - Shell structures

Another way of designing an FRP structure is by using double curved shapes. These shells have a very high stiffness which minimises material use: the shell structure can be quite thin.
The costs of these structures can however become quite high, due to moulding costs when the structures become more complicated.
An example of a (theoretical) design for a shell structure as bridge is given in figure 2.26.

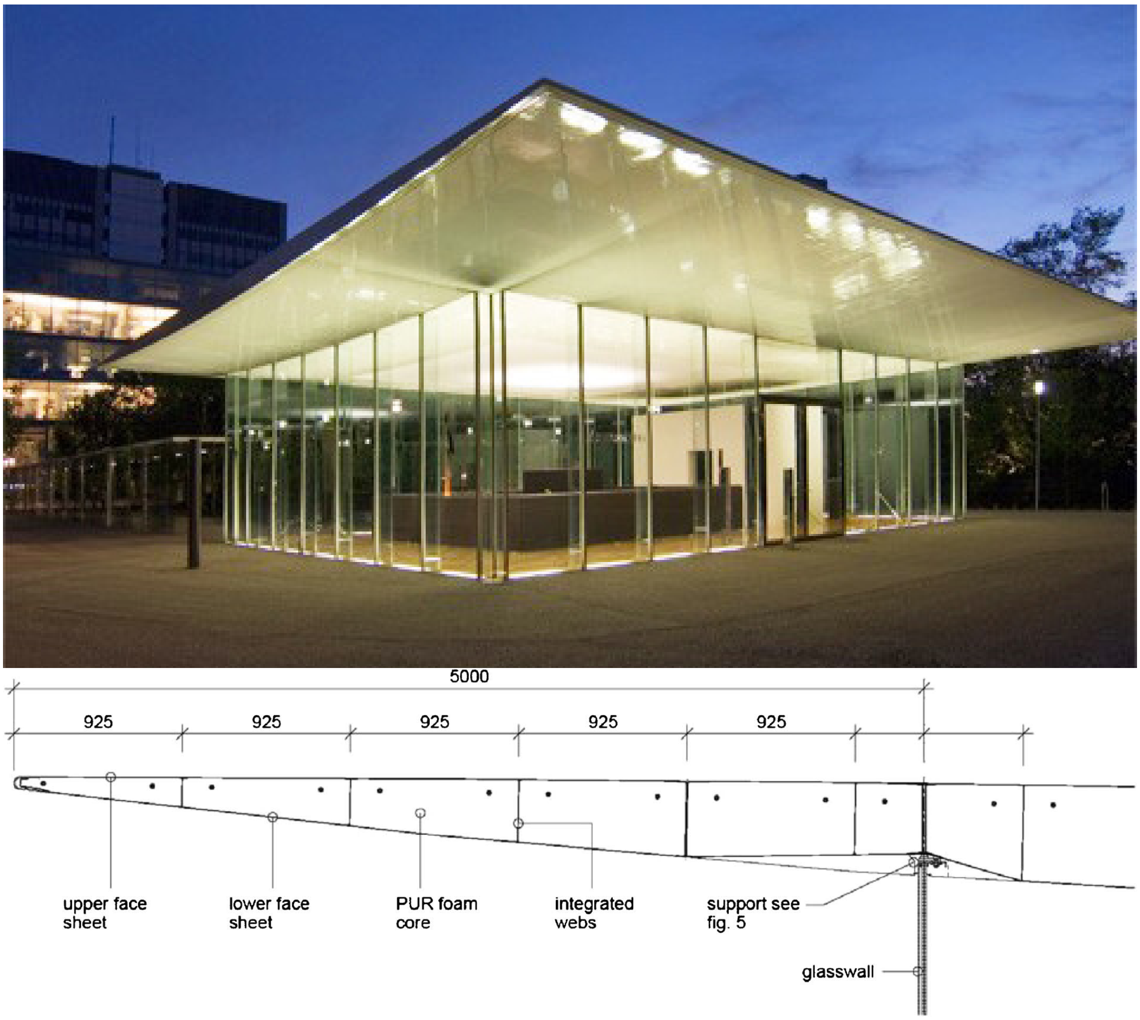


Fig. 2.25 - Monocoque construction of the roof of the Main Gate of the Novartis campus in Basel Switzerland by Keller in 2006

Fig. 2.26 - Shell shaped bridge design: "The cross-section of the deck curves upward, forming part of the bridge's parapet. As the bending momentum increases toward the middle, so does the height of the shell." [Smits, 2016]

2.11.5 - FRP cables

Fibre reinforced polymers have interesting properties to be used as wires and cables in bridges. In particular CFRP has high tensile strength, high fatigue resistance, low weight and excellent chemical resistance.
A disadvantage is the anisotropy of the material, which decreases the anchoring strength of the cable. Another disadvantage is the sensitivity of the material for UV degradation, wind and moisture. The cable needs a cover of for example polyethylene to be protected. The EMPA (Swiss Federal Laboratories for Materials Testing and Research) in collaboration with BBR developed a system, consisting of an anchor sleeve with conical inner boring filled with graded layers of ceramic granules and polymer resin (see figure 2.27). This system has been used in the Aberfeldy FRP bridge in the UK (see chapter 4.3).

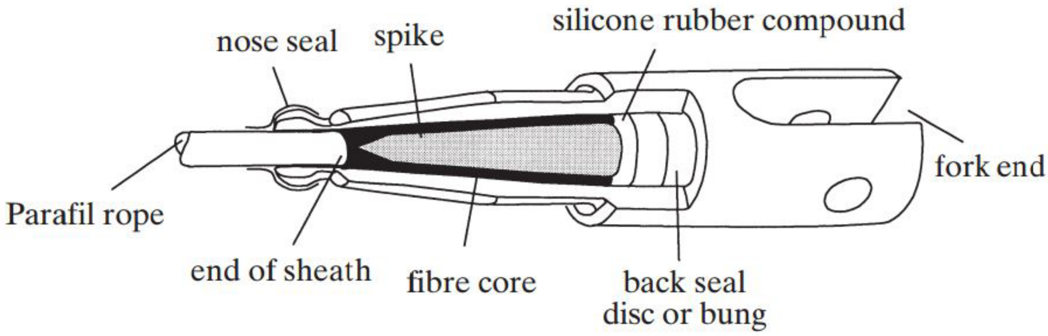


Fig. 2.27 - Parafil aramid cable system developed by the EMPA in collaboration with BBR

2.12 - Conclusion

FRP is a composite material with fibres in a polymer matrix. The fibres define the largest part of the strength of an FRP material while the resin acts as glue to distribute the forces evenly.

FRP has some general material characteristics, however the material can for a large part be designed to fit the needs of the project. Generally the material has low density, high corrosion and oxidation resistance, relatively high mechanical properties, high fatigue resistance and a lot of freedom of form. It is a brittle material so the ultimate strength and breaking strength is the same.

FRP is a sustainable material in terms of embodied energy, but in terms of recycling it is not yet sustainable. However, it is also a very durable material due to its long life expectancy.

There are two main production methods that can be distinguished to produce FRP products: open moulding and closed moulding. Several methods can be used to create FRP, each with its advantages and disadvantages depending on the product that has to be made.

Connections can be divided in four groups: the mechanical joints, bonded joints, welded joints and interlocking joints. Each joining method has advantages and disadvantages depending on the use. A few advantages of bonded joints are the uniform distribution of the forces, they are more rigid than bolted joints and lighter and faster to apply. Disadvantages are the lack of design rules and sudden failure of the connection.

The structural use of FRP developed from mimicking steel profiles to pultruded bridge decks to new material adapted forms like the monocoque and shell structures. These shapes explore the possibilities of the material best and will be used in the future to build bridges and other structures.

3 General material research: reinforced structural glass

Fig. 3.1 - Apple Store on Fifth Avenue in New York: an example of the structural use of glass [Source: http://loving-newyork.com/apple-stores-in-new-york/]

3.1 - Introduction

Besides the theoretical study concerning FRP it is also necessary to assess the state of the art of structural glass to be able to combine the materials in an optimal hybrid design.
In this chapter the general material properties like the manufacturing of glass, types of glass and assembly methods are researched, following the research question of this chapter:

What are the (mechanical) properties of reinforced structural glass?

The result of the research is summarized in a conclusion and followed by several design guidelines to be the basis of the preliminary design variants of the hybrid bridge.

3.2 - What is structural glass?

To make structural glass from normal glass it is necessary to enhance the safety of the material. This can be done by adding safety concepts to the material. The main safety concepts for structural glass are based on over-dimensioning and redundancy.
First of all high safety factors are used when constructing with glass. This results in structural elements which are over-dimensioned.
Secondly, structural glass generally consists of multiple layers of glass laminated together with the use of interlayers. This enhances the safety when one of these glass layers breaks - the remaining layers of glass will carry the load.
The safety can be further enhanced by reinforcing the glass. This is generally done by adding a steel profile along the edge of the glass. This profile will minimize the consequences of a total glass failure. The glass will fail in a more ductile way, thus enhancing the post-breakage behaviour.

3.3 - Mechanical properties

Glass is considered to be a special ceramic material with corresponding qualities, such as a high stiffness, an elevated yield stress and an elevated chemical resistance. It also has a high density comparable to the density of concrete. However, like ceramics, glass behaves brittle, has a low toughness and a low thermal shock resistance. Only small reversible deformations are possible. [Bourhis, 2008]
Glass shows linear-elastic and isotropic behaviour. It does not fail in a plastic manner like for example steel and its properties do not depend on direction or orientation like FRP. Since glass is not able to redistribute stresses by means of plastic deformation, it is highly sensitive to stress concentration. This results in a strength of glass which is not a material constant, but depends on various parameters [Louter, 2011]:

"In theory glass is an homogeneous and isotropic solid material displaying ideal, perfectly elastic behaviour up to very high stresses, but in reality its usable strength is governed by fracture mechanics and is determined by the presence of microscopic cracks in the glass surface." [Smith Anthony, 2005]

3.3.1 - Tensile strength of glass

The microscopic cracks in the glass or in the surface of glass are due to imperfections which occur during the production process. These imperfections can result in stress concentrations - for which glass is highly sensitive - which makes it very difficult to predict the (tensile) strength of glass. High local stresses will gather around such cracks. Since glass has a high yield strength it is not able to deform plastically, so redistribution of the stresses is not possible. Near the tip of the crack the stress will reach the highest strength - enough to tear the atomic bonds apart, allowing the crack to grow. This will ultimately lead to failure of the glass depending on the condition of the surface, the stress history (intensity and duration), the residual stresses acting across the crack and the environmental conditions.

Therefore these cracks dominate failure in glass, so strength and toughness is closely related to the surface and edge finish of glass elements. [Ashby et al, 2007]

Low maximum bending stresses have therefore be taken into account when calculating with glass:

- The calculation value of annealed glass is 20MPa and 6MPa when allowing for corrosion
- The calculation value for heat-strengthened glass is 40MPa
- The calculation value for fully tempered glass is 80MPa

These values are based on failure stresses that statistically occur in 1 in 10.000 tests. [Veer, 2016]

3.3.2 - Compressive strength of glass

Glass has a very high compressive strength and hardness caused by the silicon in glass materials. Cracks will not develop when the material is subjected to compression. Therefore the compressive strength is not the governing factor in failure of glass structural elements: glass will either fail due to buckling or tensile forces caused by other factors. The theoretical strength of glass could exceed 14.000 MPa. [Pepi, 2014] According to the glass construction manual (2007) the compressive strength of normal float glass is 7.000 MPa.

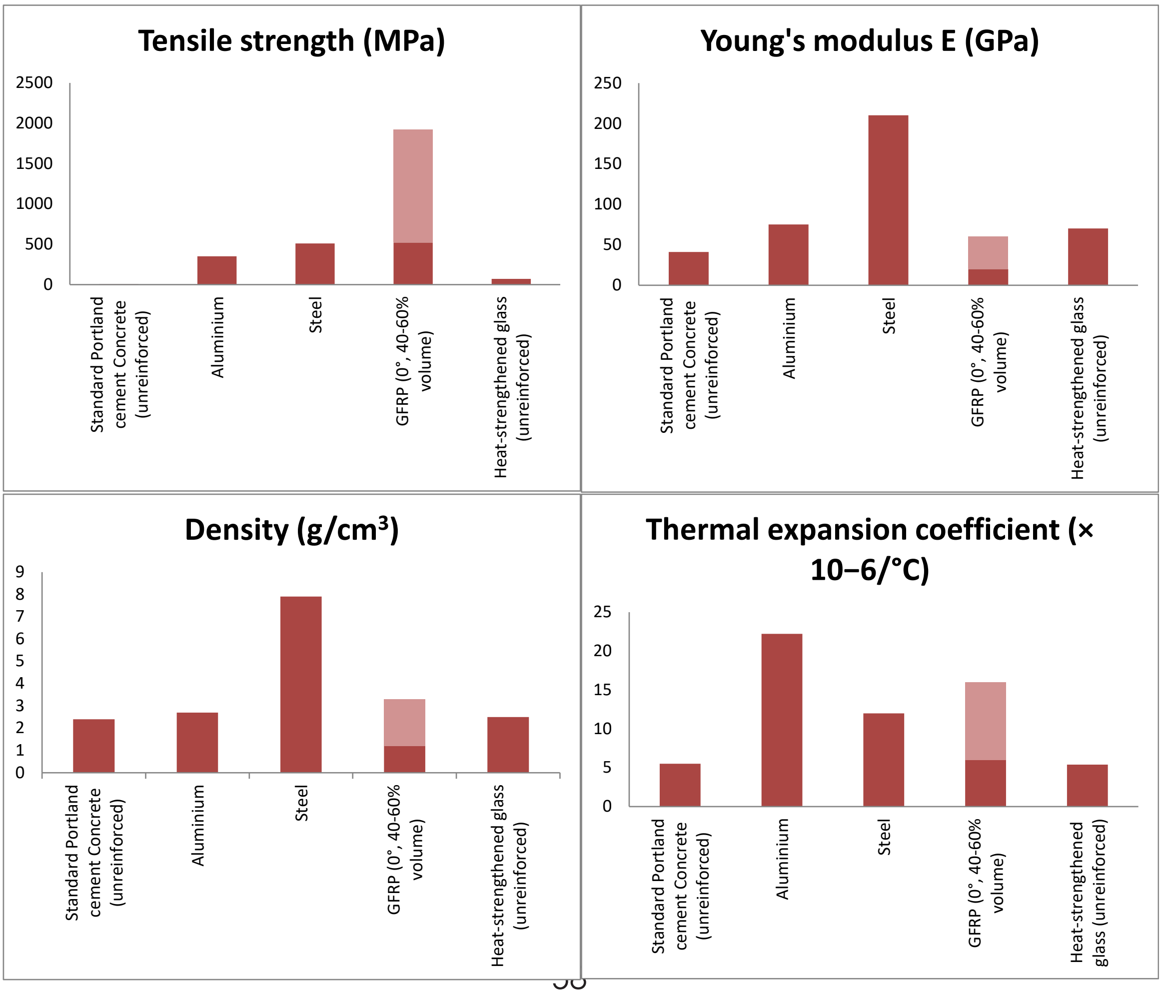


Fig. 3.3 & 3.4 - Comparison of heat strengthened glass with conventional materials plus GFRP [Glass construction manual, 2007]

3.4 - Production methods

Glass can be formed in several mechanical production methods into planar, linear or compact semi-finished products. The making of basic glass is generally followed by several processing stages in which the material is optimized for specific functions. For example, solar control, structural use or aesthetical aspects (see figure 3.5). [Wurm, 2007]
About 90% of glass is manufactured with the float glass production process. About 10% of glass is produced with a drawn or rolled process.

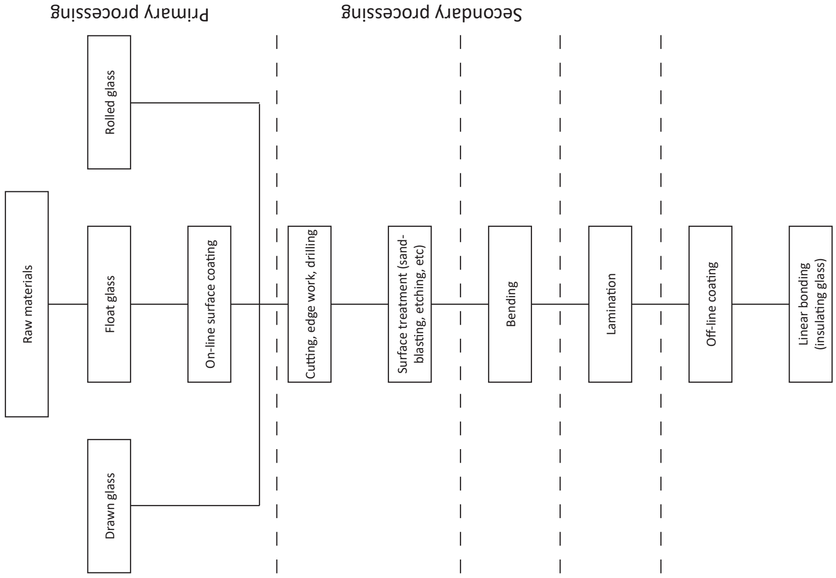


Fig. 3.5 - Overview of processing stages of glass

3.4.1 - Material ingredients

There are a lot of materials that can be used to make glass, but the basis of almost all glass is amorphous silica. It can be mixed with Na_2O to create soda-lime glass or with B_2O_5 to make borosilicate glass. For structural purposes, the most commonly used type of glass is soda-lime-silica glass.
Soda-lime glass consists for up to 60 - 80% of silica, which is obtained in a manufacturing process from quartz sand. The sodium oxide, which accounts for about 15% of the ingredients, acts as a flux to lower the transformation temperature to approximately 550 degrees Celsius to simplify the production process. About 10% of the glass consists of lime (CaO) to increase the chemical resistance. Further additives include magnesia or alumina for better optical, electrical and chemical qualities of the glass. [White, 2007] When the molten mass cools, the glass will gradually solidify without forming a regular symmetrical or periodic crystal lattice. [Nikolao, 2017] About 90% of the produced glass nowadays is soda-lime glass [Phillips, 2007].

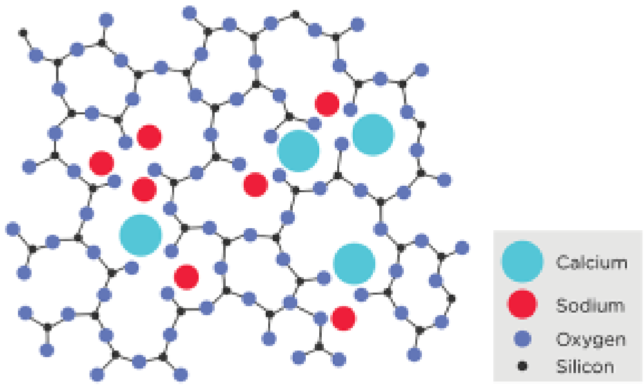


Fig. 3.6 - Chemical composition of soda-lime-silica glass [Source:http://www.koppglass.com/blog/3-common-glass-types-properties-applications/]

3.4.2 - Float glass production

The normal float glass or annealed glass is made by pouring molten glass onto a bed of liquid tin in a nitrogen atmosphere. The liquid glass moves from the hot oven - where it reaches a temperature of 600C - to the annealing lehr, where it is slowly cooled down to prevent residual stresses, solidifying in the process. Coatings can be applied during this process on the hot glass at the nitrogen side. After the glass leaves the tin bath the glass is cooled down slowly and cut.

Since defects in the glass reduce the strength, the edges are treated by CNC processing afterwards. They can be polished, rounded or faceted. [Veer, 2007] [Louter, 2011] It is very important that this happens carefully due to surface flaws that can affect the strength of glass and the fact that this process is not possible after thermal treatment of the glass.

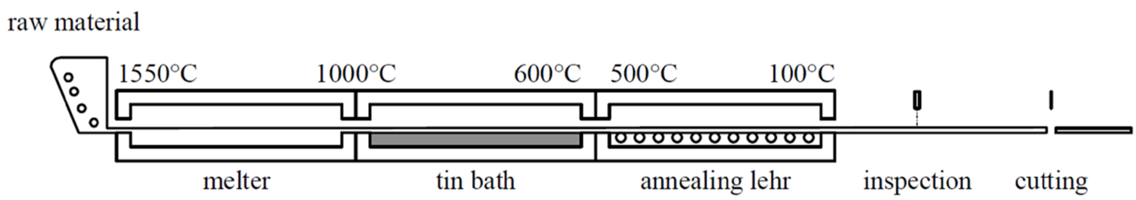


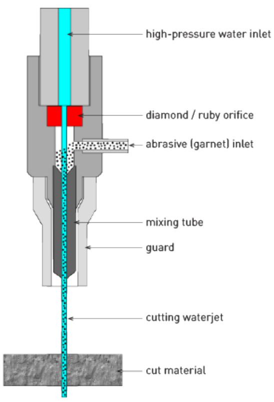
Fig. 3.7 - Schematic representation of the manufacturing process of annealed glass; [Louter, 2011]

3.4.3 - Size of glass

The maximum standard size of float glass is 6*3.21 m. The width of glass is a standard dimension while the length can be adjusted, but it does not normally exceed 6 meter. However, it is also possible to obtain greater lengths. In China it is possible to achieve glass lengths of about 12 meter. However, to obtain these larger lengths, the costs will become significantly higher.
A way to obtain larger beam lengths in glass without producing one single costly element, is by splice laminating the glass. This process will be explained under chapter “3.5 - structural glass”.

3.4.4 - Cutting of glass

Glass is mostly immediately cut after production (before treatment and/or lamination). This is done by scratching a line on the glass using a scoring wheel of high hardness, mostly a diamond tipping cutting arm. The glass is bent or heated locally to put the scratch into tension which leads to unstable crack growth from the scratch through the thickness of the plate. [Veer, 2007] The rough edges are then ground to create a flat and clean surface with no defects or cracks and thus higher strength.
It is important to use the right cutting wheel, the right lubricant and the right pressure when cutting glass. A blunt wheel can cause damage in the glass which will affect the strength significantly. [Veer, 2007]
Another way to cut glass is abrasive water jet machining. This has many advantages: it has no restrictions on the cut geometry, no heat is generated during the cutting process, it is environmentally friendly as it is clean, it does not create dust and cut products are of higher accuracy and edge strength. [Vu Ngoc Pi, 2008] The biggest disadvantage is the estimated time and cost intensity of this process.



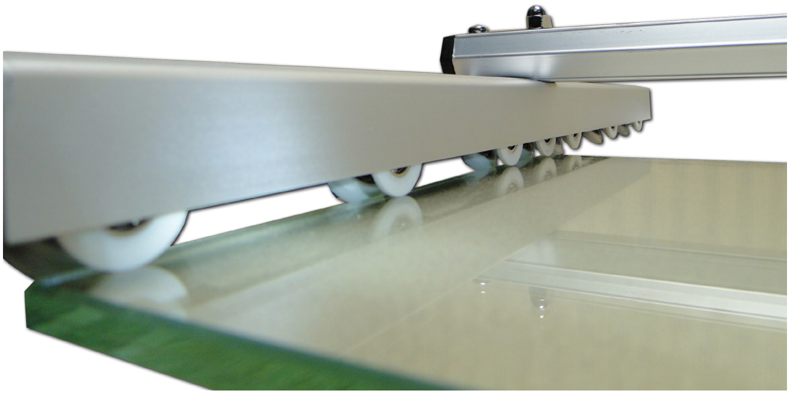


Fig. 3.8 - Left: schematic representation of abrasive water jet cutting. [Source: https://wiki.harvard.edu/confluence/display/fabricationlab/Waterjet+Tutorial] Right: Diamond cutting arm to cut glass. [Source: http://www.xinology.com/Glass-Processing-Equipments-Supplies-Consumables/glass-cutting/glass-mirror-cutting-tools/CUT-T-024.html]

3.4.5 - Heat-treated glass

In order to increase the strength of a glass pane, it can be thermally treated, which will lead to higher thermal shock resistance and higher strength of the glass. There are, however, a few conditions: the glass must be at least 4mm thick and the glass shape should be final before heat-treatment as it is not possible to drill or cut the glass after treatment.
Heat treated glass is made by heating up the annealed glass (after cutting to the final shape) to about 620 to 675ºC in a furnace and then cooling it rapidly using jets of cold air (figure 3.9) [Haldimann, 2006] The surface of the glass will cool rapidly, but the centre of the glass remains liquid. This puts the surfaces in compression when the centre cools down and shrinks. This compressive residual (pre-)stress at the glass surface effectively enhances the tensile (bending) resistance of the glass (see figure 3.10). [Louter, 2011]
Failure of the glass occurs, when the local stresses around a defect exceed the tensile capacity. In case of heat-treated glass, the residual compression stress has to be exceeded. In this way a higher strength of the glass pane is obtained.
There are three types of heat treated glass depending on the cooling rate of the glass (figure 3.10).

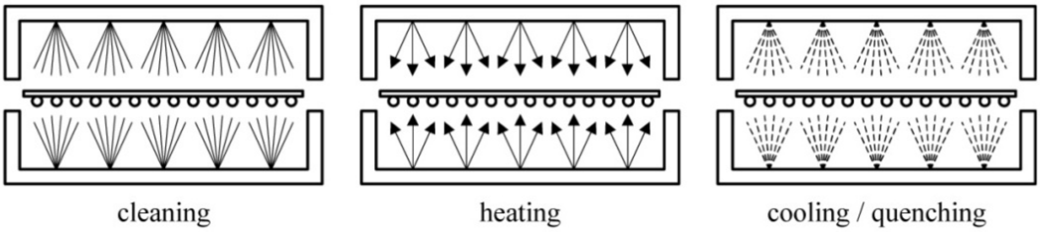


Fig. 3.9 - Schematic representation of the tempering process; (Worner, Schneider & Fink, 2001)

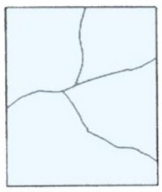
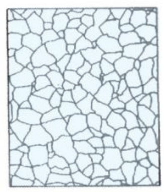
Terminology	Annealed glass	Heat-strengthened glass	Fully tempered glass
Fracture pattern			
Pre-stress level	Normal	Medium	High
Characteristic tensile bending strength	45 MPa	70 MPa	110 MPa

Fig. 3.10 - Characteristic breaking pattern and maximum tensile bending strength per type of glass [Belis, 2012]

3.4.5.1 - Annealed glass

Annealing can be defined as the process of slowly cooling down liquid glass to prevent residual stresses in the glass. This is what happens with normal float glass. Annealed float glass can be re-annealed to remove objectionable stresses in the glass by re-heating to about 600 degrees followed by slow cooling. Annealed glass can have bending strengths between 20 and 70 MPa.

3.4.3.1 - Fully tempered glass

Fully tempered glass is cooled down the fastest and is therefore the strongest glass type. The residual compressive surface stress varies between 80MPa and 150MPa for fully tempered soda lime glass. The calculation value for the tensile strength of fully tempered glass is 110MPa. [Veer, 2016]
Besides an effect on the strength of glass, heat treating also has an effect on the breaking pattern of glass. Fully tempered glass breaks in a million pieces when it fails (figure 3.10).

3.4.3.2 - Heat-strengthened glass

Heat strengthened glass has a lower cooling rate than fully tempered glass, but a higher cooling rate than annealed glass. This causes the residual compressive surface stress to be lower than for fully tempered glass.
The breakage pattern of heat-strengthened glass is similar to annealed glass. It breaks in larger pieces than fully tempered glass, due to which it can keep its loading capacities: it breaks into large fragments which allow the transfer of (compressive) forces, especially through overlapping sheets. [Bos, 2009] The calculation value for the tensile strength of heat-strengthened glass is 70MPa (see figure 3.10). [Veer, 2016]

3.4.4 - Chemically treated glass

Glass with a high sodium content can also be chemically treated for higher strength. The glass is pre-stressed by immersion in a hot potassium chloride bath. Exchange of sodium ions and densification of the molecular structure of glass create large compressive stresses in the surface. This effect is limited to a small depth, leaving the glass still susceptible to surface defects. Chemically strengthened glass can be cut to a limited extent. The process is suitable for a wide range of thicknesses, including very thin and very thick glass, complex glass geometries and can maintain very high surface planarity. [Nikolaou, 2017]

3.5 - Structural glass

Besides the use as a non-structural building component, glass can also be used structurally, as mentioned before. Several measures have to be taken to ensure the safety of a glass structural member and to overcome the problem of the brittle failure of glass, to use glass structurally.
The general safety concept of glass is based on redundancy. Large safety factors are used and the glass is strengthened in several ways.

3.5.1 - Heat treatment

The first way to create structural glass out of normal float glass is by applying heat treatment. This elevates the characteristic tensile bending strength and breaking pattern of glass by pre-stressing the glass (see chapter 3.4.5).

3.5.2 - Lamination

A second way to enhance the safety of glass is by laminating the glass pane to form one structural element. The structural element then consists of two or more glass planes that are welded together with an interlayer - often a foil or a resin - in between.
The principle is based on redundancy: when one of the outer layers of glass breaks, the remaining layers will still be able to carry the load - the highly ductile interlayer will hold the glass together so the intact glass layers can carry the load. [Louter, 2007] This measure minimizes the chances of complete glass failure and thus enhances the post-breakage behaviour.
An autoclave is used to create laminated glass with foil interlayers in between. This method uses heat and pressure to create the bond.
Adhesive resins are cast in place and then polymerized by UV-radiation.

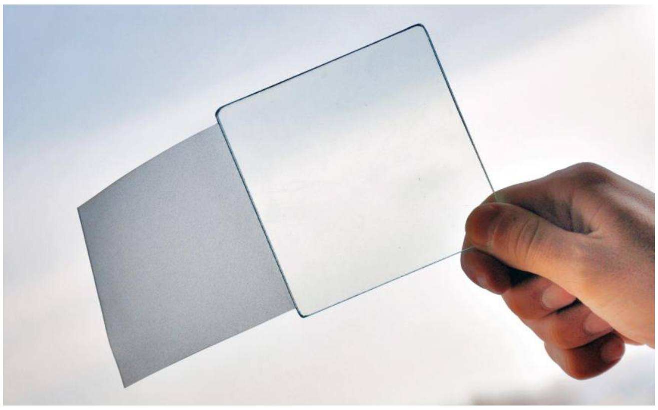


Fig. 3.11 - PVB interlayer - at the right translucent before lamination, at the left transparent after lamination (Oikonomopoulou et al., 2013)

3.5.3 - Interlayer

The interlayer that bonds the glass panes together is often PolyVinylButyl (PVB), Sentry Glass or a resin.

3.5.3.1 - PolyVinylButyl (PVB)

PolyVinylButyl (PVB) is a liquid or film (figure 3.11). The glass panes are glued together in an autoclave under high pressure and temperatures. These autoclaves are generally restricted to maximum dimensions of 2.5 by 3.6 meter. Several characteristics of PVB foil include:

- High creep, especially when loaded in shear
- Softening temperature lies within use temperature (55 degrees Celsius)

PVB can not take long term loads due to the high creep behaviour and PVB is not suitable for overhead applications due to the low softening temperatures.

3.5.3.2 - SentryGlas (SG)

SentryGlas (SG) is resistant to higher temperatures than PVB (above 30ºC). [Monasadat, 2015] In addition, SG has 5 times higher tear strength and makes the laminated component 100 times more rigid [O' Callaghan, 2009] and due to its relatively large thickness and its low viscosity when heated during the lamination process, the SG interlayer easily conforms to dimensional inaccuracies on the glass and easily flows around reinforcement sections embedded in the interlayer [Louter, 2011].

3.5.4 - Splice lamination

To obtain larger lengths - larger than the standard 6 meters - in glass it is possible to splice laminate the glass.
To do this multiple glass sheets are laminated in overlap according to a segmentation scheme. The segmentation scheme can either be symmetric or asymmetric (figure 3.12) [Louter, 2011].
In theory it is possible to create any beam length. In practice, however, the size is limited by the size of the autoclave that is used and the possibilities for transportation.

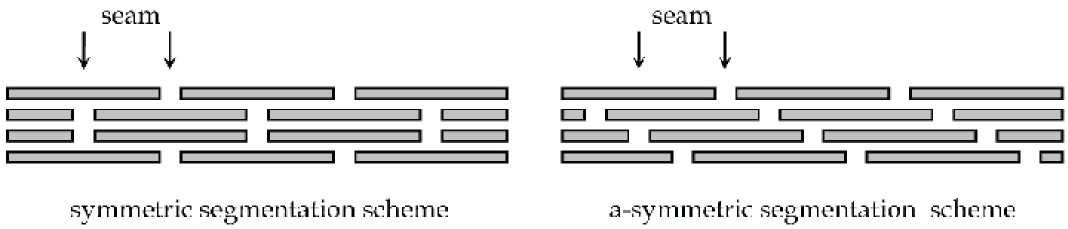


Fig. 3.12 - Two types of splice lamination schemes [Louter, 2011]

3.5.5 - Reinforcement with steel

All the previous measures minimize the probability of total glass failure. However, the chances of a total collapse of the beam laminate cannot be eliminated since failure of all glass layers might still occur due to repeating impacts, nickel sulphide inclusions, or stress concentrations caused by assembly errors at the joints or supports. [Louter, 2007]

To minimize the consequences of total glass failure and to ensure a much higher post-breakage strength, the glass can be reinforced with a steel profile. This small stainless steel section which is adhesively bonded at the tensile zone of the glass beam acts as reinforcement. This way safe failure behaviour, comparable to reinforced concrete, is obtained. [Louter, 2007] The reinforced glass beam will break in a ductile and controlled way. The consequences of a complete failure are significantly reduced, as well as the risk of a total collapse and loss of human lives. [Oikonomopoulou et al., 2013]

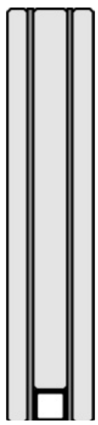


Fig. 3.13 - Schematic view of the reinforced glass beam [Louter, 2011]

3.5.6 - Reinforcement with FRP

Besides steel reinforcement glass can also be reinforced with Fibre Reinforced Polymers (FRP). A concept of carbon fibre reinforced float glass beams are researched by Palumbo. Carbon fibre reinforcement is bonded in the tensile zone of the glass beam. [Palumbo, 2005]
A glass beam with Glass-fibre Reinforced Polymers (GFRP) has been developed, where GFRP reinforcement rods have been embedded in the interlayer. This GFRP reinforced beam gives the beam higher post-breakage strength just like a steel reinforced glass beam. However, the GFRP reinforced beam has a few

advantages over the steel reinforced beam. The semi-transparent appearance of the GFRP materials offers more transparency while the high tensile strength reduces the amount of reinforcement needed. [Louter, 2010]

3.5.7 - Transportation

Transportation of glass elements can be a problem, due to the fact that glass elements like beams have to transported in one part: they have to be laminated in the factory to ensure the quality of the lamination. Therefore it might be very important to plan transportation and assembly thoroughly.

3.6 - Bent glass

Float glass can be bent in a cold forming or a thermal process after cutting, drilling, edge work and surface treatment. After bending the glass can be thermally treated and laminated.

3.6.1 - Cold forming

Glass shows linear elastic deformation, which allows it to be mechanically formed in its cold state. The glass is clamped or point-fixed on a sub-construction and subsequently bent in a curved shape. It is only possible to create a single curved glass panel with this process. The amount of curvature that can be achieved depends on the thickness of the sheet. The thicker and stiffer the glass sheet, the less it can be curved.
Cold forming results in permanent tensile bending stresses in the glass. Therefore cold formed glass has a lower load-bearing capacity than normal float glass. Only fully tempered glass can be considered for cold-forming due to the permanent high stresses induced on the glass after cold bending.

Cold formed glass therefore seems not applicable as structural glass, as the bending process causes a decrease of the strength of the panels. In addition, fully tempered glass is not suitable to be safely used in a structure.

3.6.2 - Thermal forming

Glass can also be formed in its hot viscous state. Glass is heated and suspended and then pressed into large moulds. It is cooled down slowly, either to form annealed glass or tempered glass. Afterwards the glass can be laminated. [Pariafsai, 2016] Advantages of this method include the possibility to create large bend geometries. Disadvantages of this method include:

- High tooling costs; thermal formed glass is generally only suitable for mass production.
- Bad optical quality
- Large tolerances

3.7 - Assembly methods

There are multiple connection methods for glass. Two main categories can be distinguished: mechanical connections and adhesive connections. The connections can subsequently be divided in linear, point and surface connections.
The mechanical connections can be divided in force connections and mechanical interlocking connections (see figure 3.14).

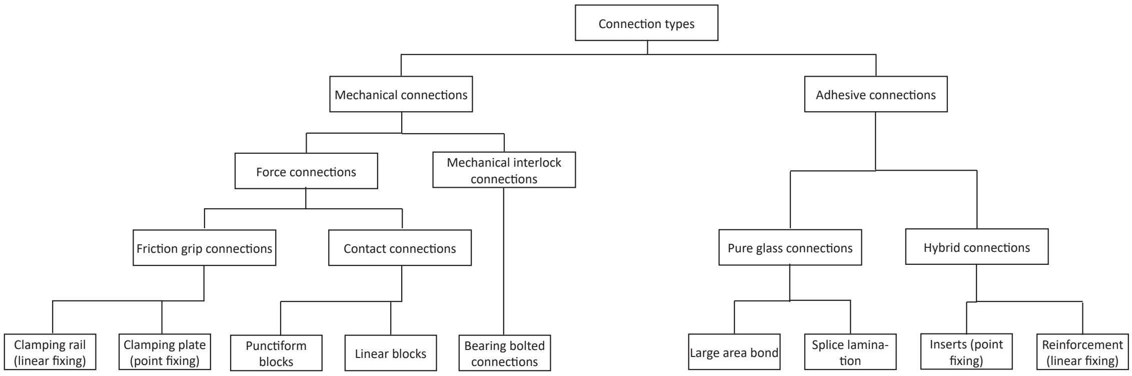


Fig. 3.14 - Typology of glass connections [Source]

3.7.1 - Force connections

3.7.1.1 - Clamping

The most classical way to connect two glass panels is by clamping. Steel plates are placed on the glass panel with a soft material separating the metal and the glass surface. Clamped connections can either be linear (figure 3.16) or in a point (figure 3.15).
This method of connecting is uncontrollable and a large metal plate compromises the transparency of the glass. In addition, the glass plates might slide at the location of the connection when loads are applied parallel to the glass surface. [Nijsse, 2004]

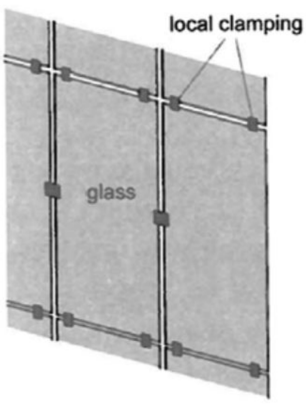


Fig. 3.15 - Point clamped facade

Fig. 3.16 - Linear clamped connection

3.7.1.2 - Friction grip connection

A friction grip connection is a pure force connection where two plates are pressed against a glass plate by a group of pre-stressed bolts. The magnitude of the forces (bending, shear and normal stress) that a grip connection can carry depends on the contact pressure and the friction of the involved surfaces.

These connections generally have a higher load capacity than bearing bolt connections. Advantages of this connection detail compared to the bearing bolted connection include less stress concentrations and simple accommodation of tolerances by creating larger boreholes (the holes do not have to fit the bolt exactly).

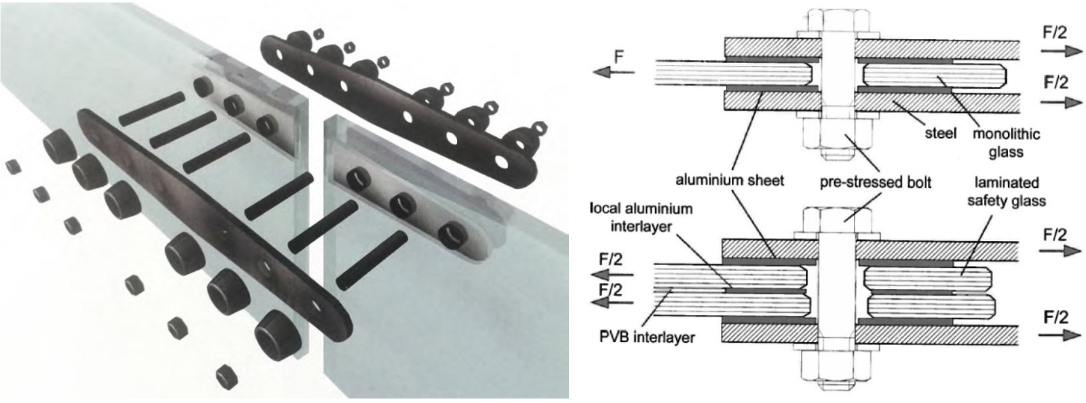


Fig. 3.17 - Friction grip connection (section and 3D) [Louter, 2016]

3.7.2 - Mechanical interlocking connections

3.7.2.1 - Bearing bolt connection

Metal fixings can be bonded to glass to provide point connections. Holes about five times the diameter of the bolt are drilled in the glass in advance - these holes are polished to remove damage from drilling. The principal concerns of this connection are the peak stresses that occur at the drilled holes, the difficulty of laminating these holes and the difficulty of tempering the holes. [White, 2007] Therefore the use of these bolted connection are not ideal for glass structures like bridges.

Fig. 3.18 - Bearing bolt connection - a “spider” [Source: http://alufabglazetech.com]

Fig. 3.19 - Contact connection

3.7.2.2 - Contact connection

Contact connections consist of point blocks or linear blocks that transfer compressive forces between the glass elements by edge pressure in the plane of the plate. An increase in the length of the block minimizes stress concentrations at the supports, but places higher demands on the smoothness of the connection detail. When the contact surface is not planar, this can lead to twisting and slipping of the fixings. Contact blocks should be placed at a distance between two and three times the glass thickness from the glass corners.

3.7.3 - Adhesive connections

Besides point and linear connections it is possible to divide adhesive connections in two different categories: hybrid linear and point connections and pure glass linear, point and surface connections.

In hybrid connections a different material is adhesively bonded to the glass to make a connection. In a pure glass connection the glass surface or edge is directly bonded with another glass element.

3.7.3.1 - Hybrid connections

An example of a hybrid connection is the use of metal inserts in the glass. Inserts of titanium or aluminium are placed and laminated between the glass panes. This way only one interlayer will break in case of failure.
This type of connection is used in for example the Apple Store in New York. The most important aspect for this connection is the thermal expansion of the material that is laminated in between the glass. This should ideally have a thermal expansion coefficient comparable to glass.

Another example of a hybrid connection is by using the steel or aluminium (lower thermal expansion coefficient) reinforcement in the glass as a connector between elements. [Oikonomopoulou, 2012]
The reinforcement is embedded in the glass element as a connector. This has two advantages: the post breakage behaviour of the construction is ductile and a slender, reversible, firm and through-the-whole-length is created. By connecting the glass panels throughout their whole length local high stress concentrations are prevented. At the same time the edges are protected by the profiles to prevent damage during transportation and assembly. [Oikonomopoulou et al., 2013]

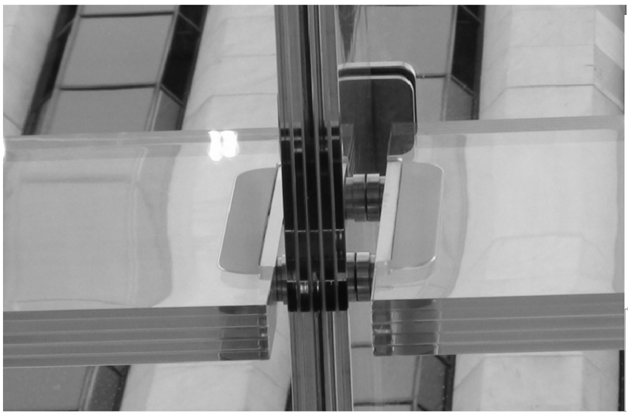


Fig. 3.20 - Insert as a connection

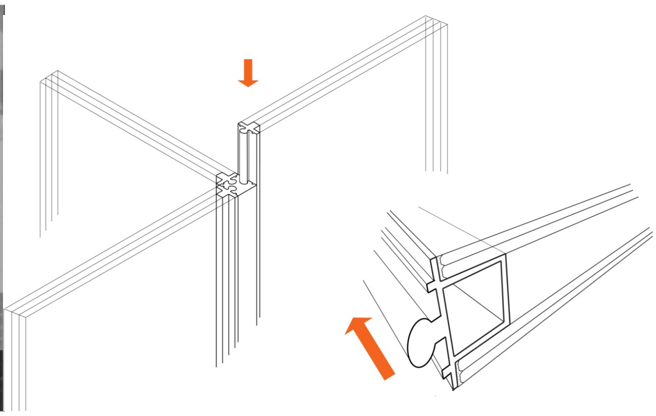


Fig. 3.21 - an innovative way of using the reinforcement profiles as connectors [Oikonomopoulou et al., 2013]

3.7.3.2 - Pure glass connections

The first pure glass connection is the use of interlayer materials to splice laminate the glass. This can result in larger structural elements than possible with conventional production methods.

The second type of pure glass connection is the large area bond. Glass-to-glass connections can be made using soft sealants and adhesives. This will result in a moment-stiff connections between materials with the same thermal expansion coefficient. Special care should be given to the kind of adhesive that is used. There are several kinds of adhesives that can be used:

- Silicone; has very low strength and stiffness, high durability against UV and moisture.
- Polyurethane; has medium strength and stiffness, less brittle than epoxies and acrylates and has low

UV resistance.

- Epoxy; has high strength and stiffness, small optimal thickness, but is brittle.
- Acrylate; has a high shear strength, small optimal thickness, but is brittle.
- Laminated glass interlayer materials; like PVB and SG (discussed in previous chapter).

It is important that the surfaces are very clean before glueing and that the surfaces match. The general process of glueing consists of the following steps [Louter, 2016]:
1. Surface pre-treatment; cleaning and degreasing and optional additional pre-treatments.
2. Adhesive preparation; mixing of the components
3. Application of the adhesive
4. Joining the substrates; thickness control is done.
5. Curing; either for 2 components in a chemical reaction, or cure to air, or UV-curing.

Figure 3.22 - adhesive pure glass connection between glass elements [Nijsse, 2004] [Louter, 2016]

3.7.4 - Drilling

Cutting glass and drilling holes in the glass will affect the strength of the glass. This leads to stress concentrations due to defects in the glass that often cannot be seen with the naked eye. [Veer, 2007] When a hole is cut in the glass, this has to be polished to remove little cracks or any other damage due to the drilling. These defects will otherwise lead to stress concentrations and ultimately failure of the glass element.

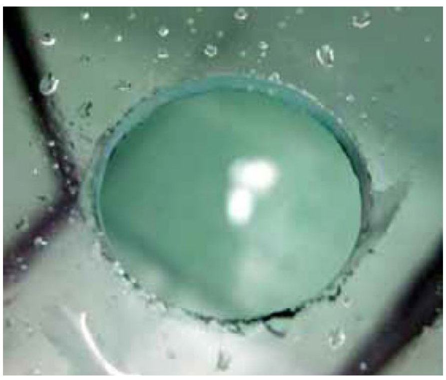


Figure 3.23 - Borehole with poor edge quality [Louter, 2016]

3.8 - Structural shapes

The purpose of this thesis is to create a hybrid bridge from glass and FRP. However, by looking at other structure types it is possible to find new methods of using glass in structures that can possibly be applied to bridge design. Glass is mostly used in structural applications as a flat element. However, it is possible to use glass in several other ways. The advantages and disadvantages of the use of these elements is discussed in this chapter.

3.8.1 - Curved glass

There are several examples of using curved glass elements for structural applications. Corrugated glass is for example used in the Museum aan de Stroom in Antwerp (figure 3.24). Corrugated panels can be used both as façades and as load carrying walls. Due to their shape they are stiffer than flat glass panels, are less likely to buckle and are more stable. A limitation of these panels is their manufacturing lengths: they cannot be produced in lengths exceeding 6 meter. [Nijsse, 2009]

Fig. 3.24 - The facade of Museum aan de Stroom in Antwerp from corrugated glass panels of 5,5 meter length [Nijsse, 2009]

Another possible application of curved glass is by using it as a shell in a double curved shape. [Pariafsai, 2016] However, the costs of these elements are very high.

Curved glass elements can be produced in a warm bending process or a cold-bending process. During the warm bending process the flat glass is placed in a mould and then heated to be formed. Subsequently it is cooled slowly either to form annealed glass or a tempered glass. After tempering the panels are laminated. A cold bending process can only be applied to tempered glass with high long-term strength. This type of glass has better visual quality and a wide variety of coatings can be used on it. Disadvantages are the permanent load-bearing stresses that are created in the curved glass elements and the fact that only single-curved elements can be created. [Pariafsai, 2016]

In general the limitations of curved glass elements are the high manufacturing costs and the tolerance related difficulties encountered in the production of laminated curved elements.

3.8.2 - Faceted shell

To avoid the high costs of producing double curved shapes in glass it is also possible to create a faceted double curved shell in glass. This type of shell carries the load via membrane stresses in the facets and distributed shear along the edges. The forces in the connections of a faceted shell are, however, higher than in a smooth shell. [Pariafsai, 2016]

Fig. 3.25 - Faceted double curved structure [Pariafsai, 2016]

3.8.3 - Glass brick

Glass can also be melted in the form of bricks. These bricks can be used in structures in a similar way as regular bricks. An example can be found in the design of the Glass Masonry Bridge in Delft (see chapter 4 - precedent research). Another example is the construction of a Chanel store in Amsterdam by MVRDV (figure 3.26).

Fig. 3.26 - Glass bricks in the facade of a Chanel store in Amsterdam by MVRDV [Scagliola, D & Brakkee, 2016]

Glass bricks are glued together in this design leaving minimal tolerances for errors in the manufacturing of the bricks and the assembly. The design results in a self-supporting glass masonry wall system, consisting of annealed soda-lime solid glass blocks bonded together by a UV-curing, colourless adhesive. The bricks are fully loaded in compression: the strength of glass. [Oikonomopoulou et al., 2014]

3.8.4 - Glass column

The column seems a very suitable to be built from glass due to the high compressive strength of glass. There are several glass column types developed: tubular columns, stacked columns and hollow square columns.
The tube is one of the best shapes for a structural glass column. The advantages of the tubular glass column are:

- It does not buckle due to its high buckling strength compared to its compressive strength.
- A tubular column is more transparent than a stacked column.
- The risk of de-lamination is low, due to the shorter exposed length of the interlayer.

Disadvantages of the tubular glass column are the high probability of local stresses due to distortions at the ends of the tubes and connecting these columns to external structures. [Pariafsai, 2016]

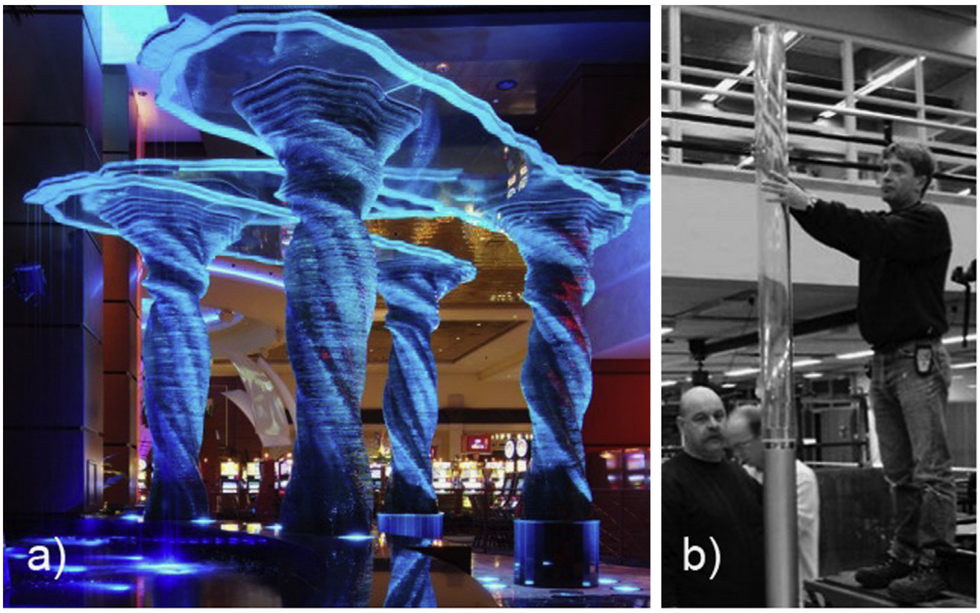


Fig. 3.27 - Two types of glass columns: a. stacked columns and b. glass tubular column [Pariafsai, 2016]

3.9 - Conclusion

Glass shows linear-elastic, isotropic behaviour and exhibits brittle failure. Since glass is not able to redistribute stresses by means of plastic deformation, it is highly sensitive to stress concentration. The strength of glass is not a material constant, but depends on various parameters. Generally glass is very stiff, brittle, has high compressive strength and low tensile bending strength.

Three types of glass can be distinguished: annealed glass, fully tempered glass and heat-strengthened glass. Heat strengthened glass can keep its loading capacities after breaking and is therefore the most ideal type of glass to use as structural glazing. The calculation value for the tensile strength is 40MPa.

Structural glass is laminated with an interlayer in between to minimize the probability of glass failure. The strongest interlayer is the SentryGlas interlayer: this interlayer is 5 times stronger and 100 times more rigid than a PVB interlayer. To minimize the consequences of glass failure and ensure high post-breakage strength, the glass can be reinforced with steel or FRP to achieve ductile post-breakage behaviour. By reinforcing the glass with FRP more transparency can be achieved than with a steel reinforcement.

Glass sheets with lengths up to 12 meter can be produced - with high costs. Therefore it is can have larger lengths when being splice laminated. This raises the costs of glass significantly and complicates transportation of glass elements.

The most sensible choice is to either use adhesive connections or a connection to the reinforcement of glass. A drilled hole will damage the glass and will cause peak stresses - this has to be evaded.

Besides flat structural glass elements there are several other structural shapes being used: double curved glass elements, corrugated glass elements, glass bricks and glass columns.
Curved glass elements are stiffer and less likely to buckle than flat glass elements. The limitations of curved glass are the costs and the tolerance related difficulties encountered in the production of laminated curved elements.

3.10 - Comparison glass & FRP

After performing a research into both FRP and glass it is possible to compare these materials: a focus will be on the largest differences and similarities between the materials. This comparison can lead to insights of how to combine these materials in a bridge design. Their strengths and weaknesses can lead to possibilities or situations to evade. The insights can be translated to several design guidelines, that are summarized at the end of this chapter.
This comparison will be structured as the previous material research chapters, starting with a comparison of the general material properties.

3.10.1 - General material properties

FRP is a composite material while glass is a homogeneous material (on macro level). This means that FRP is a very designable (moldable) material. Its composition can consist of a wide variety of materials, while this is more limited in glass composition. This also means a wider variety of mechanical properties for FRP depending on the desired design. Special care for the composition of FRP is therefore necessary, while this is less important for glass (still glass composition should be assessed).
FRP is an anisotropic material, meaning it can best distribute forces in one direction. Glass is an isotropic material where the forces are distributed in both directions. This major difference can be softened by designing the FRP material to be quasi-isotropic.
FRP generally has higher tensile strength than glass. However, glass has higher compressive strength than FRP materials. The maximum tensile strength of heat strengthened glass is 70 MPa while quasi-isotropic GFRP has a tensile strength in the range 180-280 MPa. [Rasheed, 2015] The compressive strength of glass can be in the range 360-420 MPa [Bos, 2009] while FRP has a compressive strength of about 55% of the tensile strength, thus in the range 99-154 MPa. [Rasheed, 2015]
Also, the E-modulus of FRP is much lower than the E-modulus of glass. This means that glass is a stiffer material than FRP. For comparison: heat strengthened glass has an E-modulus of 70 GPa while quasi-isotropic GFRP has an E-modulus of 14-21 GPa. It is, however, possible to compose a FRP material with an E-modulus in the range 100-140 GPa (unidirectional CFRP), but this material has very limited application.
Finally, the big difference between glass and FRP is the transparency: glass is generally fully transparent, while FRP is non-transparent. This transparency should be used as an aesthetic feature in glass bridge designs, while in FRP bridge designs transparency plays no role.

The materials also have some common features: both materials have a high corrosion resistance and oxidation resistance. This means they are both very suitable in certain 'harsh' environments. It also makes these materials very durable, because they do not degrade much over time.
Furthermore they both show linear elastic brittle material behaviour: glass as a ceramic while FRP is mainly brittle along the fibre direction.
This brittleness also has an effect on the importance of safety for both materials. For glass this means the application of several safety concepts to make the material safe to use structurally like lamination, reinforcement, anti-slip and heat-treatment. For FRP this used to mean over-dimensioning and conservative safety factors and nowadays it means the addition of coatings and better care for the composition of the FRP material.
Special care has to be taken in regards to the fire safety of both materials. Both FRP and structural glass are sensitive to heat. Additives and coatings can be applied to FRP materials to enhance the fire safety. To enhance the fire safety in glass, coatings can also be applied.
Lastly, both materials have a relatively low thermal expansion coefficient. For comparison: quasi-isotropic GFRP has a thermal expansion coefficient of 6 $\times 10^{-6}$/C, while this value for heat strengthened glass is 5,4 $\times 10^{-6}$/C. [Bos, 2009] [Rasheed, 2015]

3.10.2 - Production methods

While FRP is partially made from raw materials that are quite unsustainable (polymers, carbon), glass is made from a very sustainable material source: sand. Glass can also be recycled by remelting the glass elements. This is not possible with the thermoset resins used for FRP materials.
Both materials are very durable though, due to their corrosion, oxidation and chemical resistance. Both materials do have to be loaded in the right way to reach a very long lifespan.

FRP is made with several production processes using either moulds or a pultrusion process while the production of structural glass is almost completely limited to one type of float glass production. The difference between glass types is made in the thermal treatment after the glass production, which results in different breaking behaviour of the glass. So while FRP has a wide choice of production processes depending on project demands, glass only has a choice in three types of thermal treatment after production.
This also has its influence on the possible sizes of structural elements. Glass structural elements are limited to about 12 meter, while FRP elements can theoretically have unlimited sizes (depending on the exact production process). The costs of glass elements of this size (12m) will be very high, resulting in an acceptable maximum size of 10 meter when considering costs.

3.10.3 - Assembly methods

Due to the brittleness of both glass and FRP it is not sensible to use a mechanical (bolted) joint. For glass this means drilling, which will cause peak stresses possibly resulting in cracking of the glass. For FRP there will also be an occurrence of peak stresses causing a non-ideal fracture pattern which will eventually lead to failure.
Bonded joints are the best choice in both FRP and glass assembly, due to the even distribution of forces over the bonded area. However, replacement of parts is more difficult in this type of connection.
Another possibility which works for structural elements in both materials is the use of interlocking connections. In glass this means the connections with the reinforcement of the glass, while in FRP it means the use of pultruded interlocking components. This type of connection has as disadvantages limited structural abilities and very small tolerances.

3.10.4 - Structural shapes

Both FRP and structural glass are new materials in the building industry. FRP was first used as a copy of conventional structural materials like steel. This resulted in non-material adapted and mostly over-dimensioned designs in FRP. Glass was already treated differently from the beginning of its use in the building industry. Its fragility and more limited production methods resulted in a limitation to flat elements.
New structural (material adapted) shapes are being developed and built in both materials. For FRP this results in double curved shapes like the monocoque and the shell which have better structural behaviour. The moldability and designability of the material is an important factor in this development. It also resulted in several optimized designs for FRP bridge decks. These decks have very high strength and low weight (compared to conventional structural materials).
For glass this development resulted in single curved shapes (like the corrugated glass panels) and structural glass beams, columns and bricks. However, the glass beams, columns and bricks are made with a different type of production process, that is not yet fully optimized. For now this causes tolerance related problems for the finished structural elements. Further optimization of the production process is necessary before these new structural shapes can freely be used in structural designs.

3.11 - Design guidelines FRP & glass

The previous comparison can be translated to several design guidelines, considering the design of a hybrid FRP and structural glass bridge. These design guidelines will lead to several preliminary bridge designs in chapter 6.

1. The FRP material composition and production method should be designed to meet the specific concept to have the most optimized mechanical properties.
2. Safety should be addressed in this bridge design: glass should have a safety concept based on redundancy (lamination), reinforcement of the glass (ductile post-breakage behaviour), heat-treatment (elevated strength) and an anti-slip layer should be added. Safety in FRP should be incorporated in its composition: additives, coatings and material choice.
3. The anisotropic (quasi-isotropic) behaviour of FRP and isotropic behaviour of structural glass should be optimally combined in the bridge design.
4. In a bridge design, FRP should resist the most tensile strength, while glass resists the most compressive strength.
5. Structural glass should be used to stiffen the bridge design, due to the higher E-modulus of glass compared to FRP.
6. The transparency of glass should be used in a bridge design, as this is the most important aesthetic feature of glass.
7. The hybrid bridge can be placed in a “harsh” environment or on a location where durability is important as both FRP and glass are very durable materials.
8. Tolerances in connections between glass and FRP can be relatively small, due to a comparable thermal expansion coefficient.
9. The most sustainable bridge design should be made from glass and GFRP.
10. Large elements (>10m) in a bridge design should be made from FRP, while smaller elements (<10m) should be made from either glass or FRP.
11. Mechanical (bolted) joints should not be used in a FRP and glass bridge design.
12. Either bonded joints or interlocking connections should be used in the bridge design.
13. The most efficient bridge structure should be made with material adapted shapes: for FRP this means the monocoque, shell structures or pultruded bridge decks. For glass this means single curved glass panels, glass columns, glass bricks and glass beams.
14. The bridge should be designed with flat glass elements, due to high costs, the lack of precision and the difficulty of connecting to external structures of other structural shapes in glass.

4 | Precedent research

Fig. 4.1 - The Pontresina bridge gets assembled - transportation by helicopter [Source: fiberline.com]

4.1 - Introduction

A combination of FRP and glass in a bridge design has not yet been implemented. However, many bridges from both glass or FRP have been designed in the past few decades. Several of these precedents will be analysed in this chapter to answer the research question:

> *What precedents (structural glass and FRP) have been built and what are their structural characteristics?*

The bridges will be analysed in means of structural design - the joining method, type of fibres/type of glass, production method and assembly - and in terms of safety and sustainability. The biggest advantages and disadvantages of these designs are finally summarized.
From the conclusions of this precedent research several design guidelines can be drawn for the creation of an optimal hybrid bridge design.

4.2 - All-FRP bridges - Pontresina Bridge

This pedestrian bridge has been built in 2001 in Switzerland to cross the Flaz River. In spring the bridge is disassembled due to possible damage of gravel and stones being carried with the flowing water.
The most important requirements for this bridge were:

- It should be lightweight, because the bridge has to be disassembled in a short time period.
- It should be durable in the harsh and cold environment. The corrosion resistance of FRP was therefore another important factor.

The bridge has a span of 25 meter and is placed on pre-cast concrete foundations.

Fig. 4.1 - View on the Pontresina bridge in winter [Keller et al., 2015]

4.2.1 - Structural design

The bridge - with a weight of 3300 kg and a load capacity of 500 kg/ m^2 - consists of two lateral multilayer trusses, connected by cross beams and stabilized by a wind bracing truss, of both 12,5 meter: one part is glued and the other part has bolted connections. In the middle of the river the parts are supported by a concrete foundation. The deck is made of a pultruded GFRP grated floor, which is installed on the cross beams.
The material safety factor used in the structural calculation of this bridge is 1,8. After inspecting the

bridge after a 17 years of service in the cold, harsh and wet environment in Switzerland it is expected that the bridge will not reach a critical situation for another 45 years. However, there were some signs of degradation of the FRP material:

- Fibre blooming on the top surfaces exposed to high UV irradiation had increased dramatically.
- The strength of the bridge's GFRP profiles was significantly affected by combined freeze thaw cycles and UV radiation. This resulted in increased humidity ingress. The structural safety was not affected, due to the conservative design values of 1996.
- Some cracks had formed in the small area adhesive bonds of the bridge. The large area bonds were not affected. The design of small area adhesive bonds is therefore more critical than the design of large area bonds since stress concentrations in the former may be much higher.

Fig. 4.2 - Close-up on the bolted connections of the trusses of the Pontresina bridge [Keller et al., 2015]

4.2.2 - Joining method

The bridge uses two types of connections: bolted and adhesive connections. The joints in one of the spans are bolted, while the joints in the other span are adhesively bonded using a two-component epoxy adhesive. The bonded surfaces are quite small: 100x160 mm^2. Therefore backup bolts were inserted. Adhesive connections were not used in any bridge design before this bridge was built.
All connections were prefabricated in a workshop to ensure the quality and to reduce costs.

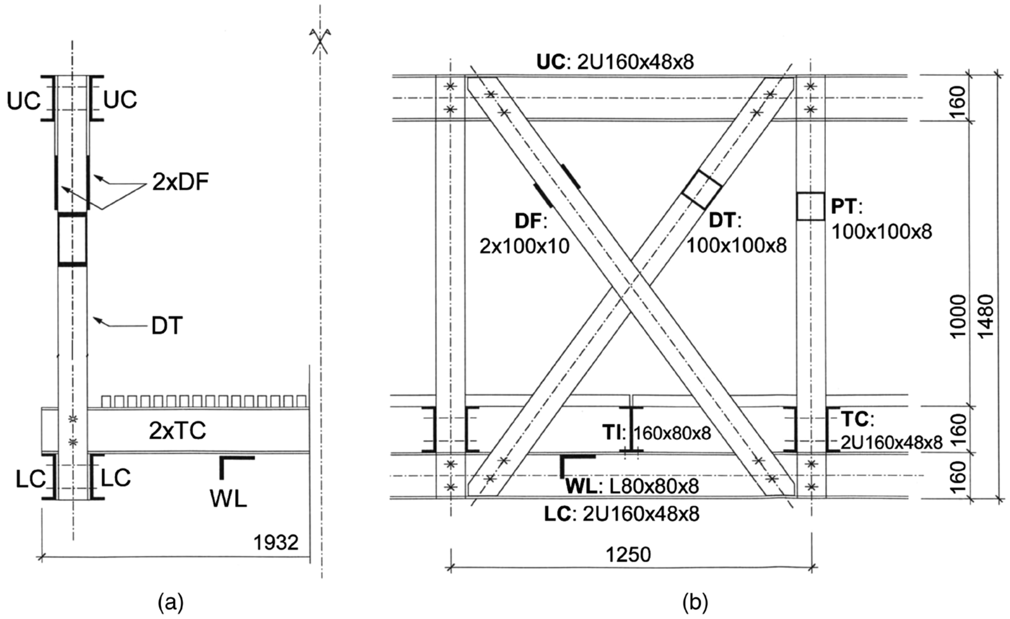


Fig. 4.3 - Technical drawings with detailing of the Pontresina bridge. [Keller et al., 2015]

4.2.3 - Fibres, production & assembly

The entire bridge is built with pultruded profiles made of E-glassfibres embedded into an isophtalic polyester resin. The fibres are arranged as UD-rovings in the centre and in one or two outer combined mats. These mats are composed of chopped strand mats and fibres in the transverse and longitudinal direction which are stitched together.
The fibre volume fraction is approximately 50% of which 70% are rovings and 30% combined mats. A polyester veil covers the outer mats.

The bridge was assembled in a factory in two parts. After assembly the two parts were transported to the remote site by helicopter. On site the two elements were placed on the foundation and connected to each other. Every spring the bridge is disassembled due to high water carrying harmful stones and gravel.

4.2.4 - Advantages & disadvantages

This bridge is a very early FRP bridge design. It is not a material adapted design as the profiles are clearly mimicked from steel profile design (and highly overdimensioned).
The bridge shows the durability of the material - being more than 15 years old - and the durability of an adhesive connection. The degradation of the material proves, however, that coatings are needed for FRP bridges in harsh environments. Without coating or additives in the material the strength of the profiles will be affected by moisture ingression and UV-radiation. When building an optimized bridge in FRP materials (not overdimensioned) the absence of coatings or additives would most likely have resulted in collapse of the bridge.
It also shows the ease of installing an FRP bridge. The lightweight parts can be transported by helicopter to a remote area.

4.3 - All-FRP bridges - Paradis bridge

This is a, still to be build, FRP pedestrian bridge in Norway designed by Royal Haskoning in 2015. The length of the bridge, spanning a road and a tram route, is 42 meter in a single span. The bridge is designed as an alternative for a steel truss bridge. The requirements stated by the Norwegian client were that the bridge should be maintenance free, it should be quick to install (<72 hours), it should be a single span bridge and it should be easy to transport and easy to build on site. All these requirements pointed towards the use of FRP.
Further demands on the durability of the bridge and thus the durability of the FRP elements were to minimise the number of connections and minimise the ingress of water or dirt.

Fig. 4.4 - Close-up on the bolted connections of the trusses of the Pontresina bridge [Haskoning, 2015]

4.3.1 - Structural design

The bridge is designed as a truss, with several diagonal members to provide stability and to support the deck. At the top of the bridges' trusses a bracing frame provides stability and minimises shear forces. A large hollow continuous beam spanning from one side to the other, supports the deck with the help of several stays.
The deck is made of the two continuous beams with profiles in between as shown in figure 4.6. The bridge follows the CUR96 and EuroComp design codes for FRP. It also uses some conversion factors for a wet environment.

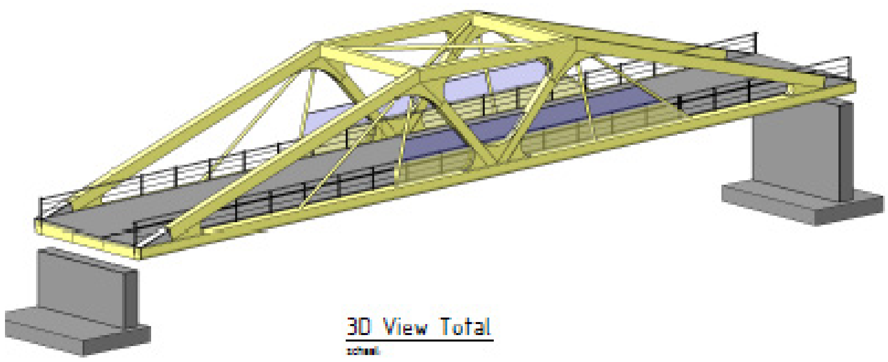


Fig. 4.5 - Overview of the structure of the bridge. In yellow the FRP members, in grey the bridge deck and concrete pylons. [Haskoning, 2015]

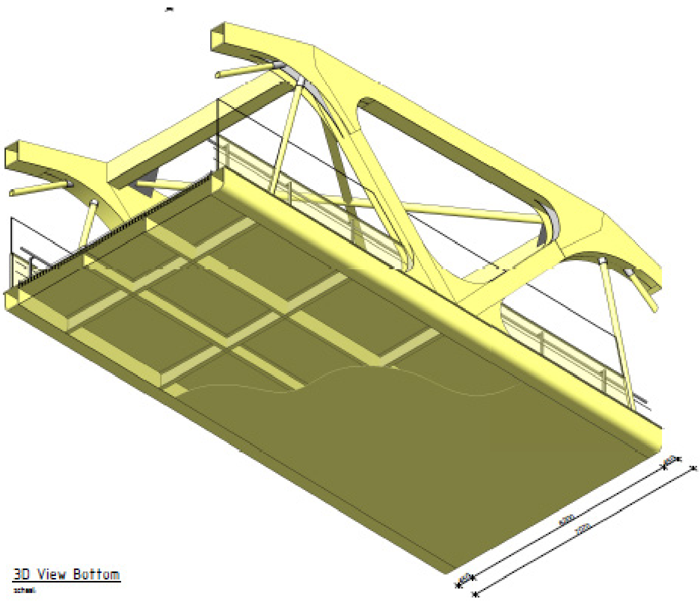
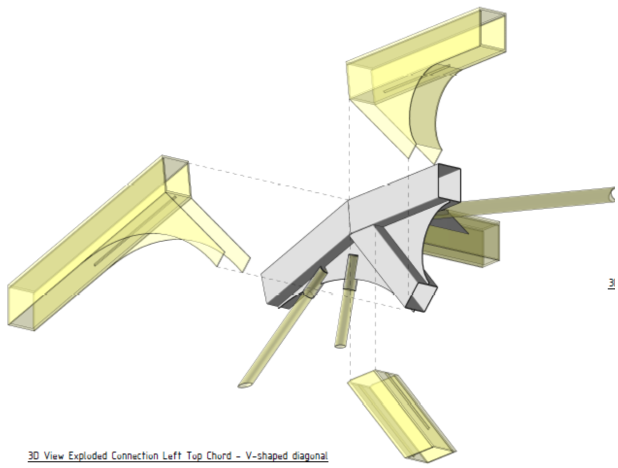


Fig. 4.6 - 3D view showing the structure and dimensions of the bridge deck. [Haskoning, 2015]

4.3.2 - Joining methods

The connections of the main beams at both ends of the bridge are clamped to prevent buckling of the bridge. These connections are made with steel inserts for easier assembly. (Figure 4.7)
The connections at the upper beams and the diagonals are also made with steel inserts. The connection between the profiles of the deck are a hybrid connection - both bolted and glued. The rest of the deck is made from laminated connections.



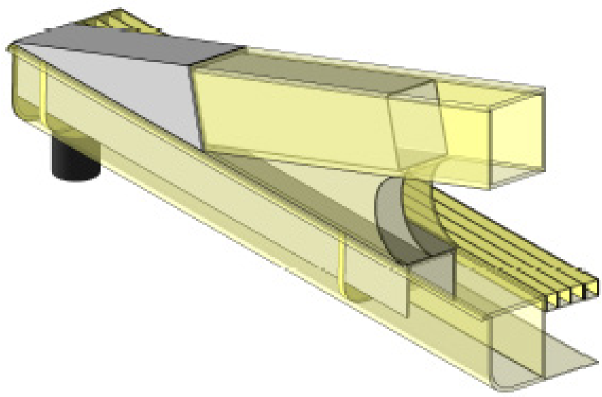


Fig. 4.7 - 3D view of the connections at the bridge deck with its steel insert (upper picture) and the connections at the top of the bridges' truss with steel inserts for easier assembly. [Haskoning, 2015]

4.3.3 - Fibres, production & assembly

The bridge is fully made from glass-fibre reinforced polymers. An important reason to do this are the costs of these fibres - they are the cheapest type of fibres.

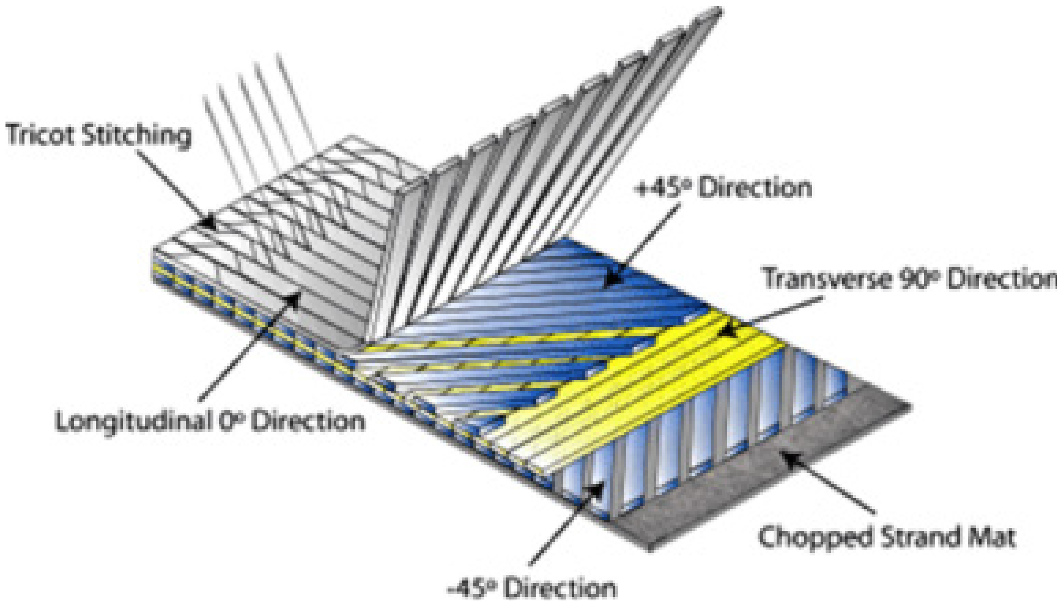


Fig. 4.8 - 3D view showing the structure of the FRP material. [Haskoning, 2015]

The fibres are placed as shown in figure 4.8. A chopped strand mat with fibres in a 45° direction on top followed by fibres in subsequently the transverse direction, another 45° direction and fibres in the longitudinal direction. This results in a quasi-isotropic behaviour of the FRP elements.

Most parts of the bridge have been made using vacuum infusion. Vacuum infusion ensures the quality of the pieces in the wet and cold environment of Norway. Durability was one of the most important demands for the design of this bridge. Several smaller beams (for the deck) have been pultruded.

4.3.4 - Advantages & disadvantages

The bridge is designed to be a cheap, stable, maintenance free, and lightweight pedestrian bridge in a very wet climate. These requirements are easier met when building in FRP than in traditional materials like steel. Steel is heavier, requires more maintenance and is thus in the end more expensive. Steel which is capable of resisting the wet Norwegian environment is more expensive.
The truss design displays, however, a lot of similarities to traditional steel design. Steel is also still used to connect the most important connections of the bridge for easier assembly. This design is therefore not yet fully material adapted.

4.4 - All-FRP bridges - Aberfeldy bridge

This cable-stayed pedestrian bridge in Aberfeldy, Scotland is built in 1992 to cross the river Tay. It has a length of 113 meter and a width of 2,23 meter. It was the very first large span all-composite bridge in the world and is probably still the longest span in the world.
It is designed for golfers on foot to cross, but has been strengthened in some areas (where the stress concentrations were highest) with CFRP to allow golf "buggies" to cross.

Fig. 4.9 - View of the Aberfeldy bridge in Aberfeldy, Scotland. [Source: http://happypontist.blogspot.nl/2012/07/scottish-bridges-23-aberfeldy.html]

4.4.1 - Structural design

The Aberfeldy bridge is a cable-stayed bridge with a main span of 63 meter and two back spans. Two towers with a height of 17,5 meter - with pylons meeting each other at the top - support the deck. The towers weigh only 1,25 tonnes each and were brought to the site by road, then bonded together, pinned to the foundation and then rotated to their final position.
The deck consists of 600mm wide ACCS panels (see figure 4.10) stiffened by edge beams and cross beams. This bridge is one of the oldest all-FRP bridges in the world. In its 20 years of service the deck had to be strengthened with GFRP pultruded plates due to cracking caused by overloading.
It managed to withstand hurricane winds, snowfall and flooding above the bridges' deck level without any damage - the structural performance of the bridge is not affected.
The cable system might be not stiff enough. Even at a gentle walking pass the bridge will develop a highly noticeable bounce. The cables are under low tension, which is due to the low mass of the bridge. [Potyrala, 2011]

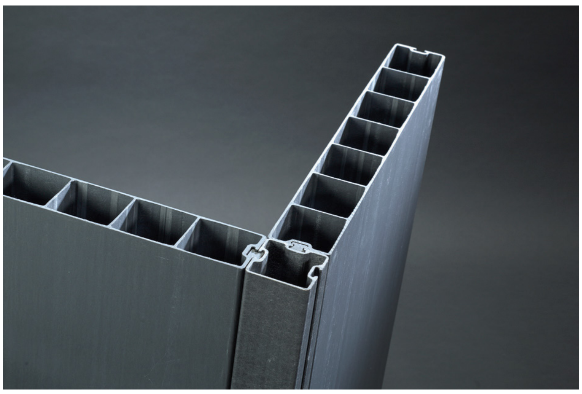


Fig. 4.10 - ACCS panel from Composolite used for the bridge deck [Strongwell, 2016]

4.4.2 - Connections

The bridge deck consists of ACCS panels, which are connected to each other by an interlocking profile which slides into the groove of the panels. The rest of the connections are a mix of bonded and mechanical connections. Most of the bridges' profiles are bonded in a daily cycle of preparation, trial assembly and then bonding.

Fig. 4.11 - Close-up of the deck and pylon of the Aberfeldy bridge. [Source: http://compositesandarchitecture.com/?p=2398]

4.4.3 - Fibres, production & assembly

The bridges' deck and the towers are made out of GFRP with E-glass fibres in an isophaltic polyester resin matrix. The structural elements of the deck and the ACCS panels for the deck are all pultruded and especially the GFRP profiles mimic conventional material shapes.
The cables are made from Parafil cables, which are Kevlar aramid fibres sheeted in an extruded protective low-density polyethylene coat (see figure 4.12). [Potyrala, 2011]
The GFRP pultruded profiles of the bridge were assembled on site, due to which the deck was finished in two weeks. The pylons of the central towers were also brought to site, then bonded and pinned to the foundation and ultimately rotated to their final position. This was possible without the use of a crane due to the low weight of the towers.
The GFRP cross beams were assembled on site, attached to the cables and then held in position across the river with temporary wires. This was then used as a framework to pull the entire deck in place. After completion of the main span the side spans were assembled and the cross beams of the deck were lowered into slots in the deck structure. Ultimately, the bridge was finished by adding handrails and removing temporary cables used for erection.

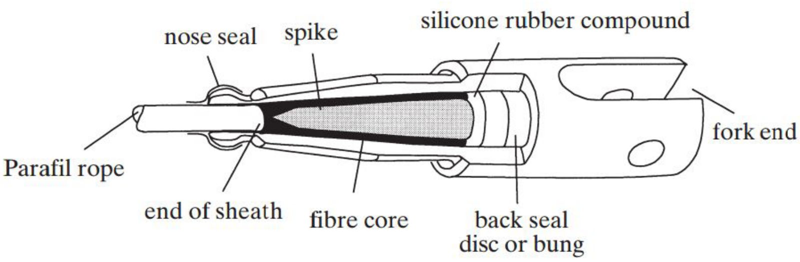


Fig. 4.12 - Close-up of the Parafil cables [http://linearcomposites.net/?pageid=Parafil.xml]

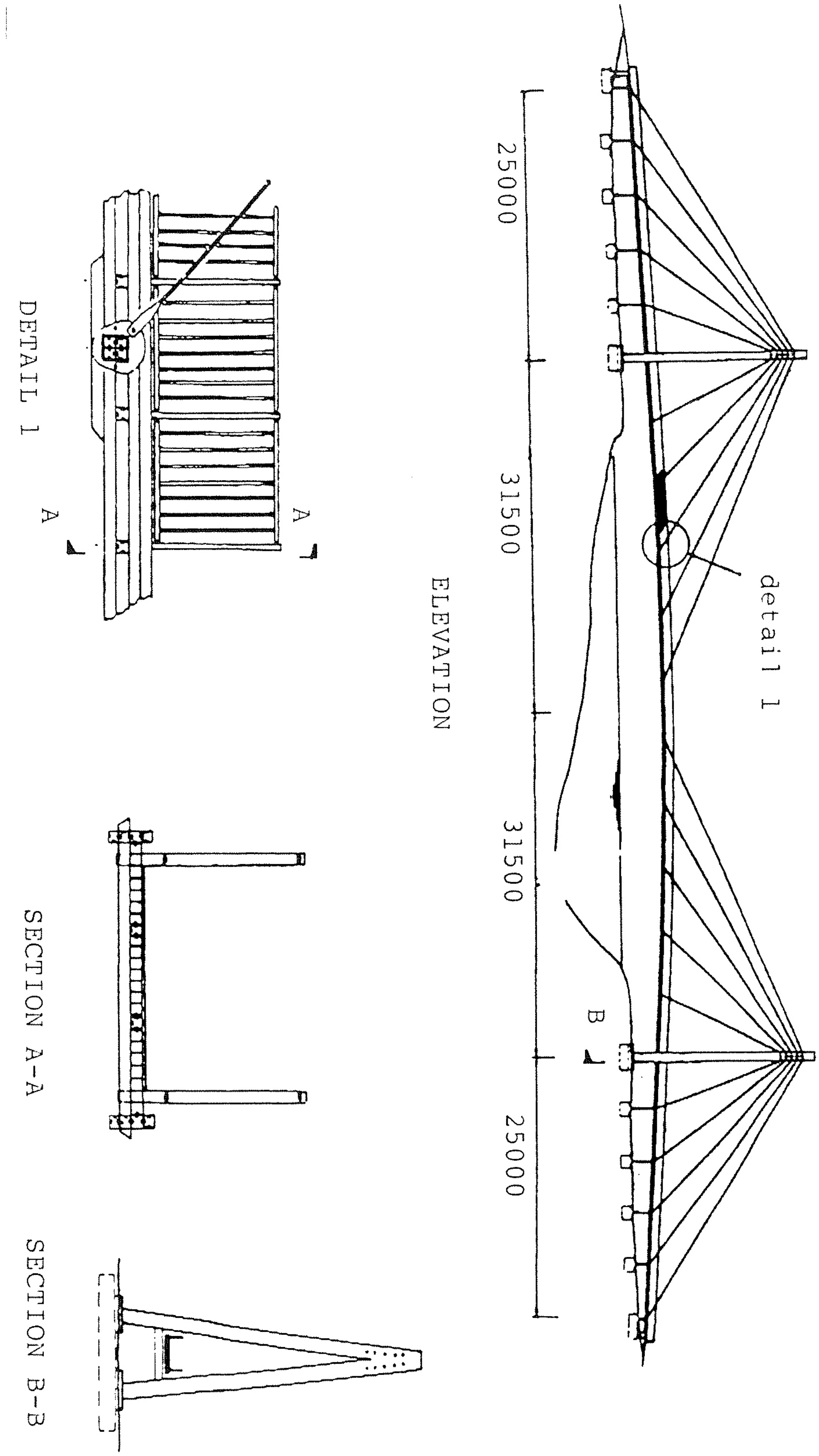


Fig. 4.13 - Technical drawings of the Aberfeldy bridge [Source: http://compositesandarchitecture.com/?p=2398]

4.4.4 - Advantages & disadvantages

The lightweight construction of this bridge was a huge advantage during the construction phase. A short construction time and low construction cost were the result. However, the low weight also poses the biggest disadvantage of the bridge: the cables are under low tension causing the bridge to bounce under a very low load. It is therefore important to assess vibrations on the bridge.
After 20 years of service the structural performance did not decline much. Only the secondary elements like the parapet show cracks due to leaving too little room for movement during construction - this bridge is very durable.

4.5 - FRP hybrid - Lleida Footbridge

This arched footbridge was built in Lleida, Spain in 2001 to cross a road, a railway and a high-speed railway. The most important requirements for this bridge were minimum maintenance, easy and quick erection and no electromagnetic interference with the railways.

Fig. 4.13 - View of the Lleida footbridge in Lleida, Spain. [Source: http://www.wikiwand.com/en/GFRP_Lleida_Pedestrian_Bridge]

4.5.1 - Structural design

The bridge consists of two parallel double-tied arches with a maximum height of 6,2 meter and a width of 3 meter and a total span of 38 meter. The arches are made from two U profiles of 300x90x15 mm joined with glued flat plates to form a beam tube. The hangers that connect to the deck are I-profiles of 160x80x8 mm.
To provide stability diagonal members are constructed along the arches. These diagonal members are square tubes of 100 mm size. The arches are inclined to 6º for aesthetic reasons and forked outwards at both ends to reduce deformation due to wind pressure. Finally, the deck is made of transverse I-beams of 200x100x10 mm every 0,6 meter.

The bridge is designed for an uniform load of 4 kN/m^2 according to Spanish Bridge Design Code. Safety factors for material properties to verify the Ultimate Limit States were: 2 for normal stresses and 3 for shear stresses.

To avoid fractures in the tubes of the arches, some of the joints were filled with mortar. The diagonal elements were sometimes filled with PVC blocks for the same reason.

Fig. 4.14 - One half of the arches being painted and constructed. [Source: fiberline.dk]

Fig. 4.15 - View on the deck of the Lleida footbridge showing the diagonal and cross beams. [Source: fiberline.dk]

4.5.2 - Connections

All connections were bolted using stainless steel brackets and bolts. However, an epoxy adhesive was also used at the beam joints.

4.5.3 - Fibres, production & assembly

Only continuous E-glass fibres combined with woven and complex mats with a minimum fibre content of 50% were used for the structural members. These structural members were produced in a pultrusion process. The large elements were produced in a factory in Denmark and transported to the building site.

Due to the total weight of the bridge - which was only 19 tons - it was possible to install the bridge in only 3 hours. First the reinforced concrete ramps were installed, then the construction of temporary columns next to the ramps was completed to allow lifting of the FRP structure. Thirdly, the deck was assembled after which the vertical elements and the arches were assembled. To finish the bridge, the profiles were painted and the temporary columns were demolished.
The assembly of the bridge was very simple due to the low weight of the bridge and because of the possibility to use simple hand tools.

4.5.4 - Advantages & disadvantages

The use of two profiles that are bonded together with a plate to form a hollow arch profile seems to be unpractical. It would be easier to use one pultruded profile.
The added mortar or PVC blocks are also an addition which should not have to be necessary. The fact that at some joints it was impossible to fill the profiles with either mortar or PVC does not strengthen this design choice.
The assembly of the bridge took only 3 hours due to the low weight, however, the largest profiles had to be imported from Denmark. This significantly adds to the transportation and environmental costs.

4.6 - Glass hybrid - Suspended Bridge in China

This glass bridge with a steel primary structure is built to give visitors a spectacular view of the environment. The bridge is located in the Province Zhangjiajie and connects two mountaintops. It opened in 2016 and spans 430 meters on a height of 300 meters above ground.

Fig. 4.16 - View of the suspended glass bottomed bridge in China [Source: http://edition.cnn.com/travel/article/china-zhangjiajie-glass-bridge-closed/index.html]

4.6.1 - Structural design

The bridge is suspended from two towers on both ends of the bridge, with steel cables. The steel cables are attached to steel beams which form the base of this bridge. Glass plates are placed on the steel beams to create a view into the canyon.
The glass type is most likely heat-strengthened when the breaking pattern in figure 4.17 is taken into account.

4.6.2 - Connections

The glass plates are adhesively bonded to the steel substructure. The glass panes have a bonded surface of about 15 cm all along the edges.

Fig. 4.17 - Destruction of the laminated glass panels with sledgehammers to demonstrate the safety of the bridge [Source: https://www.thestar.com/news/world/2016/08/03/china-opens-terrifying-tianmen-mountain-glass-walkway.html]

Fig. 4.18 - Driving a car over the bridge to demonstrate the safety of the structural glass. [Source: https://www.thestar.com/news/world/2016/08/03/china-opens-terrifying-tianmen-mountain-glass-walkway.html]

4.6.3 - Safety

This bridge will carry 8000 people each day, due to which safety is an important issue.
The most important safety issue for this bridge is the psychological safety: most people do not trust the safety of this bridge. Therefore several tests have been executed to prove the safety of the glass bridge. The glass panes were destroyed with hammers, but did not fail. A car was driven over the bridge to show how much weight the bridge could take and the bridge did not fail either. This gave people a bit more trust in the safety of the bridge. (Figure 4.18).

4.6.4 - Advantages & disadvantages

This bridge is a real architectural statement to show how beautiful glass can be in a bridge design. However, the glass does not have any real structural function besides allowing people to walk over it. This project can be seen as a showcase to give people trust in the capabilities of structural glass. It also gives a spectacular view over the valley.

4.7 - All glass bridges - Glass footbridge in Rotterdam

This small bridge was built in 1995 to connect two buildings in Rotterdam and was designed by Kraaijvanger Urbis in collaboration with ABT. It has a span of 3,2 meter and is located on the first floor of the buildings. The all-glass structure forms a large contrast with the adjoining buildings.

Fig. 4.23 - View of the glass footbridge in Rotterdam. [Kraaijvanger, 1998]

4.7.1 - Structural design

The bridge can be divided in a structural part and a “raincoat”. The raincoat is an independent structure, consisting of the walls and the roof. The structural part consists of the glass floor supported by two glass beams. These glass beams have a curved shape based on the bending moment diagram to provide the most strength on the right place.
The bridge is protected from the outside by three large glass panes connected to the bridge deck. In order to maintain the structural independent behaviour, the floor and walls were connected by a cable, which

does not transfer internal moments or shear forces.

4.7.2 - Connections

The glass panels are connected to each other and to the buildings with standard steel glass fixing pieces. The connections are point-fixed as illustrated below:

Fig. 4.24 - Point fixed detail of the connection between the roof panel and side panel [Kraaijvanger, 1998]

The glass plates are anchored to the buildings with special laser cut stainless steel plates.
The connection between the glass beams and the glass floor is by means of a structural silicone. [Nijsse, 2003]

4.7.3 - Safety

The glass used is 10mm laminated safety glass of three layers with PVB interlayer for the beams. The floor panels and the side and top glass panels are made of two layers of 10mm laminated safety glass. The glass is not reinforced with steel or any other material.

The bridge was vandalized with a street tile once, showing that the safety concept of multiple layers works: the outer layer was cracked, but the bridge remained intact.
However, reinforcement is missing in this bridge design, making the bridge more dangerous when a glass element breaks: the post-breakage strength is much lower.
There is also no sacrificial top layer of glass on this bridge, therefore breaking a glass panel would mean the replacement of that entire element.

4.7.4 - Advantages & disadvantages

This glass bridge has many disadvantages in the used type of glass, used connections and used interlayer due to proceeded knowledge. However, it shows the beauty of a full transparent bridge design. It is also a proof that it is possible to make a bridge of glass.

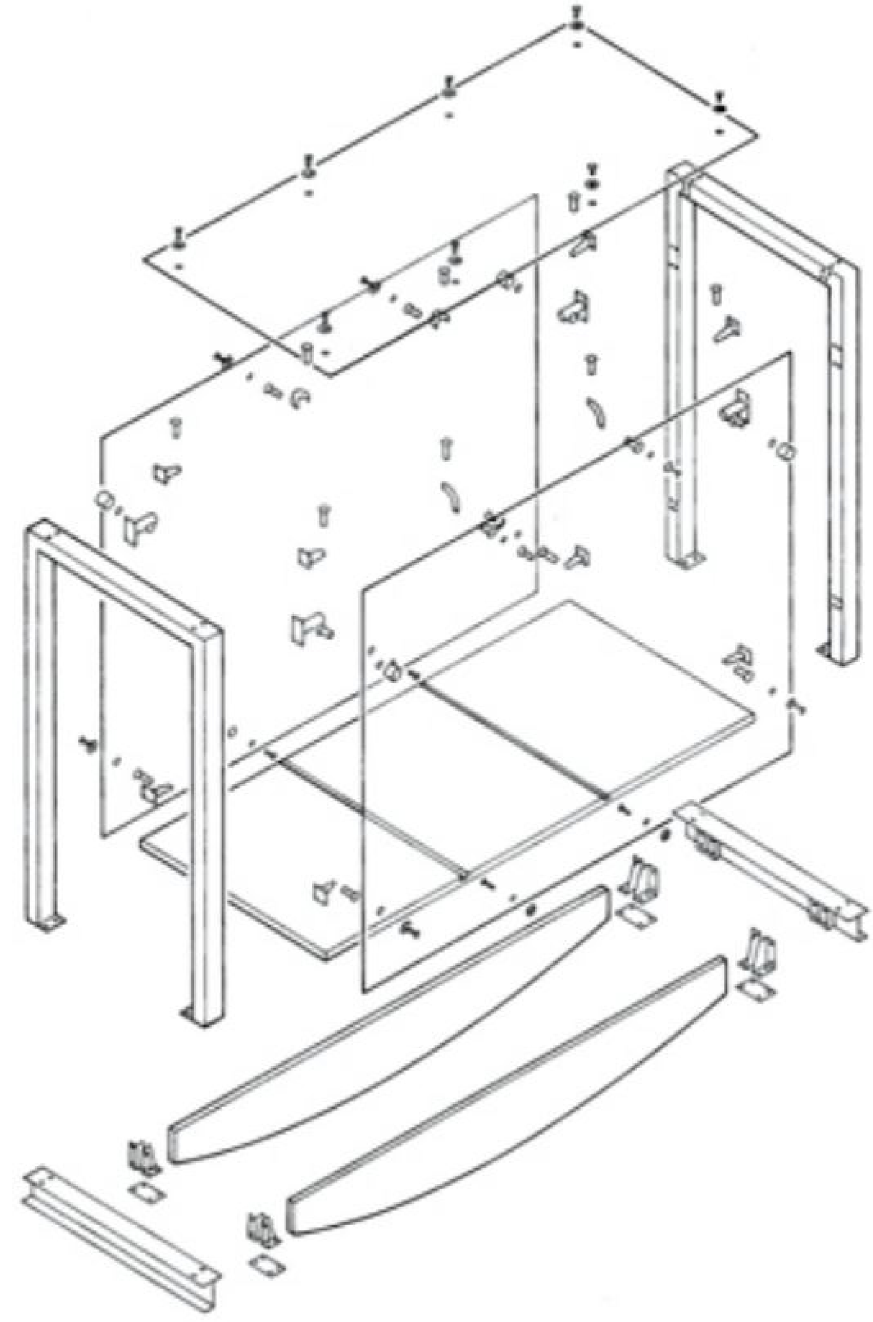


Fig. 4.25 - Axonometric view of the structural elements and connections for the glass footbridge in Rotterdam. [Kraaijvanger, 1998]

4.8 - All glass bridges - Glass lobby bridge

To complete the look of a hotel in Toronto, Halcrow Yolles designed a glass bridge spanning 9 meter across the lobby on the mezzanine level. This bridge was built in 2010.

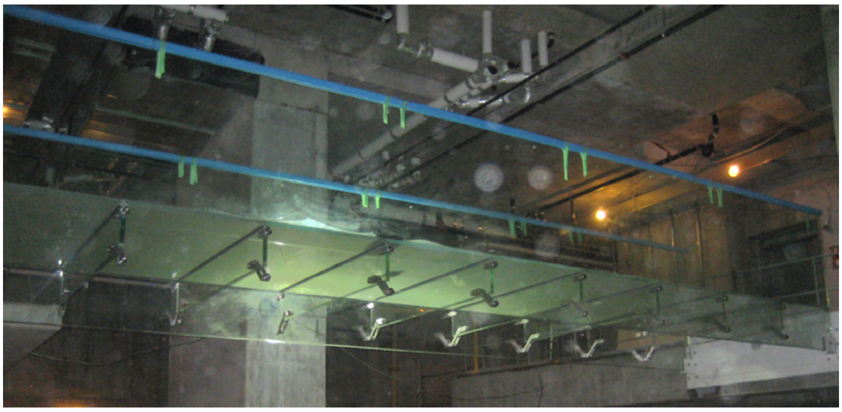


Fig. 4.26 - View of the glass bridge in the lobby of a hotel in Toronto, spanning 9 meters ending in a steel platform of 0,5 meters on both ends. [Krynski et al., 2012]

4.8.1 - Structural design

The structure consists of two main beams, which are at the same time the balustrades. Cross beams, in which the glass floor panels are secured, span between them.
In the original design, the balustrade was splice laminated and consisted of three separate parts. This was done due to the limited production sizes of glass. However, during the project the availability of larger sizes grew and beams of around 9 meter were possible to produce. By reducing the original span from 10m to 9m, the balustrades could be produced in one piece. This resulted in a more transparent bridge with less connections. The gap due to the 1 meter reduction of the span was filled with steel platforms. [Wittenberg and Krynski, 2012]

4.8.2 - Connections

Stainless steel brackets connect the main- and cross beams (see figure 4.27) The amount of steel was minimized by doing a FEM analysis on the bridge. The transparency was maximized by doing this analysis.

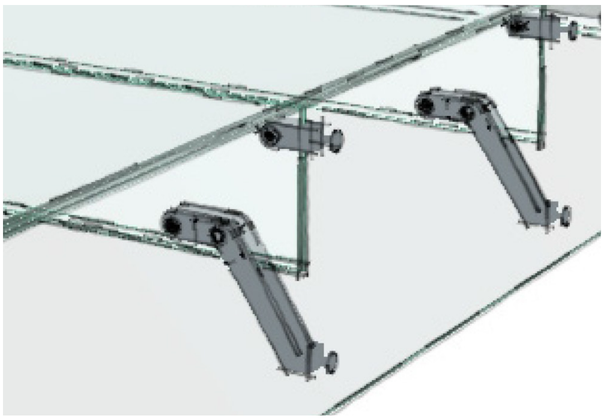


Fig. 4.27 - Connecting brackets between the main beam and the cross beams. The amount of steel was minimized due to FEM analysis. [Krynski et al., 2012]

4.8.3 - Safety

This bridge is made of heat-treated glass: both fully tempered glass and heat-strengthened glass is used. Fully tempered is used on the exterior layers, while heat-strengthened glass is used for the remaining layers.
The safety concept of the bridge is based on the application of laminated glass. All elements consist of three layers of glass with PVB interlayers in between. The exterior and exposed layers are fully tempered to increase the impact resistance. The remaining layers are heat-strengthened to ensure adequate post-breakage rigidity.

4.8.4 - Advantages & disadvantages

The bridges' load-bearing structure is very simple, consisting of two main beams that at the same time function as parapet. Therefore the bridge is very transparent and not so many connections have to be made, which would weaken the glass.
However, the connections that are made in the glass are point fixed. Point fixed connections have the disadvantages of peak stresses at the weaker, drilled holes in the glass.

4.9 - All glass bridges - Movable Glass Bridge

This bridge is designed as a thesis in 2015 to show the structural potential of glass as a movable bridge. It spans 10,35 over the Rijn-Schiekanaal in Delft and is openable.

Fig. 4.19 - Rendered view of the movable glass bridge in Delft at the location of the Koepoortbrug. [Monasadat, 2015]

4.9.1 - Structural design

This bridge is a hydraulic folding bridge of glass beams and glass plates. It consists of two separate lanes each with two longitudinal beams, shaped to the bending moment diagram, which support the deck. The beams are highest in the middle where the bending moment is maximal.
Secondary beams in lateral direction strengthen the construction in the other direction in a grid of 1,25 x 3 meter.
A sacrificial glass pane with a thickness of 0,01 meter is glued to the three glass panes with PVB interlayer

of the glass panels. This panel can be easily replaced when broken without affecting the structural performance of the bridge deck.

4.9.2 - Connections

The main beams in the longitudinal direction and the secondary beams in lateral direction are connected by sliding the metal bars of the secondary beams inside the connection blocks on the main beams (figure 4.20).

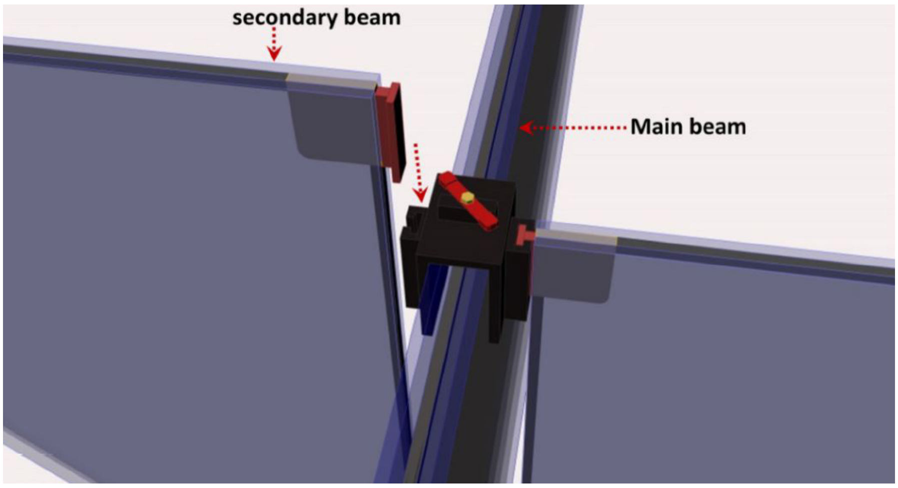


Fig. 4.20 - Detail of the connection between main beams and secondary lateral beams.

The bottom of the secondary beams is also connected to the main beams with the connection in figure 4.21.

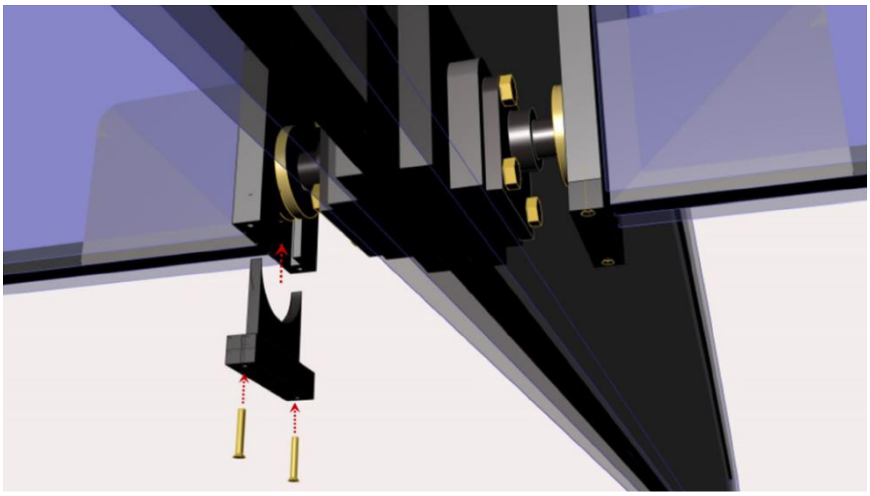


Fig. 4.21 - Connection at the bottom of the main beams and secondary lateral beams.

These connections are all made with inserts in the glass.
The glass plates of the bridges' deck are connected to the beams by inserting a rectangular metal plate in the middle layer of the glass panel of the deck. A propeller-like connector is used to fix the bridge deck to

the main beams (figure 4.22).

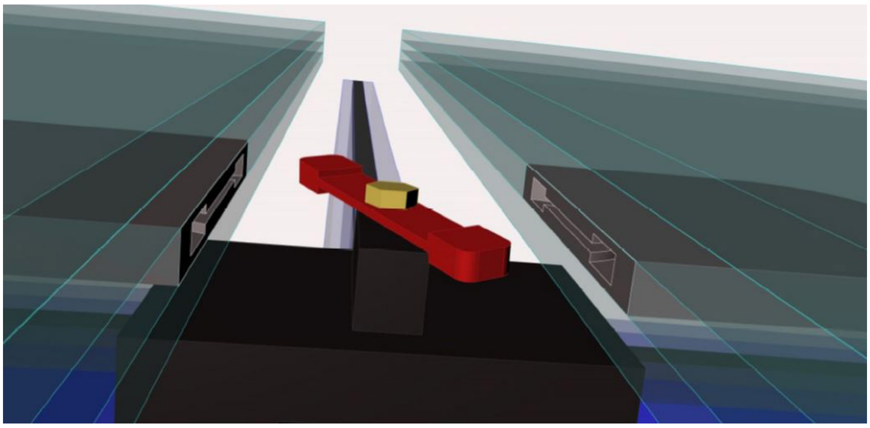


Fig. 4.22 - Propeller like connection to fix the bridge deck panels to the main beams.

4.9.3 - Safety

The type of glass used for this bridge is heat-strengthened glass, due to its breaking behaviour. The glass panels consist of three layers of laminated glass with a PolyVinylButyl (PVB) interlayer in between.
A safety factor of 2 has been considered for the calculations of this glass bridge. Several other safety factors like psychological safety and slipping have been taken into account: the glass is partially opaque for people to feel safer on the glass and the top layer of the deck is a sandblasted anti-slip glass pane.

4.9.4 - Advantages & disadvantages

The bridge uses many different and complicated connections consisting of small moving parts. There is a risk of wearing for these parts and thus regular maintenance and high costs.
High costs are also a very probable disadvantage of this glass bridge. The large custom made glass panes and connections are not mass production and might therefore be very expensive.
The span of this all-glass bridge is 10,35 meter, which is not a lot due to the limitations of glass.

4.10 - All glass bridges - Glass masonry bridge

The idea of the Glass Masonry Bridge was born to pave the way for glass as a new structural material for bridges. It is sustainable (made from sand, infinitely recyclable) and durable (does not corrode, rust or rot). However, people do not yet trust in the strength of glass. A bridge is the best way to demonstrate the material's load-bearing capacity and safety.

The glass masonry bridge will be built as main entrance of the Green Village in Delft. It will span 14 meters and is an initiative from the TU Delft in collaboration with Royal Haskoning.
The idea was born to pave the way for glass as a new construction material for bridges. Glass is sustainable as it is made from sand which is infinitely recyclable and it is durable as it does not corrode, rust or rot.
Glass is however not yet trusted as structural material. A bridge is the best way to show the material's load-bearing capacity and safety. [Smits, 2015]

Fig. 4.23 - Rendered view of the glass masonry bridge in the Green Village in Delft.

4.10.1 - Structural design

The design is based on a brick arch, spanning 14 meter in total. The height difference in the middle will be 700 mm. The thickness of the glass bricks will be around 350mm and the width of the bridge will be 2,2 meter.
The forces in the bridge are transferred by compressive normal forces through the thickness of the bridges' glass material.

Fig. 4.24 - Rendered view showing the glass bricks.

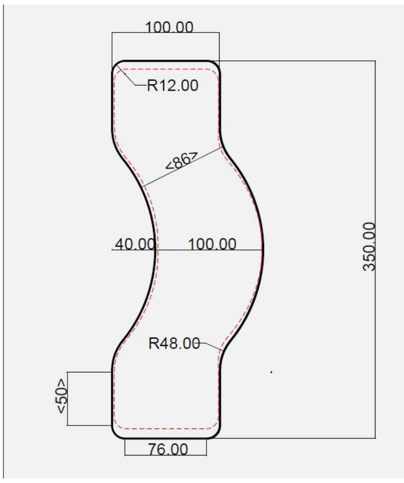


Fig. 4.25 - Technical drawing of the optimized glass "belly" brick shape with dimensions. [Sombroek, 2016]

4.10.2 - Connections

The bricks are dry assembled and do not have an interlayer to be connected for easy disassembly and recycling. The shape of the brick is shown in figure 4.25.

4.11 - Conclusion & comparison FRP & glass

FRP bridges are often built in wet and 'harsh' environments. This is due to their high corrosion and oxidation resistance. These bridges are very durable in these climates - even after 17 years of service in these climates they have not lost their structural capabilities. It is best to use vacuum infusion as production method to ensure the quality of FRP. This production method is the most precise. When coatings are applied these FRP bridges in harsh environments will have an even longer lifespan.
Glass bridges also have a high corrosion and oxidation resistance and have not declined much in their service years, resulting in a high durability. Glass bridge are however much more susceptible to damage due to their brittleness. Safety concepts should minimize the risk of failure due to damage. The safety concept of redundancy through lamination has resulted in several cases in the remaining of the structural load-bearing capabilities of an all-glass bridge after severe damaging of the glass.

For both materials it is important that the built bridges are tested and analysed to prove their strength and durability. This can give people more trust in the capabilities of these "new" materials. There are practical examples for glass bridges where the usefulness of safety concepts is proven: damage does not lead to failure of the structure.

Both glass bridges and FRP bridges have high initial costs. However, both materials are very durable so ultimately the total costs of the bridge are less high. The cheapest variant of FRP is GFRP: most bridges are therefore made from this material.

Connection types in FRP bridges that have been tested on durability include bonded and mechanical connections. Both types of connections prove to have endured and kept their structural capabilities in all of the analysed precedents.
Connection types in built all-glass bridge are mainly bolted connections. These connections have proven their durability, but are not structurally ideal: stress concentrations can occur in these connections. The capacity of other bonding methods will probably be larger.

FRP bridges are also often used in remote areas where transportation and assembly is complicated. The low density of FRP makes it easy to handle and transport structural elements of this material.
Glass bridges are not particularly used in remote areas, due to the higher weight and fragility of the material during transport.

FRP is a material with a low density, resulting in a high susceptibility to vibrations. This is especially noticeable in FRP cable stayed bridges with a very long span. These cables can be made from aramid fibres which have a very high shock resistance. Glass bridges are much heavier and therefore do not have this disadvantage. A hybrid bridge would therefore solve the problem of vibrations for the lightweight FRP material.

The most FRP bridge designs are still based on designs in conventional materials like steel, concrete and aluminium, while glass in bridges is mostly combined with conventional materials. Glass is then used as a purely aesthetic feature: the transparency can give people a spectacular view.

Bridges that do have glass as a primary load-bearing structure have very short spans. The span of these (theoretical) designs does not exceed 21 meter. This is due to the production method limitations and the structural (safety) limitations of glass. When larger glass elements would be used this can result in more transparency and more structural unity in a bridge design.
The all-glass bridges with short span do show how well the safety concepts in glass work in practice. The safety concept of redundancy through lamination resulted in several cases in the remaining of the structural capabilities of an all-glass bridge. FRP bridges have been built with much longer spans, even exceeding 100 meter.

4.11.1 - Design guidelines

These bridges show the advantages and disadvantages of using either glass or FRP in a bridge design. These advantages and disadvantages can be caught in several design guidelines. For both materials these design guidelines are as follows:

1. FRP can be used in places where quick and easy assembly/disassembly is necessary, due to its low weight.
2. FRP can be used in places where transportation is an issue, due to its low weight.
3. The used structural adhesive should be properly designed to withstand a harsh environment (if applicable) and keep its structural capabilities.
4. FRP can be used in areas with harsh environments, due to its high corrosion resistance (when coated).
5. To achieve the highest quality of FRP products vacuum infusion should be used as production method.
6. FRP can be used when low maintenance requirements are necessary (when vacuum infusion is used as production technique for high quality of the product).
7. Psychology should be assessed when building bridges with a large span and/or a large height.
8. Safety concepts (like lamination) in glass should be applied due to possible damage (and collapse when no safety concept is applied) of the glass bridge.
9. To achieve the highest transparency it is necessary to produce larger glass elements up to 10 meters (even 12 meters for much higher costs).
10. When creating new types of glass forms (for example glass bricks) new safety concepts, production methods, forms, etc. should be developed.
11. Vibration should be assessed when designing a FRP bridge with very long span (exceeding 100m).
12. Aramid cables can be used to build lightweight cable-stayed bridges.

5 | Hybrid systems

Fig. 5.0 - Testing the GFRP reinforced beam [Louter, 2011]

5.1 - Introduction

In a hybrid system one material cooperates with another material. The function of one material complements the function of the other material. In other words:

> *"The advantages of the hybrid structural systems include the cost effectiveness and the ability to optimize the structure based on the material properties of each constituent material." (Kitane et al, 2004)*

In the design of a hybrid construction you strive therefore for an optimized collaboration of two materials in a material adapted design. This hybrid structural design can come in a larger scale - an entire bridge - or a smaller scale - only one structural component being hybrid.
This chapter will focus on both concepts, trying to filter the most important advantages and disadvantages of these structural systems. The research question of this chapter is therefore:

> *"What hybrid systems in FRP and glass exist and what are their advantages and disadvantages?"*

The conclusions will be filtered into a set of design guidelines that can be used for the preliminary design variants in chapter 6.

5.2 - Structural glass beam with FRP reinforcement (Louter, 2010)

This beam with glass-fibre reinforcement developed by Louter (2010) is an addition to the ongoing research on metal reinforced glass beams. Some beam specimens were tested in a four point bending test and a pull-out test.
In the four point bending test the beams were placed in a frame where the displacement was measured after being exposed to a certain load.
In the pull-out test the specimen was placed in steel brackets. The lower bracket was moved upwards, while the upper bracket was fixed. [Louter, 2010]

Fig. 5.1 - Test specimen of the structural glass beam with rounded glass fibre rods embedded in the glass sheets [Louter, 2010]

5.2.1 - Materials

The materials used are glass-fibre rods - flat or round, laminated structural glass and a SentryGlas interlayer. The round glass-fibre rods consist of E-glass fibre filaments with a polyester matrix. The flat glass-fibre rods consist of S-glass fibre filaments with an epoxy matrix.

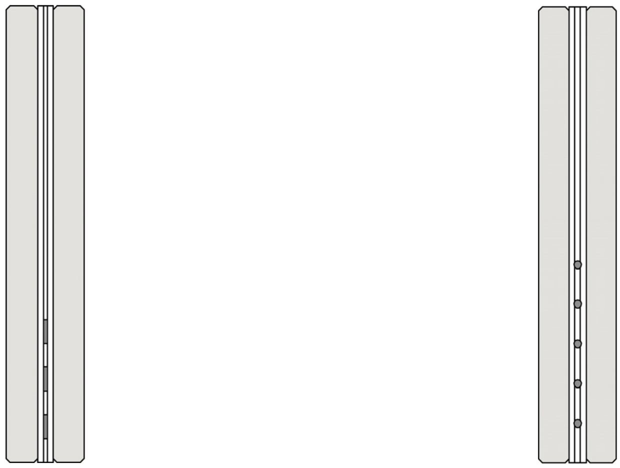


Fig. 5.2 - Two types of glass fibre rods: flat and round [Louter, 2010]

5.2.2 - Structural design

The beam consists of two layers of annealed structural glass with three layers of SentryGlas (SG) interlayer in between. Embedded in the middle interlayer sheet are the glass fibre rods, which consist of glass fibre filaments embedded in a polymer matrix. Due to the high flow characteristics of the SG interlayer, any differences in thickness between the rods and the SG have been levelled during heating at the lamination process.

Two beam designs were tested: one beam had 5 round glass fibre rods embedded in the interlayer, the other beam had 3 flat glass fibre rods embedded in the interlayer.

The round glass fibre rods with a diameter of 2mm, consist of E-glass fibres embedded in a polyester matrix. The flat glass fibre rods with dimensions of 0.8 x 6 mm, consist of S-glass fibres embedded in an epoxy matrix. [Louter, 2010]

5.2.3 - Production process

The rods have been kept in place by the middle SG interlayer during the lamination process of the beam. This lamination process included heating and bonding the glass layers to the three SG interlayers with the glass fibre rods in between (figure 5.2).

5.2.4 - Connection

The connection between the structural glass and the FRP rods is an adhesive connection. The SG interlayer is the adhesive in this case.

More research has to be done concerning the bonding between SG and both types of glass fibre rods.

5.2.5 - Advantages & disadvantages

Besides the advantages of a reinforced glass beam where the safety is enhanced, due to better post-breakage behaviour, this beam has some extra advantages:

- The semi-transparent appearance of the glass fibre rods enlarges the overall transparency of the beam.
- The high tensile strength (compared to traditional materials) results in less material use, which further enhances the transparency of the beam.

A disadvantage of this beam design is:

- The brittle failure behaviour of the FRP reinforcement. This caused the flat FRP rods to detach from the glass laminate during testing.

5.3 - Structural glass beam with FRP reinforcement (2)

There are several other similar hybrid systems like the previous one, which have also been tested. An example is the beam with the section shown in figure 5.3. This beam has been reinforced on the outside of the beam instead of the inside.

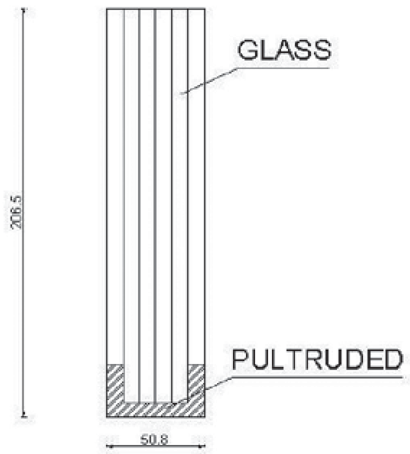


Fig. 5.3 - Section of glass beam of 6 layers with pultruded FRP profile in the tensile zone. [Speranzini et al., 2011]

5.3.1 - Materials

The structural glass used for this beam is annealed float glass. The sheets are bonded together by a two-component epoxy resin with excellent mechanical and chemical properties and optical qualities.
The pultruded GFRP profile was bonded to the glass beam by the same epoxy resin.

5.3.2 - Structural design

This beam consists of six layers of structural float glass with a GFRP pultruded U-profile with dimensions 50,8x6x26 mm, glued to the glass.
The outer glass layers rest on the 'wings' of the pultruded profile. The total dimensions of the cross section of the beam are 50,8x206,5 mm.

Fig. 5.4 - Bending test with structural glass beam. [Speranzini et al., 2011]

5.3.3 - Production process

The glass beams were provided by a single producer and subjected to the same working and handling. The lamination has been done after thoroughly cleaning the surface of the glass.

5.3.4 - Connection

The connection between glass sheets and the GFRP profile is glued by means of an two-component epoxy resin with excellent mechanical and chemical properties and optical qualities.

5.3.5 - Advantages & disadvantages

This glass beam has, in comparison to the previous FRP reinforced glass beam, a less transparent appearance. The edges of the beam, however, are better protected than in this beam design.

5.3.6 - Similar beam designs

Some other beams have been designed with the same idea of reinforcing glass with a form of fibre reinforced polymers.

1. Structural glass sheets bonded together with a GFRP interlayer. [Speranzini & Neri, 2011] This results in a translucent and very heavy beam.

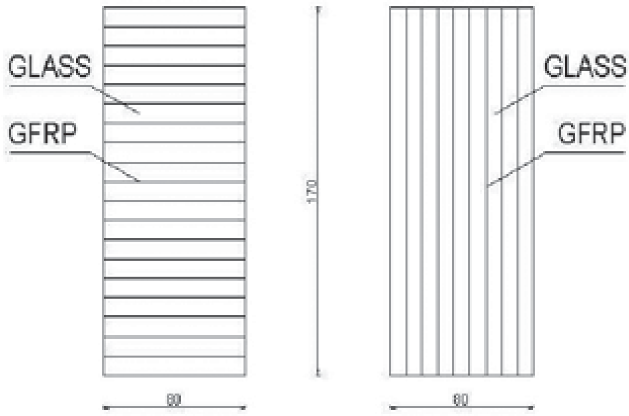


Fig. 5.5 - Section of glass beam with GFRP interlayers [Speranzini et al., 2011]

Fig. 5.6 - This results in a translucent beam [Speranzini et al., 2011]

2. Structural glass with a Steel Reinforced Polymer (SRP) strip in the tensile zone of the glass beam. [Speranzini, & Agnetti, 2014]

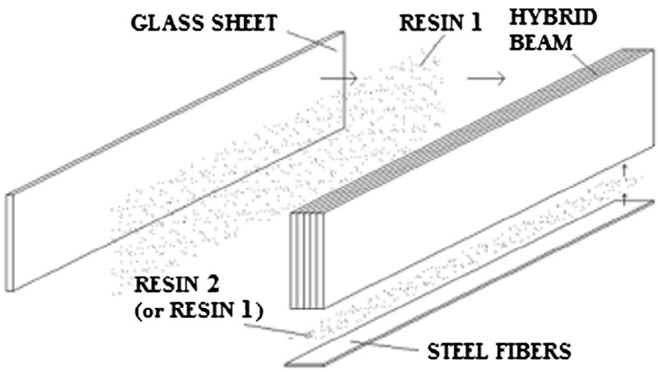


Fig. 5.7 - Schematic drawing of glass sheets bonded with resin and steel fibres adhesively bonded with the same resin to the bottom of the beam. [Speranzini et al., 2014]

3. Structural glass beam with a carbon fibre strip in the tensile zone of the glass beam. [Palumbo & Mazzucchelli, 2005]

5.4 - Glare FRP panel with aluminium elements

This type of panel is developed by the TU Delft for the aerospace industry to achieve weight reduction and improved damage tolerance.

5.4.1 - Materials

The Glare sandwich panels consist of thin aluminium sheets bonded to glass fibre reinforced polymer layers.

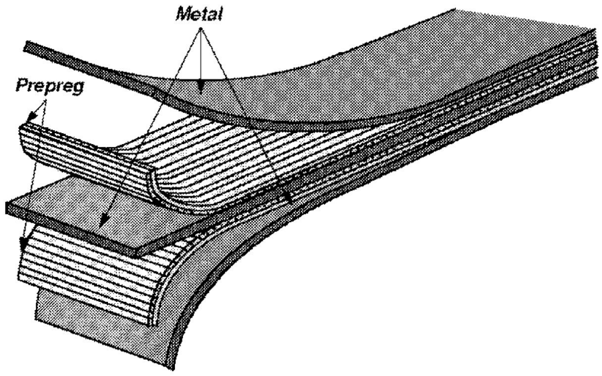


Fig. 5.8 - Schematic view of the layers in a Glare FRP panel

5.4.2 - Structural design

The GFRP and aluminium layers are splice laminated together. This way larger panels can be produced than in conventional aluminium structures and it reduces assembly costs (figure 5.9).
The glass fibres in a Glare panel can be placed in a few different ways - each manner is a different grade. All are based on unidirectional glass fibres embedded with epoxy adhesive in prepregs with a fibre volume fraction of 60%. These prepregs are placed in different fibre orientation which results in different grades and different mechanical properties.
The prepreg fibres protect the inner aluminium sheets against corrosion, while the aluminium sheets protect the fibre reinforced polymer layers from picking up moisture. [Gunnink, 2000]

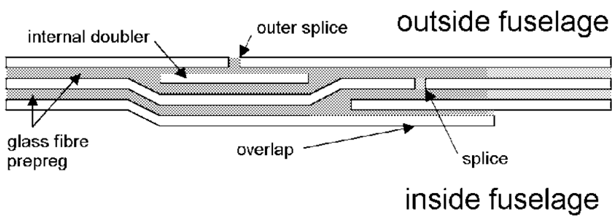


Fig. 5.9 - Splice lamination of the Glare panels with overlap

5.4.3 - Production process

The Glare panels can be produced as semi-finished sheet material or as a complete structure - large curved panels with co-cured doublers and stiffening elements. To make these complete structures an autoclave is used.
According to Botelho et al. (2007) the production of these composite components involves in general these five activities:

1. Preparation of tools and materials. The aluminium layer is pre-treated with chromic or phosphoric acid to remove the bond between the adhesive system and the aluminium alloy.
2. Material deposition, including cutting, lay-up and debunking.
3. Cure preparation and vacuum bag preparation and in some cases tool cleaning and part transferring.
4. Curing, including the flow-consolidation process, chemical curing and the bond between metal and fibre.
5. Inspection by means of ultrasound, X-ray, visual techniques and mechanical tests.

5.4.4 - Connection

The connection between aluminium and FRP is made with a rubber toughened epoxy adhesive.

5.4.5 - Advantages & disadvantages

The Glare panel has several advantages when compared to traditional or conventional materials in the aerospace industry:

- Large panel sizes are possible due to the splice laminating technique.
- The panel has excellent fatigue, impact and damage tolerance.
- The panel uses the FRP layers as a barrier against corrosion of the inner metallic sheets, while the metal protects the fibre from picking up moisture.
- The laminate has very high burn-through resistance as well as good damping and insulation properties.

Disadvantages of this panel are mainly the costs: the panel can be 5 to 10 times more expensive than aluminium alloys per kilogram. [Botelho, 2006]

5.5 - Concrete filled FRP

This hybrid FRP and concrete deck follows on previous developed hybrid FRP and concrete construction systems for bridges. In these previous systems the high potential for hybrid constructions of FRP-concrete where each material is optimally used, is shown: FRP being loaded in tension and concrete in compression. This bridge deck tries to eliminate disadvantages like buckling of hollow FRP sections, brittle system behaviour, insufficient interface capacity to provide full composite action between FRP and concrete and a manufacturing process that is too complicated for practical applications. [Keller et al, 2006]

5.5.1 - Materials

The bridge deck is a sandwich structure consisting of three layers: FRP composites for the tension skin, lightweight concrete as core material and ultra high performance fibre reinforced concrete (UHPFRC) for the compression skin.

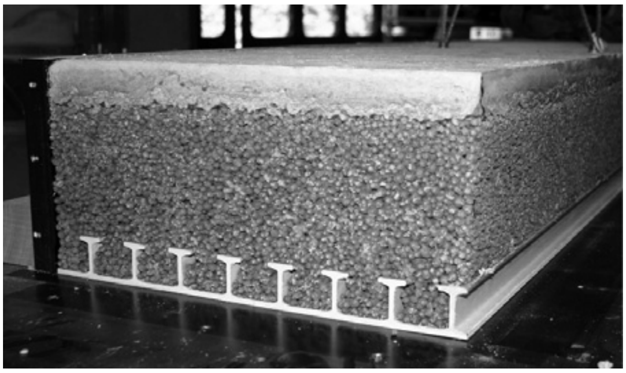


Fig. 5.10 - Sandwich element of pultruded FRP profile, lightweight concrete as core and UHPFRC concrete as compression skin. [Keller et al., 2006]

5.5.2 - Structural design

The FRP layer consists of a 5 mm thick sheet with several T-profiles. The lightweight concrete layer of about 130mm is poured over this FRP sheet. The 30 - 50mm UHPFRC layer is subsequently poured over the lightweight concrete layer. This UHPFRC layer carries local bending moments due to concentrated wheel loads.

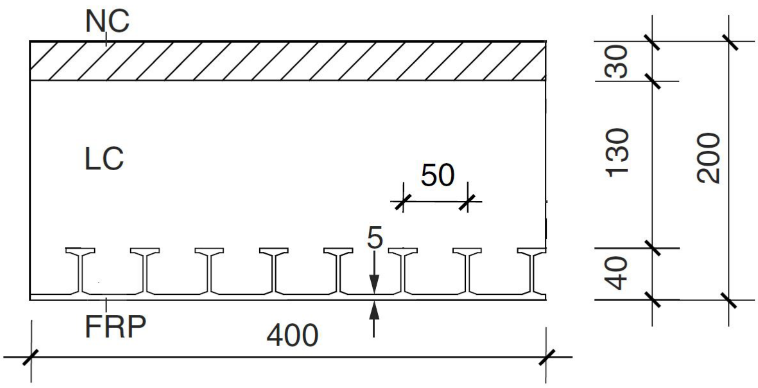


Fig. 5.11 - Section of the element with dimensions [Keller et al., 2006]

5.5.3 - Production process

The FRP layer together with the lightweight concrete layer is prefabricated in large elements (2,5m x width of the bridge) which are transported to the site and installed. Subsequently the UHPFRC layer is poured jointless over the lightweight concrete layer. Where negative bending moments are located, GFRP reinforcement grids are laid into the UHPFRC layer. [Keller et al, 2006]

5.5.4 - Connection

The T-upstands of the GFRP sheet form a mechanical interlocking between the concrete and the GFRP sheet.
The connection between the entire deck elements is adhesively bonded. The same goes for the connection between de deck elements and the main girders of the bridge.

5.5.5 - Advantages & disadvantages

The purpose of this deck was to be a further development of hybrid FRP and concrete deck designs. Some disadvantages should be solved in this design. The following advantages of this deck design can be distinguished:

- The weight of this deck is 50% of the weight of a normal concrete deck.
- A ductile behaviour can be achieved at failure in the top concrete layer due to crushing of the lightweight concrete layer.
- The elements are easily prefabricated and transported to the site and subsequently installed rapidly.
- No waterproofing is needed, because no steel is used in the design.

A disadvantage of this system would be the cost. The used materials are more expensive than standard concrete and FRP.

5.5.6 - Similar designs

Several similar hybrid systems with FRP and concrete have been designed over the years. Some examples are given below:

1. FRP and concrete bridge deck; This design consists of three trapezoidal glass fibre reinforced polymer box sections, bonded together. A layer of concrete is placed in the compression part of the section. This design reduces initial costs and increases the stiffness of GFRP composite structures. [Kitane et al, 2004]

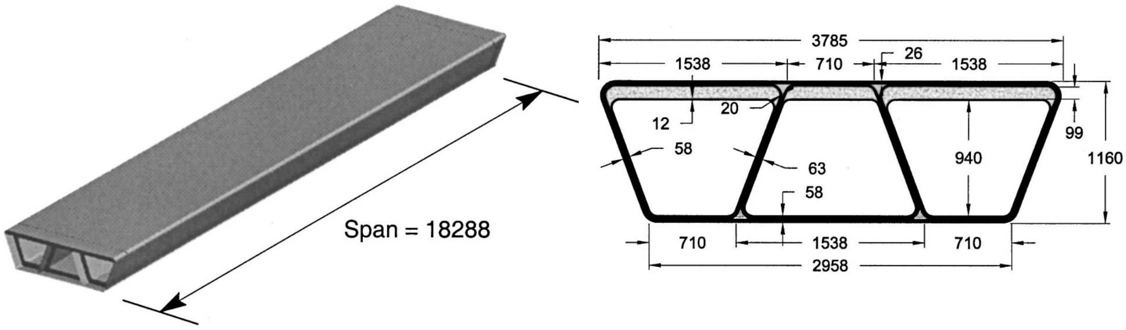


Fig. 5.12 - 3D view and section of an FRP - concrete bridge deck. Concrete is placed in the compressive part of the section. [Kitane et al., 2004]

2. GFRP, CFRP and concrete beam design; this beam design consists of GFRP box beams including a layer of concrete in the compression zone and a CFRP laminate in the tension zone. The beam was designed to create cost-effective composite members with pseudo-ductile characteristics and high stiffness and strength properties. [Deskovic, 1995]

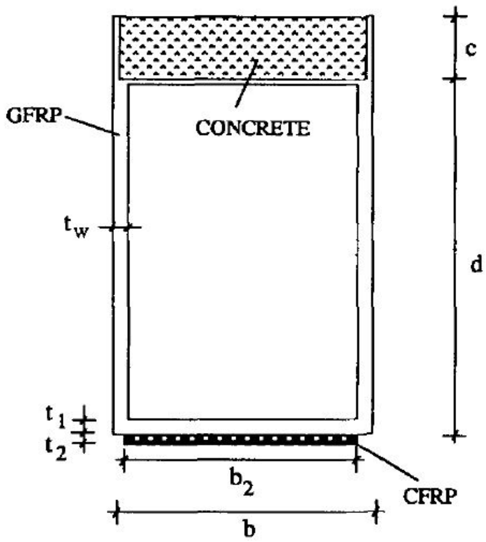


Fig. 5.13 - Section of GFRP, CFRP and concrete beam with relative dimensions. [Deskovic, 1995]

5.6 - Glass reinforced steel structure

To reach more transparent, sustainable and slender structures, glass can be used to increase the steel structure capacity. In this hybrid glass and steel design on the central station of Gouda by ABT this leads to less material usage and more transparency. [Haarhuis et al., 2016]

Fig. 5.14 - The stiffening glass elements to stabilize the steel construction on the station of Gouda. [Haarhuis et al., 2016]

5.6.1 - Materials

Tempered glass was used for this canopy, due to the local concentrated loads for maintenance issues. Heat-strengthened glass would have had better post-breakage behaviour, but was not strong enough.

5.6.2 - Structural design

The glass provides stiffness and stability to the steel structure by in-plane lateral loading. This results in a glass reinforced steel structure without steel bracing.
Glass is isotropic and has large compressive strength and stiffness. These properties are used to stiffen the steel construction, which would - without the glass - deflect too much. [Haarhuis et al., 2016]
Due to the glass reinforcement the steel can be minimized to a very slender design with reduced section sizes. This will result in a very transparent design where the focus is on using extra glass instead of just reducing the amount of steel.

5.6.3 - Production process

The production process of tempered glass and steel is not different than the normal production process.

5.6.4 - Connection

The connection is a bolt connection into mortar filled glass holes. It is a point fixed connection for construction and replacement reasons.

5.6.5 - Advantages & disadvantages

The big advantages of using glass in this design is its stiffness. The other structural elements can be designed much smaller due to this stiffness. This leads to more optimized material use.
There were no big disadvantages after construction. Construction was a bit difficult, because temporary bracing was necessary to support the large steel beams when the glass was not yet in place.

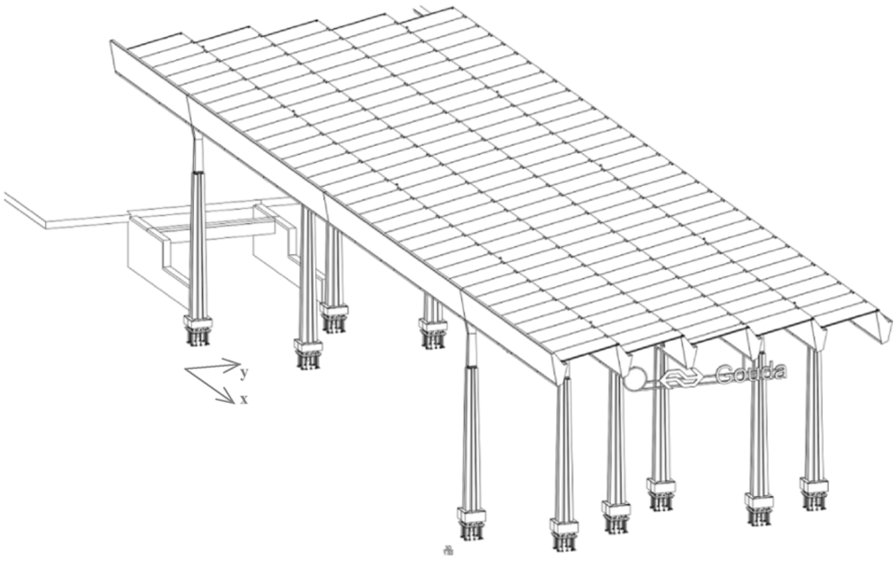


Fig. 5.15 - Axonometric view of the glass reinforced steel structure. [Haarhuis et al., 2016]

5.7 - Conclusion & comparison FRP & glass

FRP is most often used in hybrid systems for its tensile strength, low weight, low maintenance, corrosion resistance, semi-transparency (GFRP), moldability and good fatigue behaviour while structural glass is mostly used for its stiffness and high compressive strength and at the same time its transparency as an aesthetic quality. These material properties are all very different.

A weak point of FRP is its stiffness. It is often combined in hybrid designs with concrete: a very stiff material with a high compressive strength. Glass is also a stiff material with a high compressive strength with some extra aesthetic qualities, resulting in a good potential combination.

While concrete is reinforced with steel it is possible to reinforce glass with FRP. FRP in itself is, just like glass, a brittle material. However, when embedded in laminated glass it will enhance the ductile post-breakage behaviour of glass, resulting in a good potential hybrid. These embedded FRP profiles can be translucent when glass-fibres are applied as extra advantage.

FRP can also be a protection for glass. When a pultruded FRP profile is applied along the edges of glass - an area that can be very susceptible to damage - it can protect the glass from damaging. This is especially effective when combined with FRP as reinforcement of the glass or FRP for strengthening of a glass structural element in the tensile zone.

A resemblance of both materials is the application of splice lamination to create longer spanning structural elements.

5.7.1 - Design guidelines

Design guidelines that follow from these conclusions and comparison are as follows:

1. Structural glass is best used in the compressive zone of the bridge, due to its excellent compressive strength.
2. FRP is best used in the tensile zone in a structural element, due to its excellent tensile strength.
3. Glass can be used to stiffen structural elements (especially FRP which has a low stiffness), due to the high stiffness of glass - the other structural elements can then have minimal (optimized) dimensions.
4. FRP can be used as reinforcement to enhance the post-breakage behaviour and ductility of structural glass, while keeping glass as transparent as possible.
5. The edges of a structural glass beam can be protected by FRP.
6. FRP can be stiffened by other (stiffer) materials - preferably in the compressive zone.

6 Preliminary design variants

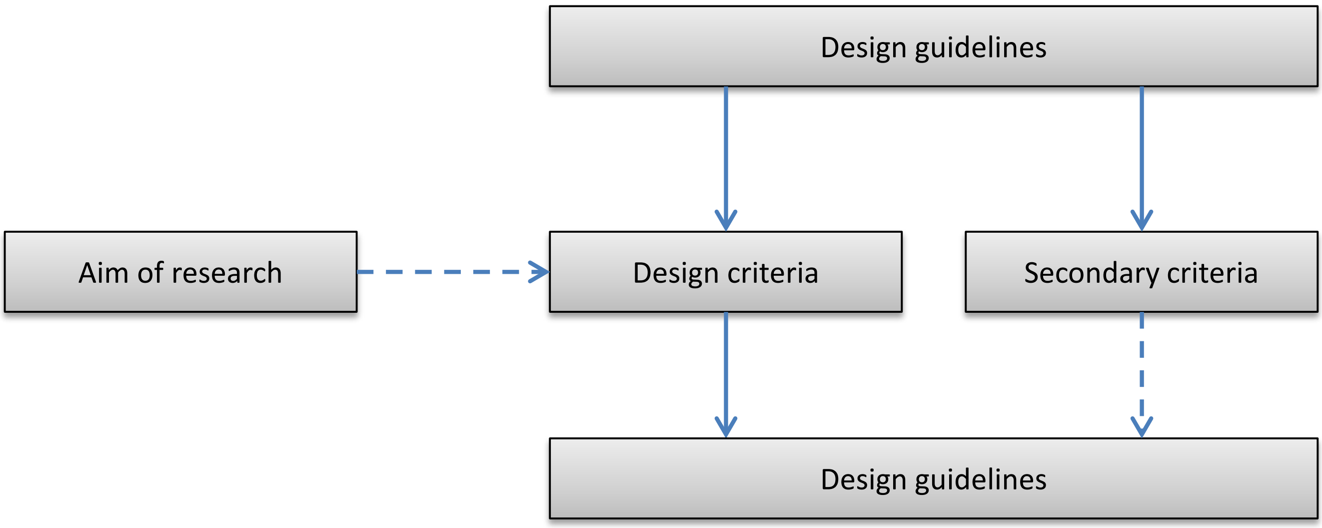


Fig. 6.1 - The best preliminary variant is based on the most important criteria for this design: the design criteria. This results in a more explanatory design solution instead of an attempt to find the perfect hybrid FRP and structural glass bridge design with a solution for every design problem. This solution would be too cumbersome to find.

6.1 - Introduction

In the previous chapters knowledge has been collected about the mechanical properties of both glass and FRP, the structural possibilities of both materials, previously built bridges and the existing combinations of both materials in several hybrid systems.
The design guidelines that followed from this research should be translated, incorporating the requirements of the location, to a design concept which can subsequently be optimized through FEM analysis. To find the best design concept it is necessary to create multiple preliminary concept variants and evaluate and grade these using criteria based on the design guidelines.

6.2 - Design guidelines

6.2.1 - Design guidelines material research

The general material research resulted in a good view on the possibilities of the material in regard to construction of a hybrid FRP and glass bridge. Several general design guidelines that are important when designing with FRP and glass are as follows:

1. The FRP material composition and production method should be designed to meet the specific concept to have the most optimized mechanical properties.
2. FRP should be used in applications where moldability of the material and freedom of shape are required.
3. Safety should be addressed in this bridge design: glass should have a safety concept based on redundancy (lamination), reinforcement of the glass (ductile post-breakage behaviour), heat-treatment (elevated strength) and an anti-slip layer should be added. Safety in FRP should be incorporated in its composition: additives, coatings and material choice.
4. The anisotropic (quasi-isotropic) behaviour of FRP and isotropic behaviour of structural glass should be optimally combined in the bridge design.
5. In a bridge design, FRP should resist the most tensile strength, while glass resists the most compressive strength.
6. Structural glass should be used to stiffen the bridge design, due to the higher E-modulus of glass compared to FRP.
7. The transparency of glass should be used in a bridge design, as this is the most important aesthetic feature of glass.
8. The hybrid bridge can be placed in a “harsh” environment or on a location where durability is important as both FRP and glass are very durable materials.
9. Tolerances in connections between glass and FRP can be relatively small, due to a comparable expansion coefficient.
10. The most sustainable bridge design should be made from glass and GFRP.
11. Large elements (>10m) in a bridge design should be made from FRP, while smaller elements (<10m) should be made from either glass or FRP, due to transportation, costs and production limits.
12. Mechanical (bolted) joints should not be used in a FRP and glass bridge design due to peak stresses.
13. Either bonded joints or interlocking connections should be used in the bridge design due to better distribution of stresses.
14. The most efficient bridge structure should be made with material adapted shapes: for FRP this means the monocoque, shell structures or pultruded bridge decks. For glass this means single curved glass panels, glass columns, glass bricks and glass beams.
15. The bridge should be designed with flat glass elements, due to high costs, the lack of precision and the difficulty of connecting to external structures of other structural shapes in glass.

6.2.2 - Design guidelines precedent research

The precedents of glass and FRP bridges showed practical examples of the possibilities, development and limitations of building bridges with these materials. The advantages and disadvantages and structural concepts of these bridges resulted in some new design guidelines and some confirmed the previously stated design guidelines:

16. FRP can be used in places where quick and easy assembly/disassembly is necessary, due to its low weight.
17. FRP can be used in places where transportation is an issue, due to its low weight.
18. The used structural adhesive should be properly designed to withstand a harsh environment (if applicable) and keep its structural capabilities.
19. Both FRP and structural glass can be used in areas with harsh environments, due to their high corrosion resistance (when coated and loaded in the right way).
20. To achieve the highest quality and lowest maintenance of FRP products vacuum infusion should be used as production method.
21. Psychology should be assessed when building bridges with a large span and/or a large height.
22. Safety concepts (like lamination) in glass should be applied due to possible damage (and collapse when no safety concept is applied) of the glass bridge.
23. To achieve the highest transparency it is necessary to produce larger glass elements up to 10 meters (even 12 meters for much higher costs).
24. When creating new types of glass forms (for example glass bricks) new safety concepts, production methods, forms, etc. should be developed.
25. Vibration should be assessed when designing a bridge with a very long span (exceeding 100m).
26. Aramid cables can be used to build lightweight cable-stayed bridges.

6.2.3 - Design guidelines hybrid system research

The research of the hybrid systems focused on FRP or glass in combination with another material to reach an optimized collaboration in a material adapted design. Therefore the results of this research show the specific roles of both FRP and glass when they are combined with another material - which disadvantageous properties are complemented by an other material to improve glass or FRP and which properties of glass and FRP can improve other materials. The following design guidelines (sometimes confirming previously stated design guidelines) resulted from this research:

27. Structural glass is best used in the compressive zone of the bridge, due to its excellent compressive strength.
28. FRP is best used in the tensile zone in a structural element, due to its excellent tensile strength.
29. Glass can be used to stiffen structural elements (especially FRP which has a low stiffness), due to the high stiffness of glass - the other structural elements can then have minimal (optimized) dimensions.
30. FRP can be used as reinforcement to enhance the post-breakage behaviour and ductility of structural glass, while keeping glass as transparent as possible.
31. The edges of a structural glass beam can be protected by FRP.
32. FRP can be stiffened by other (stiffer) materials - preferably in the compressive zone.
33. Other materials can be used to provide ductile breaking behaviour for the brittle FRP materials.

6.2.4 - Demands of location

According to the information given in chapter 1, the location demands a bridge with the following boundary conditions:

1. A span length of 33,8 meters.
2. A maximum possible width of 10 meters, due to the plans for a stepped area at the river banks in the masterplan.
3. The plans of building a pavilion in the water and the suggestion of a floating platform indicate the use of the water. This can result in traffic under the bridge - this should be taken into account in the design in terms of safety (protecting the edges of the glass) and height of the bridge.
4. Pedestrian traffic will be incidentally dense, for example when the Green Village closes and every visitor has to leave.

6.3 - Criteria

Not all of these design guidelines can and will be incorporated in a hybrid FRP and structural glass bridge design. Every guideline relates to a different facet of the bridge design. The preliminary bridge design that incorporates the most and the most important design guidelines will be nominated as best preliminary variant. To find the best preliminary variant it is necessary to formulate criteria based on these design guidelines to grade the concepts. All the guidelines can be grouped under seven selected criteria, which will be used to grade the preliminary design variants:

- Strength & stability
- Transparency
- Safety
- Transportation & assembly
- Sustainability & durability
- Costs
- Weight

The design guidelines can be categorized within these criteria as shown on page 122.

6.3.1 - Design criteria

The amount of criteria above covers nearly all facets that can be considered when building a bridge. Since the aim of this research is to find a hybrid pedestrian bridge in FRP and structural glass with a focus on structural efficiency, the three most important factors (design criteria) to focus on are (figure 6.1):

- Strength & stability
- Transparency
- Safety

Strength and stability covers the structural efficiency of the bridge, which is mentioned in the aim of research as the most important focus point of this design (see chapter 1.2). Transparency and safety are factors determined by the material choice: glass is a transparent material, while both materials need extra safety measures.

In this early stage of the design process having focus on three of the criteria would result in clearer results regarding the aim of research and most important facets of the materials. Adding all criteria (and corresponding guidelines) in the design process would result in a more explanatory model due to a surplus of guidelines instead of a more significant model considering only the most important criteria: the earlier mentioned design criteria.

Therefore the focus in this stage of the design process is on the above mentioned design criteria while the other criteria are addressed secondarily and in a lower level of importance. These criteria will be elaborated on more extensively as part of the final design later in this thesis.

6.3.2 - Strength and stability

The bridge should be evaluated in terms of strength and stability. Glass and FRP should become a unity, a hybrid. This should enhance the strength of the bridge while the bridge should also be stable. The strength of the design can be evaluated compared to the weight of the construction or in terms of stiffness and stability. It is also important to assess the structural collaboration of FRP and glass.

- Is the bridge stable and what variant has the most optimal structural stability in terms of material use?
- What is the strongest variant in terms of stiffness to weight?

6.3.3 - Transparency

The bridge should be as transparent as possible as this is the most important (advantageous) material property of glass. It is also one of the first reasons to combine FRP and glass. Therefore the transparency of the concepts will be evaluated:

- What is the overall transparency of the bridge?
- Does the transparency of the bridge have a purpose?

6.3.4 - Safety

Safety plays in both FRP and glass an important role. Glass can nowadays be used structurally, due to an improved safety concept.

Safety in FRP is less important than for glass, but FRP remains a brittle material with lacking knowledge about long-term behaviour in structures. Therefore it is important to evaluate whether safety concepts can and are used in the preliminary design and whether they are sufficient for the future use of the bridge.

- Can safety concepts be applied to the design?
- Are the safety concepts sufficient in terms of risk and consequences?

6.3.5 - Secondary criteria

6.3.5.1 - Transportation and assembly

The ease of transportation and assembly is generally an important advantage of FRP bridges. For glass this is a more troublesome category. Especially transportation of the large elements can be difficult due to the fragility of glass. Therefore the transportation and assembly of the combined materials will be assessed:

- What are the sizes, weights and costs of the elements to be transported?
- How fragile are the elements that have to be transported?

6.3.5.2 - Sustainability and durability

Glass is a very sustainable material in terms of raw materials and a very durable material when it is loaded under compression.

FRP has raw materials that are less sustainable, but in bridge designs generally is a very durable material. This difference in sustainability and durability should be assessed through the following questions:

- How durable is the design (how much FRP and glass is used in a durable way in the bridge design)?
- What are the recycling and re-use possibilities of the structural elements?

6.3.5.3 - Costs

The costs of glass can become very high when large or special elements are necessary for the design.

FRP generally has high initial costs, but the durability and maintenance free life of FRP bridges reduces the total costs. Initial costs are important though, because they can scare away potential investors and clients. Therefore the costs in the final concept should not be too high:

- What are the estimated total costs of the structural elements of the preliminary variants?
- What are the estimated initial costs of the preliminary variants?

6.3.5.4 - Weight

For FRP the weight in relation to its strength is an important advantage. Glass, however, is very heavy when compared to its (tensile) strength. The weight is also an important factor during the transportation and assembly of the bridge, but also for the design of the foundations of the bridge. Therefore this is an important criteria to assess separately. Questions that should be asked when evaluating the weight of the preliminary variants are:

- What is the estimated total weight of the bridge (what is the heaviest and lightest variant)?

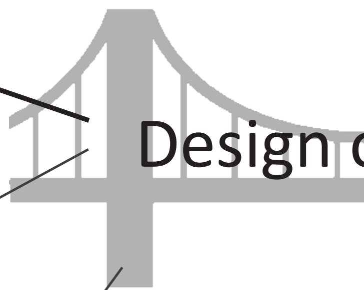
6.4 - Preliminary variants

Each of the introduced preliminary variants is based on the earlier mentioned design guidelines. A structural concept with a corresponding safety concept has been chosen with a selection of the other guidelines incorporated in each preliminary variant. The associated guidelines will be mentioned at the end of each variant.

Design criteria

Strength & stability

- Isotropy of glass and anisotropy of FRP should be combined
- Glass: high compressive strength
- FRP: high tensile strength
- Stiffness of glass to stiffen bridge
- Holes in glass & FRP compromise strength
- Bonded or interlocking connections for best distribution of forces
- Material adapted shapes
- Vibrations should be addressed for large span FRP bridges
- Heat-strengthened glass for elevated strength combined with good post-breakage behaviour



Transportation & assembly

- Low weight of FRP for easier assembly & transport
- Comparable thermal transfer coefficient for lower tolerances
- Glass elements below 10m for easier transport
- Flat glass elements for easier connection to other materials

Weight

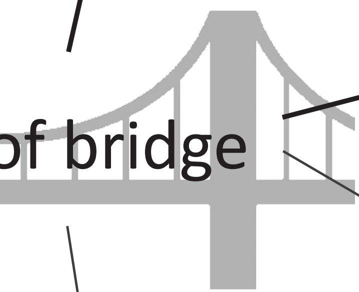
- FRP is lightweight
- Glass is heavy especially in multilayer use
- Low weight for less foundation works

Transparency

- Glass transparency as most important aesthetical feature
- Larger elements for more transparency
- GFRP is translucent when used as reinforcement

Safety

- Glass needs safety concept
- FRP safety in material composition & coating
- Psychology for glass
- FRP gives glass ductility
- FRP can protect glass edges
- Anti-slip layer necessary
- New structural forms means new associated safety concepts



of bridge

Other criteria

Costs

- High initial costs, but lower total costs for both materials
- Flat glass elements are cheapest
- Glass elements below 10m to keep costs low

Sustainability & durability

- Glass & GFRP is most sustainable
- FRP & glass have high corrosion resistance
- Structural adhesive should be properly designed
- Vacuum infusion for most precision & durability
- Coating for FRP for better durability

6.4.1 - Variant 1: Hybrid faceted shell

The first preliminary variant is the design of a shell - with a high stiffness to weight ratio - of flat faceted glass with FRP connections. This design follows from the structural advantages of a shell shape: a high stiffness to weight ratio and optimal material use. The ideal shell is mainly loaded in compression, which suits with the material properties of structural glass.

An important reason to make a faceted shell is the difference between glass and FRP: glass can best be produced as a flat element due to economic and tolerance related reasons, while FRP can easily be produced in many different forms and shapes. The flat glass elements give stiffness to the structure (glass has a higher E-modulus than FRP), while FRP provides the curvature to form a shell shape and transfers the forces between the plates (higher tensile bending strength). This combines the structural advantages of both materials with the available (precise) production techniques for these materials.

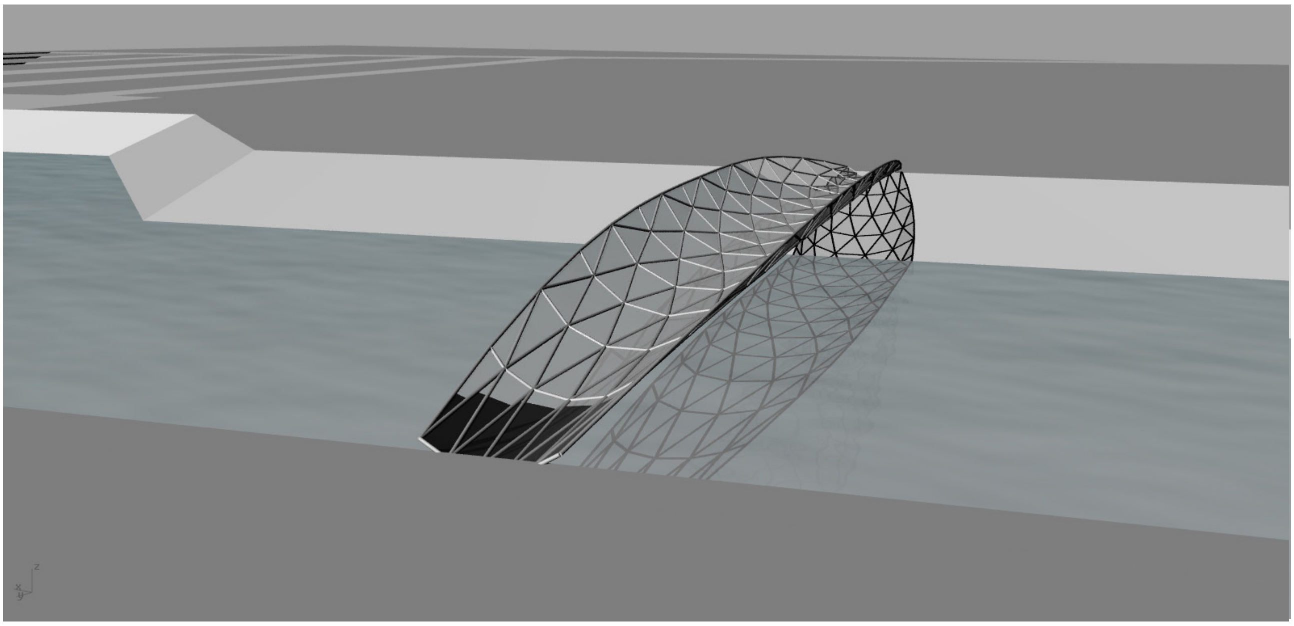
Another advantage is the possibility to use the FRP connection as a reinforcement or protection of the fragile edges of the triangular, hexagonal or quadrilateral plates by embedding the FRP between the laminated glass panes. The reinforcement of the glass edges will both provide ductile breaking behaviour and protection of the fragile glass edge, while not compromising the transparency of the bridge (as GFRP can be translucent). The thermal expansion coefficient of the FRP reinforcement is closer to the thermal expansion coefficient of glass, resulting in less internal movement and corresponding stress concentrations in the glass panes.
A sacrificial layer of anti-slip glass will be added to the glass facets to 1) prevent slipping and 2) easy replacement when this layer cracks, while the structural core is unaffected.

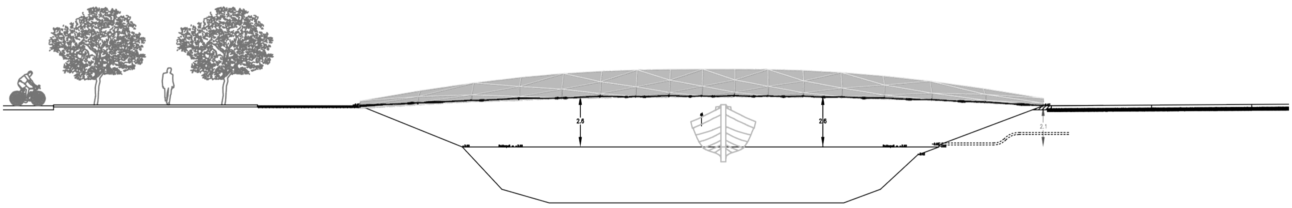
The type of glass will be heat-strengthened for elevated strength, combined with an acceptable breaking pattern.
The type of FRP can be tailored according to the load-bearing requirements. It will probably be the most isotropically composed GFRP type (quasi-isotropic). This will lead to a relatively cheap and lightweight design which can distribute forces from all directions (which will be necessary due to unevenly applied traffic loads on the bridge). Also, GFRP can be translucent which provides the opportunity to make the reinforcement as invisible as possible [Palumbo et al, 2005].

The structural elements of this bridge design will be produced in the factory (to ensure the quality and durability) and later assembled on site. The glass structural elements are small - which eases the transportation and assembly - but will to a large extent differ - this complicates the assembly. The FRP elements will either be small or very large - however, FRP does not have a large influence on transportation and assembly costs due to its low weight.

Design guidelines associated with this design:

- In a bridge design, FRP should resist the most tensile strength, while glass resists the most compressive strength
- Structural glass should be used to stiffen the bridge design, due to the higher E-modulus of glass compared to FRP
- Large elements (>10m) in a bridge design should be made from FRP, while smaller elements (<10m) should be made from either glass or FRP
- The most efficient bridge structure should be made with material adapted shapes: for FRP this means the monocoque, shell structures or pultruded bridge decks. For glass this means either compressive structural members like glass columns, glass bricks and glass beams or flat glass elements.
- The transparency of glass should be used in a bridge design, as this is the most important aesthetic feature of glass.
- The bridge should be designed with flat glass elements, due to high costs, the lack of precision and the difficulty of connecting to external structures of other structural shapes in glass
- FRP can be used as reinforcement to enhance the post-breakage behaviour and ductility of structural glass, while keeping glass as transparent as possible
- The edges of a structural glass beam can be protected by FRP

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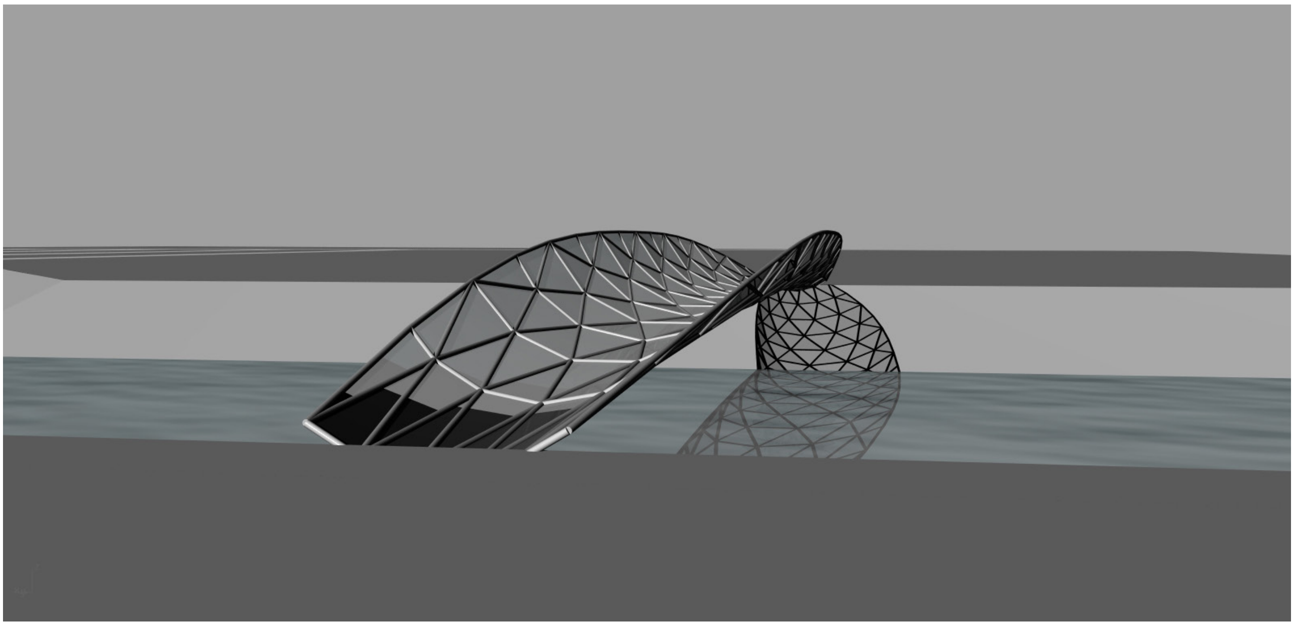


6.4.2 - Variant 2: FRP reinforced glass bridge

The second variant has an emphasis on glass and transparency. Large glass elements are used to create more transparency. Glass can be seen as the main load-bearing material, while FRP provides a safety net to minimize the risk of failure.

Flat glass elements (both beams and the deck) are splice laminated to span the entire length. They are reinforced with GFRP along the edges, but also across the entire surface of the glass. This concept follows the application of wired glass and further enhances the ductile breaking of the glass. It forms a literal safety net when the glass of the deck or the beams breaks. This should partially exclude the need for redundancy as a safety concept. Therefore less layers of glass should be applied, resulting in less weight and lower glass costs.

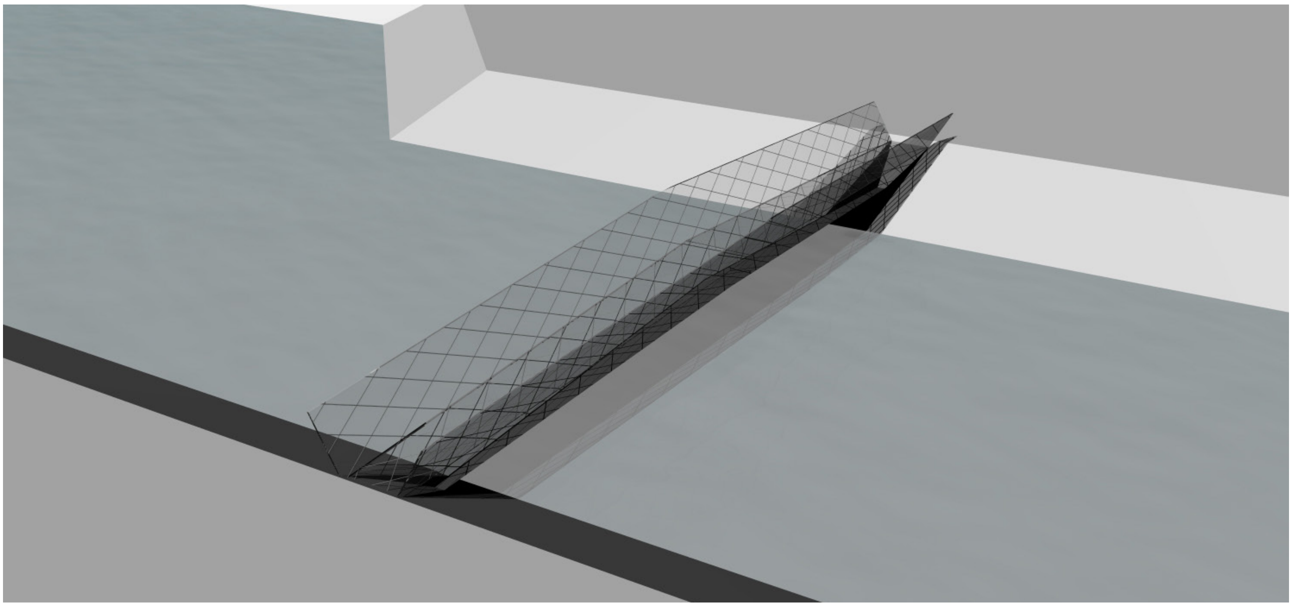
The stability of the bridge is created by placing the glass beams - that also function as parapet - in a V-shape. They are connected in the tensile zone of the bridge with a FRP profile, which also protects the bottom edges of the glass beams.
The FRP profile is placed in the tensile zone of the bridge while the glass beams mainly cover the compressive zone of the bridge. This is based on the hybrid systems where glass and FRP are commonly used in respectively the compressive and tensile zone of the hybrid structural elements.

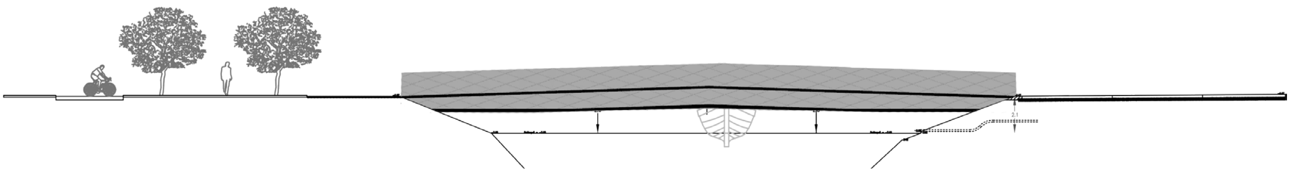
A sacrificial anti-slip layer is placed on the glass element that forms the deck to ease the replacement of a cracked glass panel without affecting the structural core.

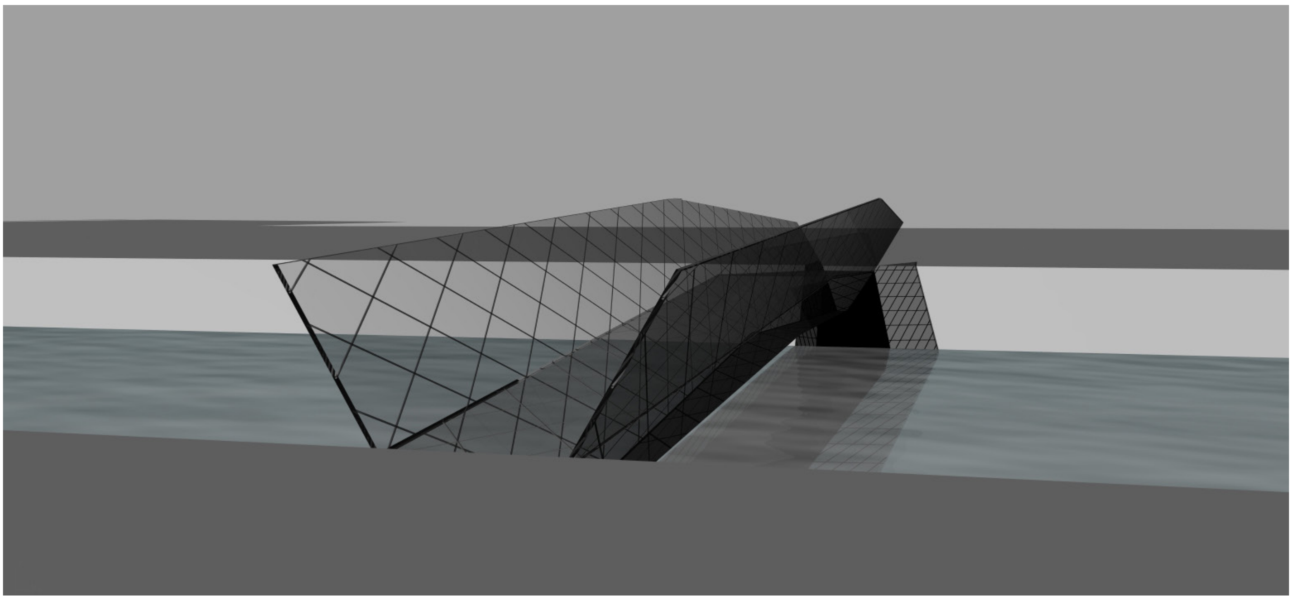
The glass beams will have to be assembled in a factory, due to the complicated lamination of the FRP rods between the glass sheets. The glass beams, which are very heavy, will then be transported to the site and placed in position with the use of a crane.
The bridge will then be assembled further on site - connecting the deck to the beams and connecting the FRP to the glass.

Design rules associated with this variant:

- In a bridge design, FRP should resist the most tensile strength, while glass resists the most compressive strength
- The transparency of glass should be used in a bridge design, as this is the most important aesthetic feature of glass
- The bridge should be designed with flat glass elements, due to high costs, the lack of precision and the difficulty of connecting to external structures of other structural shapes in glass
- To achieve the highest transparency it is necessary to produce larger glass elements up to 10 meters (even 12 meters for much higher costs)
- FRP can be used as reinforcement to enhance the post-breakage behaviour and ductility of structural glass, while keeping glass as transparent as possible







6.4.3 - Variant 3: Hybrid monocoque

The third variant is based on the monocoque structure, which is very commonly used in FRP designs. This concept can be seen as a double curved wing shape. All the stresses, both compressive and tensile, are located in the outer layer of the monocoque.

The design is formed like a large wing with several lateral glass beams to support the monocoque. The upper part of the monocoque is made of curved glass - the compressive part of the bridge. The lower part of the monocoque is made of FRP - the tensile part of the bridge. The FRP tensile skin is extended to also function as parapet of the bridge.

The curved glass deck consists of multiple parts (eight parts has been randomly chosen now), because large curved glass elements are very costly and difficult to produce and laminate. The elements are interconnected at the lateral glass beams. These lateral glass beams are mainly loaded in compression, which explains the material choice of glass.

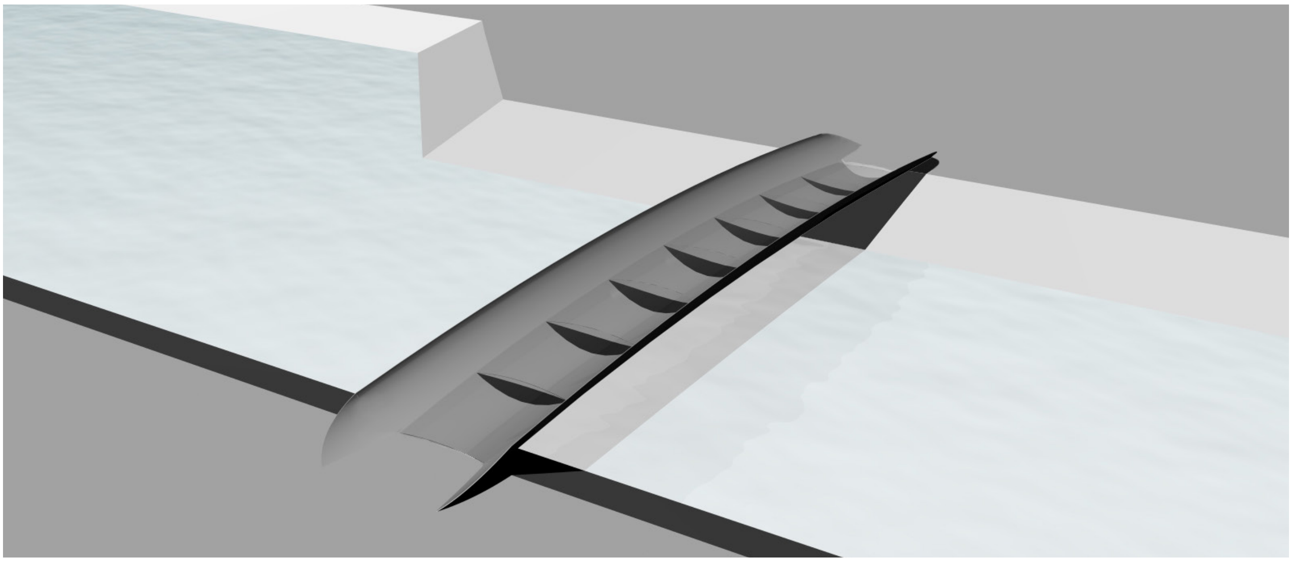
The safety concept for this bridge variant is based on redundancy: three layers of curved glass are laminated with SentryGlas interlayer material. Extra care during the lamination process is necessary due to larger tolerances of curved glass elements during production and lamination.
A sacrificial anti-slip layer should be placed on top of the curved glass elements to prevent slipping and to ease replacement of a cracked glass element without affecting the structural core.

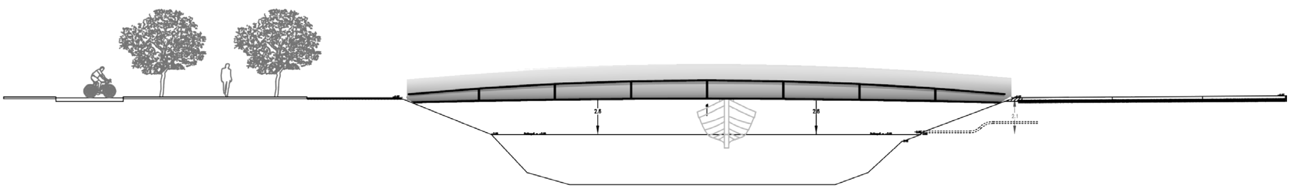
The curved shape of the monocoque is very easy to create in GFRP, while more problems arise during the production of curved laminated glass elements. These problems are tolerance and cost related.

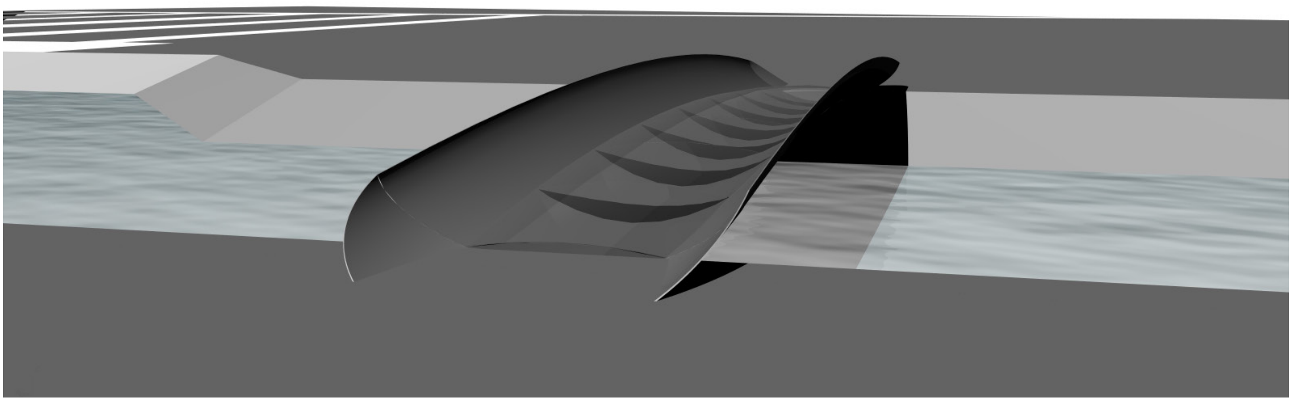
The double curved tensile skin made of GFRP can either be produced in the factory and then transported and lifted on site or be completely produced on site. The cheapest and most precise variant of aforementioned should be chosen.
The curved glass elements will be completely produced and laminated in the factory to ensure the quality and precision. Transportation should be done very precisely, due to the fragility of the curved glass elements.

Design rules associated with this preliminary variant:

- In a bridge design, FRP should resist the most tensile strength, while glass resists the most compressive strength
- Large elements (>10m) in a bridge design should be made from FRP, while smaller elements (<10m) should be made from either glass or FRP
- The most efficient bridge structure should be made with material adapted shapes: for FRP this means the monocoque, shell structures or pultruded bridge decks. For glass this means single curved glass panels, glass columns, glass bricks and glass beams
- The edges of a structural glass beam can be protected by FRP







6.4.4 - Variant 4: Hybrid folded plate

The fourth variant is based on a folded plate structure. A flat and thin surface has very limited strength and stiffness. However, when it is folded or bent its strength and stiffness are very much improved (increased moment of inertia). This type of structure approaches shells when it comes to material effectiveness, but it has the advantage of straight line construction. [Schueller, 1996]

This design is based on origami like structures. It consists of laminated flat glass elements and flat FRP elements to connect the glass elements. There are multiple variants of the origami pattern possible. Research and analysis is necessary to define the strongest and stiffest pattern.

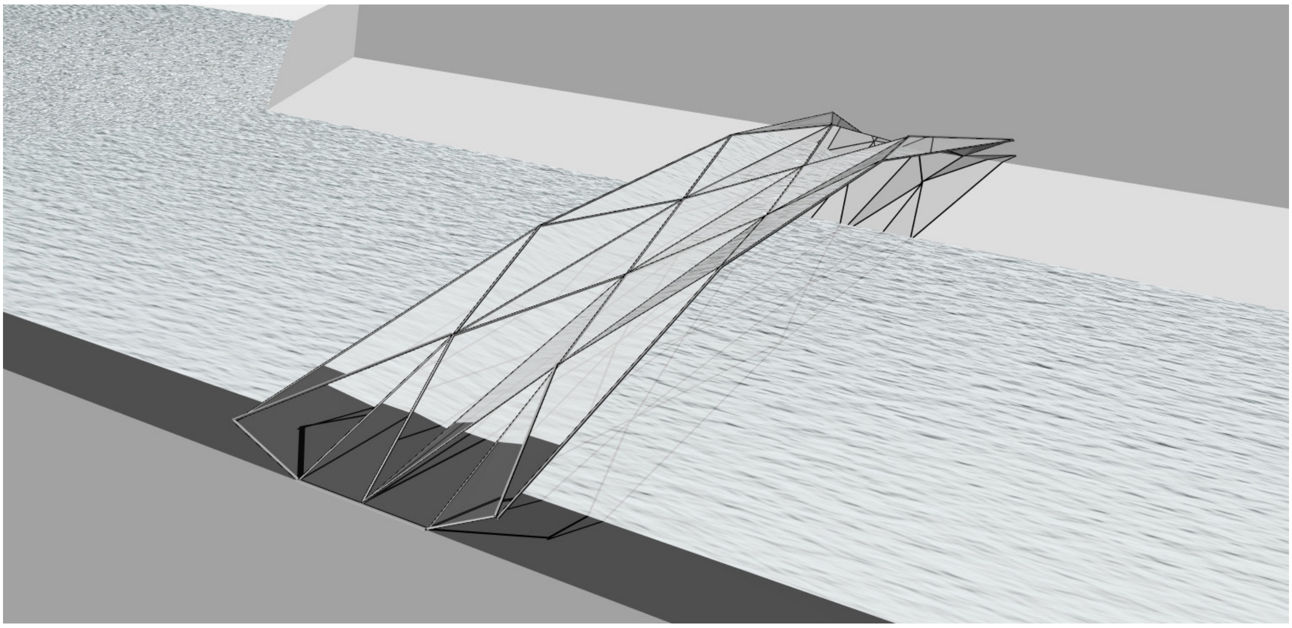
The safety concept for this bridge is both based on redundancy through lamination and reinforcement of the glass. The FRP functions as reinforcement for the glass, resulting in better ductile breaking behaviour.

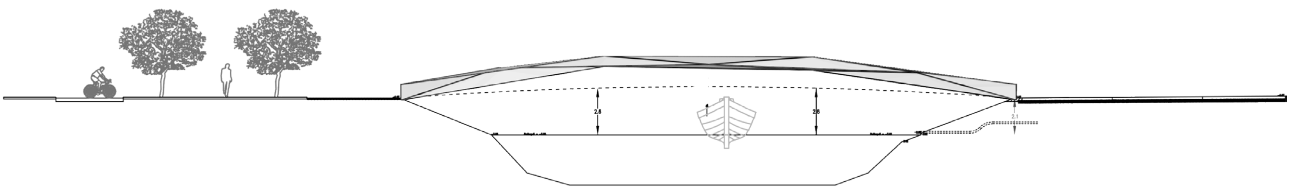
It is not yet possible to walk on the deck of the proposed design. It is therefore necessary to either create another layer of glass or FRP on top of the folded plates (resulting in a sandwich construction), or make the plate size much smaller to approach a flat surface. Again, a sacrificial anti-slip layer should be placed on top of the glass for easy replacement of a broken plate without affecting the structural core.

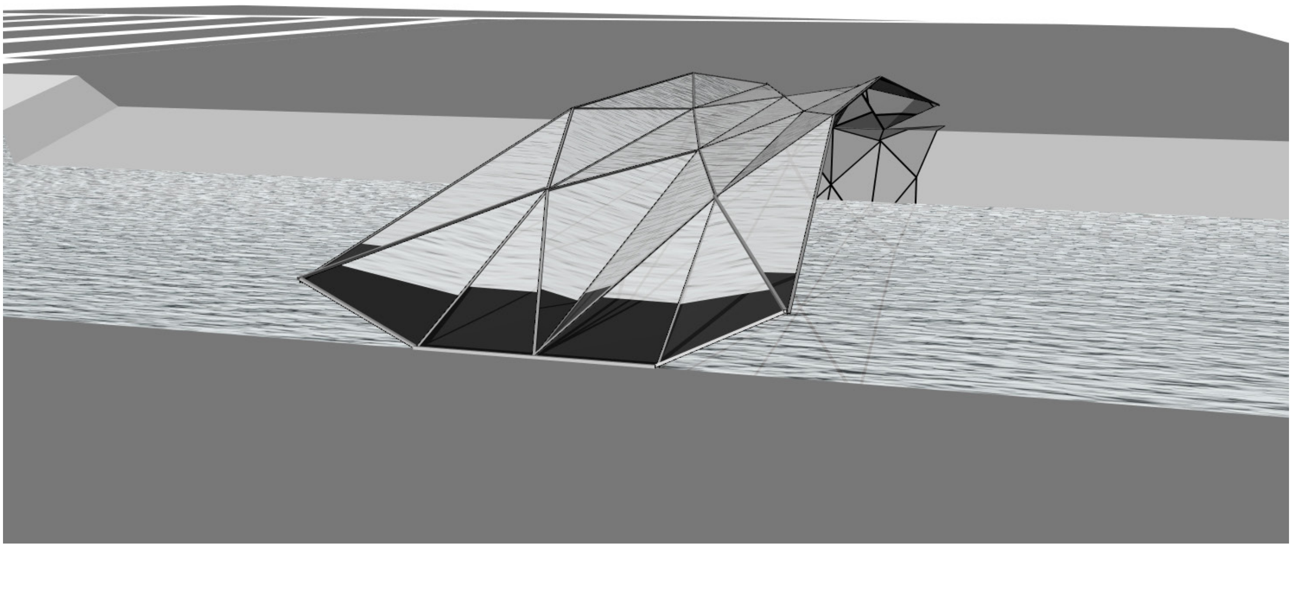
The production and assembly will be very similar to the hybrid faceted shell as they both consist of plates and FRP connections. The difference is in the folded shape versus the curved, but faceted shell shape.

Design guidelines associated with this bridge design variant are:

- The transparency of glass should be used in a bridge design, as this is the most important aesthetic feature of glass
- Large elements (>10m) in a bridge design should be made from FRP, while smaller elements (<10m) should be made from either glass or FRP
- The bridge should be designed with flat glass elements, due to high costs, the lack of precision and the difficulty of connecting to external structures of other structural shapes in glass
- FRP can be used as reinforcement to enhance the post-breakage behaviour and ductility of structural glass, while keeping glass as transparent as possible
- The edges of a structural glass beam can be protected by FRP







6.5 - Grading with design criteria

To grade the previous preliminary variants all their advantages and disadvantages will be evaluated following the three design criteria mentioned in paragraph 2 of this chapter. Their respective questions will be answered, while ranking them. This will finally be summarized in a table resulting in a grading of the variants. Subsequently the best variant can be chosen and elaborated on in the next chapters.

6.5.1 - Strength & stability

- Is the bridge stable and what variant has the most optimal structural stability in terms of stiffness, weight and material use?
- In which variant are both materials used best according to their material properties?

Variant 1 uses the very efficient shell shape with a high stiffness to weight ratio. This means that the shape and amount of material can be optimized through form-finding and analysis.
The stiffness and high compressive stress of glass can be used to stiffen the shell structure, while the high tensile strength and moldability of FRP can be used for an exact force flow through the connections or the frame. The FRP can also function as reinforcement of the glass, resulting in enhanced post-breakage behaviour.

When variant 4 - the hybrid folded plate - is double curved like a shell, it has an even higher static stiffness than the hybrid faceted shell. However, its natural frequency is lower as is its resistance to horizontal loads (and other loads that are not concentrated on the apex line). [Miura, 2008] Therefore this variant is structurally less efficient.

Variant 3 is based on the monocoque shape, where the material is used very efficiently. It is double curved resulting in a high stiffness to weight ratio (basically two thin structural shells). FRP is used in the tensile zone of the bridge, while glass is used in the compressive zone - a material adapted concept.

Variant 2 does not have a structural shape with a high stiffness or strength. The stability is based on the triangular shape of the section. The FRP does not have a real structural function besides providing ductile post-breakage behaviour - glass is the only load-bearing material.

Ranking:
1. **Variant 1 - hybrid faceted shell**
2. **Variant 4 - hybrid folded plate**
3. **Variant 3 - hybrid monocoque**
4. **Variant 2 - FRP reinforced glass bridge**

6.5.2 - Transparency

- What is the overall transparency of the bridge?
- Does the transparency of the bridge have a purpose?

Variant 2 (the FRP reinforced glass beam) is visually the most transparent bridge. The small threads of GFRP embedded in the glass are translucent and will therefore not disturb the all-glass design much. The only non-translucent element is the CFRP profile at the bottom of the bridge.

Variant 1 (the hybrid faceted shell) consists of multiple small glass facets with an FRP (translucent) connection. This connection will remain quite small, but has some effect on the transparency: It will limit the transparency a bit.

Variant 4 (the hybrid folded plate) also consists of several glass facets with an FRP connection. The folding, however, distorts the transparency of the glass more compared to variant 1. To make a flat deck it is necessary to place a second layer of glass, which will distort and limit the transparency even further.

Variant 3 (the hybrid monocoque) consists of large FRP (non-transparent) structural elements. This results in poor overall transparency.

Ranking:
1. **Variant 2 - FRP reinforced glass bridge**
2. **Variant 1 - hybrid faceted shell**
3. **Variant 4 - hybrid folded plate**
4. **Variant 3 - hybrid monocoque**

6.5.3 - Safety

- Which safety concepts can be applied to the design?
- Are the safety concepts sufficient in terms of risk and consequences?

Variant 2 uses the standard redundancy safety concept by lamination. The embedded FRP wires in the glass are a second safety concept. This safety concept enhances the post-breakage behaviour of the bridge, acting as a literal safety net.
Both safety concepts minimize the consequences of breaking or damaging of the glass. The risk of breaking is relatively high though, because the bridge is fully made of glass.

In the design of variant 3 the standard safety concept of redundancy by glass lamination will be applied. Reinforcement in the glass elements will be complicated due to the curvature of the glass, its corresponding post-breakage behaviour will be unpredictable - because not tested.
The consequences of breaking of glass are low, due to the FRP tensile skin of the bridge. This layer will remain intact when the glass breaks and completely loses its load carrying abilities, so the fall through the broken glass will not be high.

Variant 4 consists of small laminated glass panels. These panels consist of multiple laminated layers of glass: redundancy safety concept. The glass can possibly be reinforced depending on the type of connection.
A shell structure has the disadvantage of sudden collapse: the structure is optimized in terms of material use resulting in a very thin shell. Because this thin shell cannot resist a lot of bending action it will collapse very quickly when the critical load is reached. This results in more severe consequences of damage to (one of the) facets or the FRP connection. Because the folded plate shell has a certain height, due to the folds and because a second layer of anti-slip glass is applied to make a straight walking surface, this bridge will not collapse as quickly as the hybrid faceted shell.

Variant 1 is very similar to variant 4: it consists of small laminated glass panels, again using the safety concept of redundancy. The glass will or will not be reinforced depending on the connection type.
The disadvantage of this shell structure is again sudden collapse. This time the structure will be even more optimized, resulting in lesser bending resistance. The consequences of damage to (one of the) facets will be even more severe.

Ranking:
1. **Variant 2 - FRP reinforced glass bridge**
2. **Variant 3 - hybrid monocoque**
3. **Variant 4 - hybrid folded plate**
4. **Variant 4 - hybrid faceted shell**

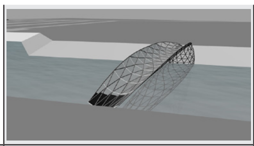
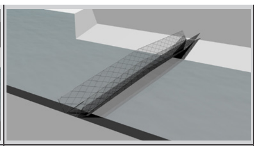
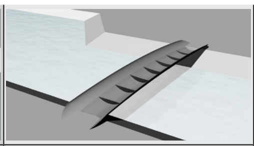
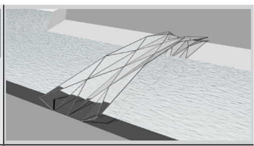
Ranking (design criteria)				
Strength & stability	○○○○	○	○○	○○○
Transparency	○○○	○○○○	○	○○
Safety	○○	○○○○	○○○	○
Total	9	9	6	6

Fig. 6.19 - Ranking of the variants per design criterium

6.5.4 - Conclusion

Variant 1: the hybrid faceted shell and variant 2: the FRP reinforced glass bridge, have an equal final score. Therefore it is not yet possible to choose the highest ranking alternative based on the design criteria. To find the best preliminary variant out of these two remaining variants, the secondary criteria should be addressed.

6.6 - Grading with secondary criteria

6.6.1 - Transportation & assembly

- What are the sizes, weights and costs of the transportation and assembly of the structural elements?
- How fragile are the elements that have to be transported & assembled?

Variant 1 consists of a lot of small flat glass elements, which can all damage during transport and assembly. Especially the sharp corners of the glass elements are vulnerable. The FRP structural elements can either be one large frame or multiple smaller elements. In the case of the frame, it will be necessary to transport this lightweight frame by helicopter - an expensive transportation method. In case of the smaller elements transportation will be very simple, but assembly might be more difficult (more parts to assemble).

Variant 2 consists of large splice laminated glass elements. These elements with the length of 30,4 meter are very difficult to transport. When they would be damaged during transport or assembly the replacement would be extremely expensive - especially due to the already embedded FRP. The weight of these structural elements is also the highest, making them harder to handle during assembly. Therefore this the hardest variant to transport and assemble.

Ranking:
1. **Variant 1 - hybrid faceted shell**
2. **Variant 2 - FRP reinforced glass bridge**

6.6.2 - Sustainability & durability

- How sustainable is the design (how much glass has been used in a sustainable way in the bridge design and how sustainable is the type of FRP)?
- How durable is the design (how much FRP and glass is used in a durable way in the bridge design)?
- What are the recycling and re-use possibilities of the structural elements?

Variant 1 consists of small laminated glass elements, possibly reinforced with FRP. This design has more connections than the previous variants, making it more likely that moisture ingression will occur - influencing the durability of the design. The durability can also be influenced when the glass facets are subjected to tensile forces. However, the shell will have to be optimized, subsequently minimizing tensile forces.
The recycling of the facets and FRP can be easy or complicated depends on the addition of materials: if the glass is reinforced with FRP along its edges, it will be more complicated to recycle the glass.

Variant 2 consists of the most glass of all variants. This glass is subjected in the structural design to a lot of bending, due to traffic. The structural principle is not based on minimizing the tensile forces induced in the glass, which makes the glass less durable. The FRP in the design will be protected from the environment by glass layers. Therefore the FRP threads will be very durable.
The recycling of the structural elements will be complicated, due to the mix of FRP and glass. The glass is laminated with FRP embedded in these layers. Separating these layers to recycle or re-use the structural elements will be complicated.

Ranking:
1. **Variant 1 - hybrid faceted shell**
2. **Variant 2 - FRP reinforced glass bridge**

6.6.3 - Costs

- What are the estimated total costs of the structural elements of the preliminary variants?
- What are the estimated initial costs of the preliminary variants?

Variant 1 consists of small flat glass plates with several corners. These corners are difficult and expensive to cut, raising the costs of production. The small FRP elements will most likely be much cheaper to produce.

Variant 2 will be the most expensive variant due to the complicated production of splice laminated glass beams with embedded FRP reinforcement rods. The large glass elements also increase the transportation and assembly costs. Carbon fibre - which is the most expensive type of fibre - will be used for the small beam at the bottom of the bridge.

Ranking:
1. **Variant 1 - hybrid faceted shell**
2. **Variant 2 - FRP reinforced glass bridge**

6.6.4 - Weight

- What is the estimated total weight of the bridge (what is the heaviest and lightest variant)?

Variant 1 - the hybrid faceted shell - is an optimized structural shape, resulting in minimal material use for maximal stiffness - a high stiffness to weight ratio. This results in the least weight among the preliminary variants when this structural design is optimized.

The structure of variant 2 fully consists of glass - which is heavier than FRP - with some added FRP. The structural design has the least natural stiffness of all variants, possibly resulting in the largest dimensions and therefore most material use and weight.

Ranking:
1. **Variant 1 - hybrid faceted shell**
2. **Variant 2 - FRP reinforced glass bridge**

6.7 - Conclusion

From the ranking per design criteria (figure 6.19) it has been concluded that variant 1 and 2 were equally good design variants. A second grading based on the secondary criteria was necessary to define the optimal preliminary variant. Variant 1 and 2 have been compared (figure 6.20) resulting in variant 1 - the shell structure - surpassing variant 2 in every secondary criterium.

Together with the earlier conclusion from the grading using the design criteria it can therefore be concluded that variant 1 - the hybrid FRP and structural glass faceted shell - is the best preliminary design variant and will be elaborated on in the next chapters.

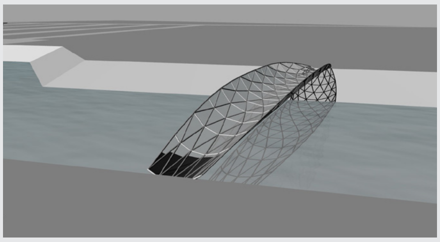
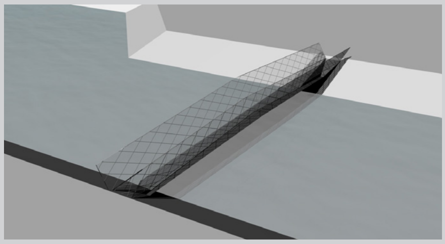
Ranking (secondary criteria)		
Transport & assembly	o o	o
Sustainability	o o	o
Costs	o o	o
Weight	o o	o
Total	8	4

Fig. 6.20 - Ranking of the remaining two variants per secondary criterium

7 The hybrid faceted shell: Theory

Fig. 7.1 - Optimized steel-glass gridshell in Slovakia [Source: http://www.knippershelbig.com/en/projects/port-mall-shopping-centre]

7.1 - Introduction

Variant 1, the faceted shell, is the best variant after grading with the aforementioned criteria. As mentioned before the glass faceted shell combines a lightweight structural concept (the shell), manageable production methods (limited size flat glass elements) with the unique transparency and aesthetics of glass.
The FRP connections combine its high tensile strength (to distribute the tensile forces and bending moments that will occur in the connection details), low weight, translucency (to not oppose the transparency of glass), similar thermal expansion coefficient, durability and moldability with providing protection and ductile post breakage behaviour at the edges of the glass elements.
The previously proposed shell design is, however, not yet structurally ideal. Therefore it is necessary to define the most efficient type of a hybrid faceted shell bridge made of FRP and structural glass. The research question for this chapter is therefore:

> *What is the most efficient type of faceted shell considering the material properties of the applied materials?*

This question will be answered in twofold: first the most efficient general type of faceted shell is chosen in terms of the possible structure types. Secondly the most efficient faceted shell type in terms of topology, shape and connection type is chosen.
These choices are substantiated by an introduction in the general theory of shell structures. Subsequently the different general types of faceted shells and their structural behaviour are introduced. Finally the topology of the most efficient general faceted shell type is treated through theoretical research and precedents.

7.2 - Shell structures

To understand a shell structure and to optimise the shape of the design it is necessary to define a shell structure and to understand its structural behaviour.
Adriaenssens et al. (2014) defines a shell structure as:

> *"A constructed system described by three-dimensional curved surfaces, in which one dimension is significantly smaller compared to the other two. It is form-passive and resists external loads predominantly through membrane stresses."*

Firstly, this means that a shell structure can be defined by its curvature: it can either be curved in one direction (developable) or curved in two directions (non-developable). A developable surface can be stretched, returning to its flat state without stretching or tearing the surface. A non-developable surface has to be torn or stretched to return to its flat state due to its double curvature. Therefore non-developable or double curved surfaces are generally stiffer than developable surfaces. The curvature of a surface can be described by the Gaussian curvature: positive Gaussian curvature means a convex or synclastic shape, negative means a concave or anticlastic shape and zero means a developable or monoclastic surface. [Bagger, 2010]

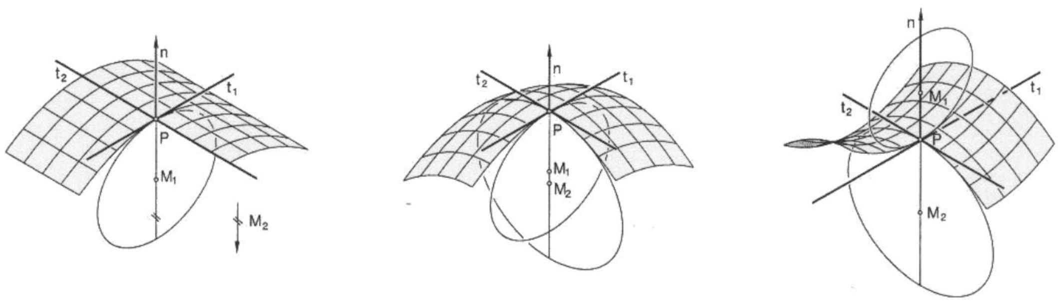


Fig. 7.1 - A surface that is a) monoclastic or developed b) synclastic or convex c) anticlastic or concave. Given are the corresponding complete circles [Borgart, 2017]

Secondly, the curved surface has a small thickness in the direction perpendicular to the surface while the length and width are significantly larger.
Thirdly, it is form-passive, meaning it does not significantly adjust its shape to varying loading conditions unlike membrane structures.
Lastly, it predominantly resists external loads through membrane stresses - which are stresses acting in the plane of the shell - and to a lesser extent through bending stress. This is called shell action and will be explained in paragraph 7.1.2. This shell action is the reason that shells are structurally more efficient than for example flat plates.

7.2.1 - Structural behaviour of a shell

Shells are used when heavy loads have to be carried or large distances have to be spanned, because they have a great load-carrying capacity due to a few features. [Adriaenssens, 2014] According to Calladine (1983) these essential features of a shell structure are its structural continuity, curvature, and its small thickness:

- Continuity makes it possible for a shell structure to transmit forces in infinitely many different directions, unlike a skeletal structure such as a truss or a space frame.
- Curvature makes it possible for a thin shell to equilibrate external loads by a suitable distribution of in-plane forces through membrane action, instead of bending and shear. A shell with good curvature can be in almost pure membrane state.
- The small thickness of a shell is determined by the buckling behaviour and bending moments near supports or free edges. A shell can have this minimal thickness because its in-plane stiffness is always greater than its bending stiffness. The high in-plane stiffness is caused by the high amount of membrane action compared to the bending action in a shell. Due to the small thickness combined with high stiffness the displacements of a shell are very small in relation to the amount of structural material.

7.2.1.1 - Shell action

Shell action - which describes the efficient structural behaviour of a shell - is based on membrane action, which acts in addition to bending action. Figure 7.2 shows the resulting in-plane stresses due to membrane action, while figure 7.3 shows the resulting stresses due to bending action in a small part of a shell.

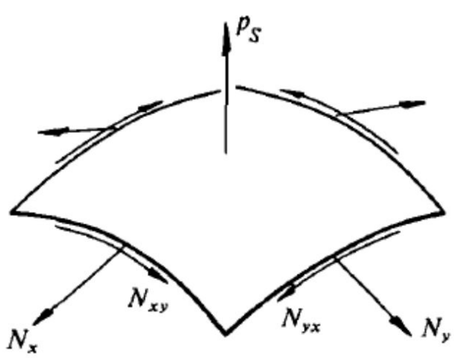


Fig. 7.2 - The resulting stresses due to membrane action: normal and shear forces. [Borgart, 2017]

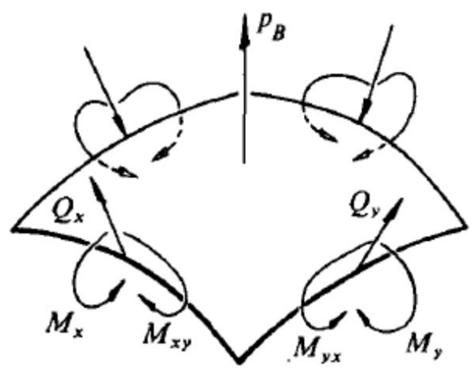


Fig. 7.3 - The resulting stresses due to bending action: bending moments in all directions. [Borgart, 2017]

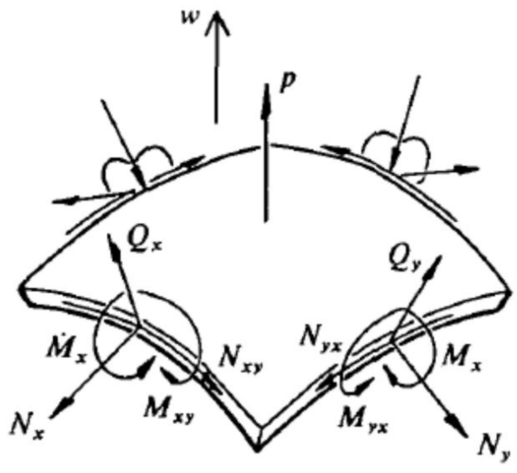


Fig. 7.4 - The resulting stresses due to shell action: a mix of bending and membrane action. [Borgart, 2017]

An ideal shell structure is evenly supported on its lower boundaries. Only membrane in-plane action will occur and the majority of forces are compressive, flowing directly to the supports following the line of curvature of the shell. In reality there will be certain conditions that will cause bending action to occur:

1. A discontinuity in shape or curvature of the mid-surface of the shell.
2. A discontinuity in the thickness of the shell or in the loading of the shell.

Therefore a combination of both bending action and membrane action is most common in shell structures (figure 7.4). [Miura & Pellegrino] This makes a shell structure statically indeterminate. [Adriaenssens, 2014]

7.2.1.2 - Buckling behaviour

A large structural disadvantage of a shell is its buckling behaviour. When the shell is too thin or not stiff enough to resist the direction and magnitude of a force - generally due to bending action - out of plane buckling can occur. This effect is mainly witnessed at its free edges: these can be made stiffer by adding a fold with negative Gaussian curvature.
When only bending occurs while membrane action (extension and contraction) does not occur this is called in-extensional deformation. In-extensional deformation generally leads to buckling of the shell. Shells with zero Gaussian curvature (K=0) over large areas are very susceptible to in-extensional deformation. [Coenders, 2006] A shell should therefore be designed that in-extensional deformation can not occur. This means that a larger curvature generally leads to a better shell.

7.2.1.3 - Flow of forces

To describe the force flow in a shell on a larger scale the thrust line of the load can be used. Whereas a form-active structure (like a rope) will take the exact shape of the funicular thrust line, this is not possible for a form-passive structure like the shell. Normally - in the case of 2D structures like a truss - this means that corrective bending moments will occur in the structure. Instead - due to membrane action in a shell - the line or surface of thrust of the load will be corrected by the hoop forces to coincide with the system line of the shell. This is illustrated for a dome in figure 7.5. Where the line of thrust falls outside the system line the hoop forces are in compression and where the line of thrust falls inside the system line the hoop forces are in tension. When the surface of thrust for any shell is known and the location of the supports is also known (and the steepest way to these supports), it is possible to determine the force flow in the shell. [Coenders, 2006]

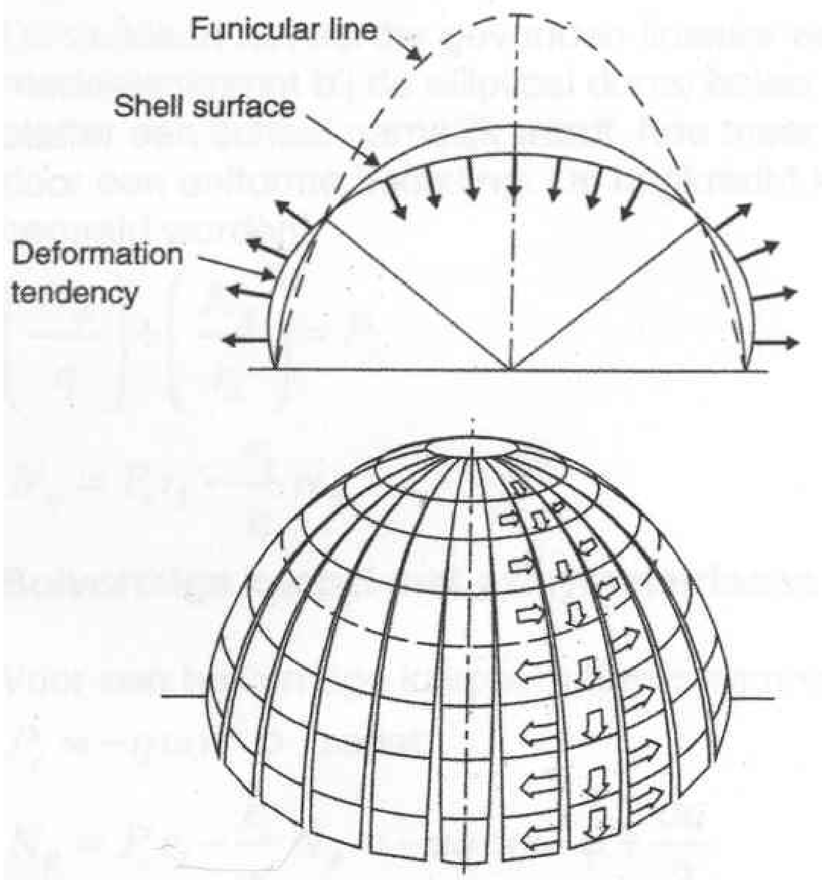


Fig. 7.5 - The effect of hoop forces on a shell structure [Schodeck, 1998]

However, in general this is a difficult way to predict the flow of forces. FE-analysis is therefore necessary to determine the structural response of a shell structure and to subsequently optimize the shape.

7.3 - Faceted shells

Previous theory refers to a smooth shell. However, in this design flat glass panels will be combined with a FRP connection to form a double curved bridge design. This results in a faceted shell.
There are three types of faceted shells that can be distinguished:

1. The gridshell
2. The lattice structure (space frame)
3. The plate shell

All three types of shells have a different definition and different structural behaviour and stability. To choose the right type of faceted shell for the hybrid bridge design, the definition and structural behaviour of all three types will be analysed, considering the material properties of both FRP and glass. When the structural behaviour of the shell type conforms with the material properties of the applied material, that will be the best faceted shell type for this bridge design.

7.3.1 - The gridshell

A gridshell can be defined as a smooth curved shell where material has been removed in a pattern of holes - a subtractive process. This means that a continuous curved structural shell will remain. When the gridshell is defined as a product of an additive process it consists of curved structural elements connected at nodes following a shell shaped form. [Otto, 1974]

Gridshells are designed to carry loads as efficient as possible. The difference between a smooth shell and the gridshell is the limitation of force transfer - the forces can only be lead through the discrete curved elements instead of the entire (smooth) shell it approximates. This leads to extra tension forces and moments in the system in addition to compressive forces that are common in smooth shells. Therefore, its cross-section should also be activated for the resistance of loadings on the system. [Rockwood, 2015]

Fig. 7.6 - The gridshell design of the Multihalle in Mannheim by Frei Otto (1975)

The gridshell will be made from FRP and glass: the continuous curved elements consists of FRP with flat glass elements covering the planes. This system has two major disadvantages concerning both the production of the materials and the structural stability:

1. The glass elements provide stiffness for the gridshell in the diagonal direction. However, FRP has a lower Young's modulus than glass. That means that FRP will have the tendency to deflect more than the glass: the glass will try to keep its shape. This can cause stress and extra bending moments in the glass.
2. The continuous FRP elements will have to be made in one part, which is a difficult production process in any other production method than pultrusion. However, making curved FRP profiles with pultrusion is not yet well developed, resulting in a high cost production process.

Large advantages of this type of faceted shell include the good approximation of smooth shell behaviour through the curved structural elements and the good stability of the system.

7.3.2 - The lattice structure

The lattice structure is point based, meaning that points are used to define each facet plane. By distributing points on a smoothly curved surface and connecting these points with straight lines, a discrete geometry of beams and nodes can be defined.
In the point-based shell structure the beams and nodes are the primary load-bearing structure. These will therefore be very visible as thick elements in the design. [Bagger, 2010]

The stability of this type of structure is different than the gridshell and the plate shell. The beams are not curved so the resulting shell is less efficient than a smooth- and grid-shell. More bending moments will occur in the structural elements.
The nodes are hinged connections so the structure should get its stability from the geometric shape. The most stable (pure) lattice structure consists of triangular planes in a convex shape that is plane-faced, closed, hollow and singularly coherent. [Wester, 1984]

Fig. 7.7 - A lattice structure made of wood connected with steel nodes [Source: http://www.archdaily.com/276056/peoples-meeting-dome-kristoffer-tejlgaard-benny-jepsen]

The beams will be made from FRP while glass triangular planes will stiffen the construction. An advantage over the previously mentioned gridshell is the easier production of the structural elements: they are all straight and discrete. The combination of FRP and glass still leads to a structural problem: the higher stiffness of glass causes extra tension and bending moments in the glass when the FRP deflects more than the structural glass. Also extra connection elements are necessary

Another disadvantage is the worse approximation of smooth shell behaviour and the resulting stability of this type of faceted shell.

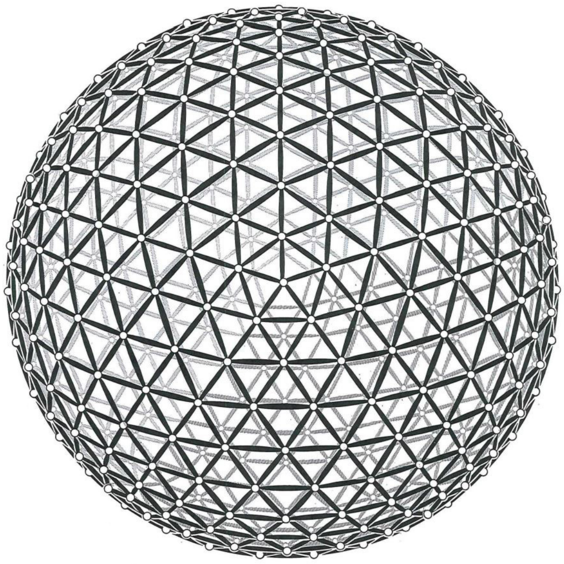


Fig. 7.8 - A stable triangular Euler+ pure lattice structure [Wester, 1984]

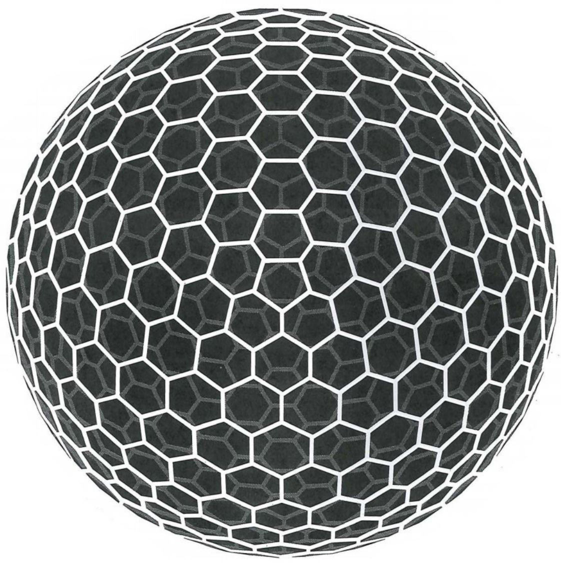


Fig. 7.9 - An internally stable hexagonal Euler+ pure plate structure [Wester, 1984]

7.3.3 - The plate shell

According to Bagger (2010) a plate shell can be defined as a plane-based faceted shell. The surface is approximated by a number of planes, meaning that the position and orientation of each plane is defined in space, and the facets' boundaries are produced by determining the intersection lines and points of these planes.
The plane-based geometry results in a shell where the facets are the primary load-bearing structure. The vertices or connections can be irrelevant for the stability of the system: the stability is based on distributed in-plane forces in the facets. [Bagger, 2010] This can lead to more transparency, because the connections can be very slender and light (depending on the efficiency the of the structure).

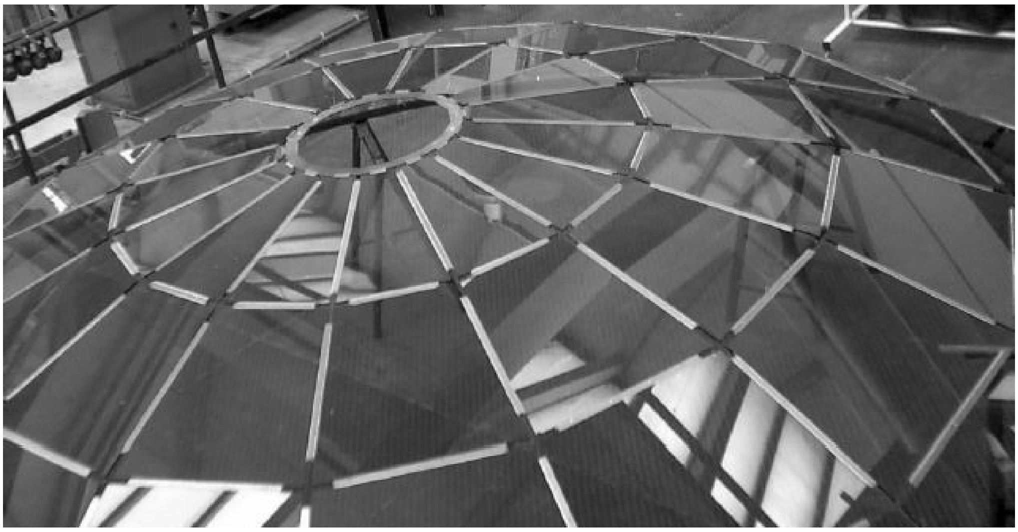


Fig. 7.10 - A structural glass dome - a plate structure [Veer, 2005]

The plate shell has structural efficiency comparable to the lattice structure: it carries load by both membrane action and bending action, while a smooth shell is dominated by membrane action and has minimal bending action. This results in displacements of a plate shell that are about 2-3 times larger than the displacements of an equivalent smooth shell. [Bagger, 2010]

In this structural system there will be no problem with the difference in stiffness between glass and FRP. The stiffest material is the main load-bearing material, while the FRP connections will only transfer small bending moments, torsional moments and shear forces. The elements thereby are all flat: the glass facets and straight FRP connecting members. Therefore production of these elements will be relatively easy.

7.3.4 - Discussion

A shell is a very efficient structural shape due to shell action: a mix of membrane action and bending action. In the ideal shell most forces will be in compression and transferred in the plane of the shell (membrane action).
A faceted shell is in fact a less efficient shell approximating the smooth shell. More bending action will occur in a faceted shell compared to a smooth shell. There are three different types of faceted shells to distinguish:

1. A gridshell with continuous and curved FRP elements as the main load-bearing material, with flat glass facets to stiffen the construction and minimize vibrations. This results in a curved FRP frame with optimized cross-sections, with glass facets of sizes depending on the FRP frame, stiffening the frame.
2. A triangulated lattice structure where discrete and straight FRP elements are connected in nodes. Glass plates are connected to the FRP beams to stiffen the structure diagonally.
3. A plate shell where flat glass plates are the load-bearing structure. FRP connecting elements of uniform width will transfer bending moments and resist some shear.

The type of faceted shell should be chosen while considering if the structural behaviour of the structural elements conforms with the material properties of the applied material:

A faceted shell where FRP acts as main load-bearing structure with glass elements to stiffen the structure, will lead to extra stresses in the glass elements. Both elements will have a different deflection - FRP will deflect easier while glass will try to keep its initial shape. This results in extra tension and bending in the glass elements. Such structural behaviour will occur in the gridshell and the triangulated lattice structure.

When glass itself is the dominant load-bearing structure then the stiffness of the entire structure will be determined by the glass elements themselves. No extra tension or bending will occur in the glass or FRP elements. Therefore a plate shell is a more efficient structure than the gridshell or the lattice structure, considering the used materials.

Apart from the structural point of view, the plate shell also offers the highest grade of transparency. The non-transparent connections can be very slender as they are not the main load-bearing structure.

The best general type of faceted shell is therefore the plate shell. It approximates the structural efficiency of the smooth shell, while no large stress concentrations occur in the glass due to the difference in stiffness between the materials FRP and glass.

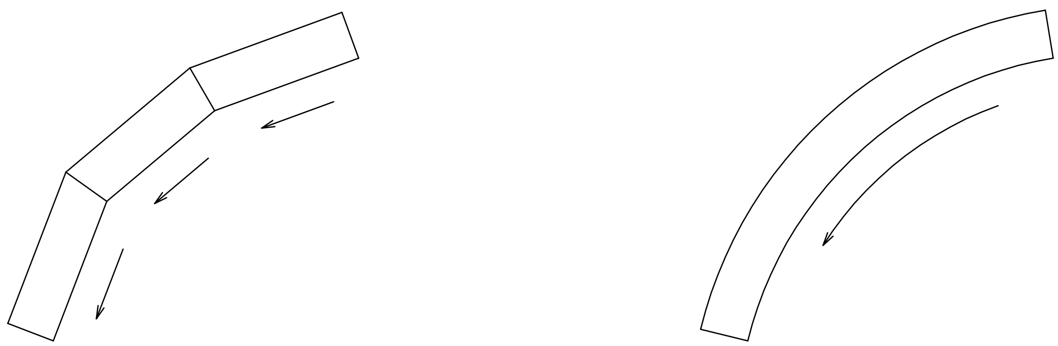


Fig. 7.11 - The gridshell has continuous curvature while the lattice structure and the plate shell are discrete leading to bending moments between the facets.

7.4 - Background of the plate shell

The plate shell has only recently started to be researched more extensively. Therefore knowledge in many facets of this subject is still lacking. This chapter will summarize the possibilities and limitations of the state of the art research into plate shells. By comparing the current possibilities in the field of plate shells with the requirements for the hybrid bridge design it is possible to make several preliminary design choices.

7.4.1 - Structural behaviour

A faceted plate shell behaves different than a smooth shell. This difference can be considered on both a larger scale - the scale of the global shell and a smaller scale - the scale of a plate:

7.4.1.1 - Global bending

On a global scale the shell is subjected to both bending action and membrane action, as mentioned before. When a plate shell is subjected to global bending action, the out of plane forces at a facets' edges are balanced out by adjacent facets and carried to the supports. Torsional moments will occur in the FRP connections to transfer this bending action.

7.4.1.2 - Plate bending

On a local scale the plate itself will also be subjected to bending - plate bending. When a facet is subjected to bending it will act like a slab, carrying the load to the edges, where the load is transformed into in-plane loads. This process is described through the following schemes taken from the research of Anne Bagger (2010) (figure 7.11 to figure 7.14, see next page). For this description global bending action of the shell is **not** considered, meaning that all out-of-plane shear forces are transformed into in-plane forces at the facet edges.

The resistance of the facets against local plate bending is much lower than their in-plane strength. Therefore it is feasible to minimise this bending action by decreasing the size of the facets, increasing the number of facets or increasing the thickness of the plates (higher stiffness). [Aanhaanen, 2008]

7.4.1.3 - Non-linear behaviour

In reality the load on a facet will not be as linear as described. Each facet will be loaded by both in-plane loads (through shell action) and out-of-plane loads (plate bending). When the load level increases the in-plane and out-of-plane stiffness of the facets will change. This leads to a rearrangement of internal forces in the facets: a stiffening effect occurs when the out-of-plane deflection becomes comparable to the plate thickness (0,5 to 1 times the thickness). A softening effect occurs as the in-plane load reaches the buckling load of the plate. This will only happen if large plate displacements occur first. [Bagger, 2010]

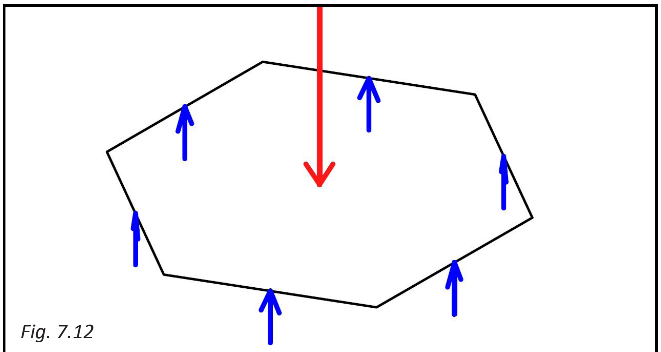


Fig. 7.12

An external out-of-plane load on a facet (red arrow) will cause bending action in the facet. The load is transferred to the facet edges through out-of-plane shear (blue arrows show the reaction for each facet edge). [Bagger, 2010]

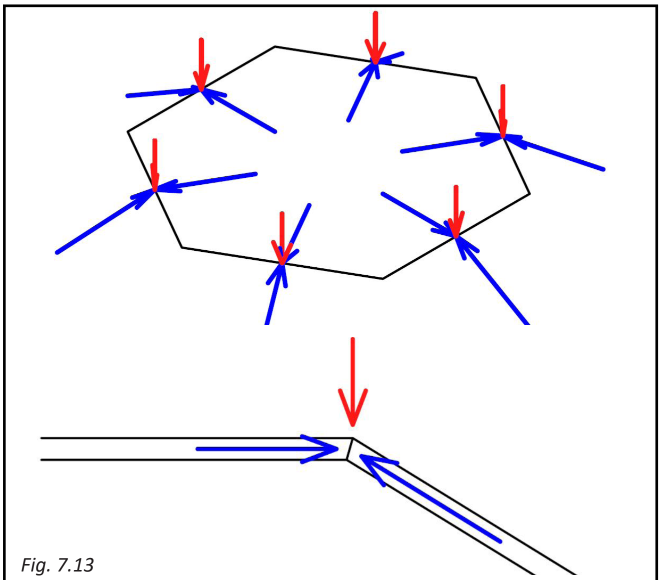


Fig. 7.13

The out-of-plane shear forces (red arrows) at the facet edges are transformed into in-plane force in the facet and the neighbouring facets (blue arrows). These axial in-plane forces are perpendicular to the facet edges. The out-of-plane shear forces (and the balancing axial in-plane forces) are not uniformly distributed along the facet edges. [Bagger, 2010]

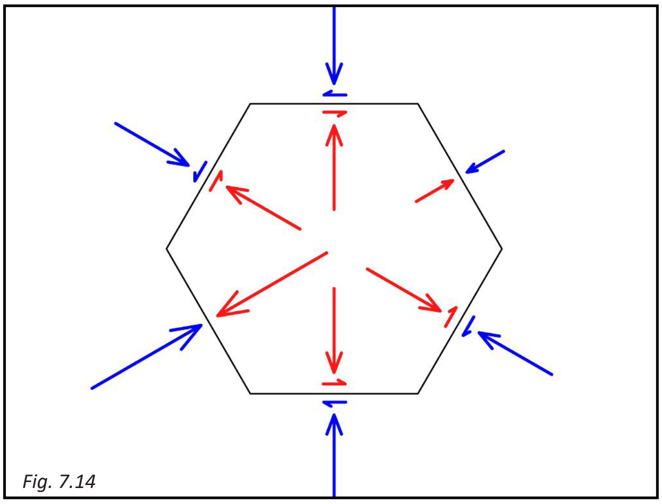


Fig. 7.14

When the axial in-plane forces in a facet are not in equilibrium along the facet edges (large blue arrows), the resulting in-plane force in the facet (large red arrows) will be transferred to the adjacent plates by in-plane shear (in the FRP connections) along some of the edges (small blue and red arrows). [Bagger, 2010]

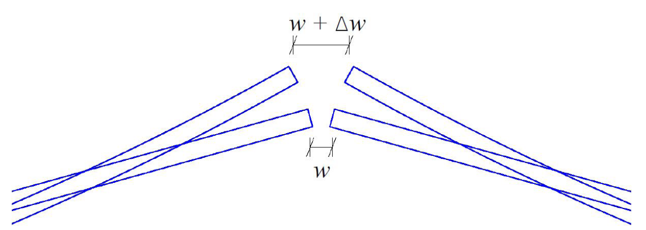


Fig. 7.15

When a facet bends, the facet edges will curve upwards with a distance depending on the stiffness of the connection detail. In-plane forces will develop at the facet edges, perpendicular to each edge. These forces will be added to the axial in-plane forces in the facets mentioned before.
The resultant of these forces summed up over an edge is zero, but locally they can become large leading to stress concentrations. [Bagger, 2010]

7.4.2 - Tessellation

The shape of the planar plate has a large influence on the stability of the entire shell structure. Secondly, the plate can have a large influence on the costs and production methods of the bridge. By considering the type of plates for the faceted shell and their corresponding structural behaviour it is possible to choose the most efficient plate shape - a topological choice. There are three main types of plate shapes to be distinguished:

1. The triangular plate
2. The quadrilateral plate
3. The hexagonal plate

7.4.1.1 - Triangular

The triangular system results in concentrated nodal forces. This is a result of the fact that the system can not act as a plate structure due to the six-way vertices. The flow of force therefore has to travel from the corners in the glass panes through the connectors to the next glass panes. This leads to fairly concentrated stresses. [Aanhaanen, 2008]

Another disadvantage of triangular plates is the large material costs. Cutting the glass panels is a costly procedure while it also makes the plate more fragile during transportation. Secondly, the drawback of this method is the high number of connecting elements that is necessary for the large number of edges.

7.4.1.2 - Quadrangular

The quadrangular plate shape has been implemented in several precedents, for example the glass dome illustrated in figure 7.16. However, this type of plate also relies on a triangular-based subsystem. This system leads to concentrated normal forces in the subsystem while the glass serves as a separation to the outside or as a stabilizing system. [Aanhaanen, 2008]

7.4.1.3 - Hexagonal

The most stable plate shell consists of hexagonal planes with Y-vertices or three-way vertices (figure 7.9) in a convex shape that is plane-faced, closed, hollow and singularly coherent. [Wester, 1984]
When three-way vertices are used, the vertices will become forceless and the system will be forced to transfer the forces through normal forces between the edges of the facets. This can be explained by considering a normal force through one of the three edges. Because there are only two other edges connected to the vertex they will not be able to counter this force unless being in the same plane. Since they are not in the same plane, the concentrated forces in the vertices can not develop. [Aanhaanen, 2008]
The hexagonal plate shape is therefore the only shape where large stress concentrations in the edges do not occur, while being stable.

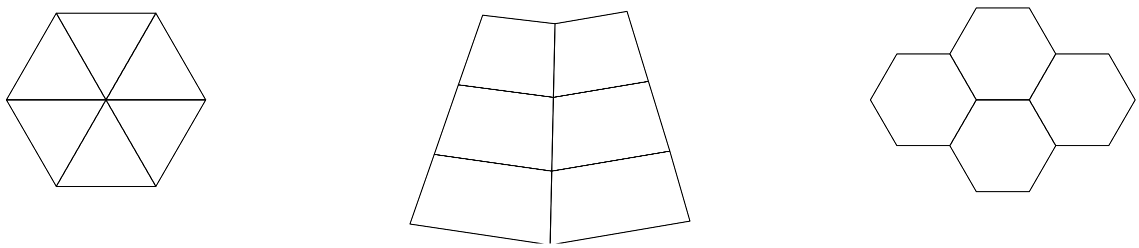


Fig. 7.16 - The three types of plate shapes. From left to right: triangular, quadrangular and hexagonal. The most stable plate shape, leading to the least stress concentrations, is the hexagonal plate due to its three-way vertices.

7.4.2 - Connections

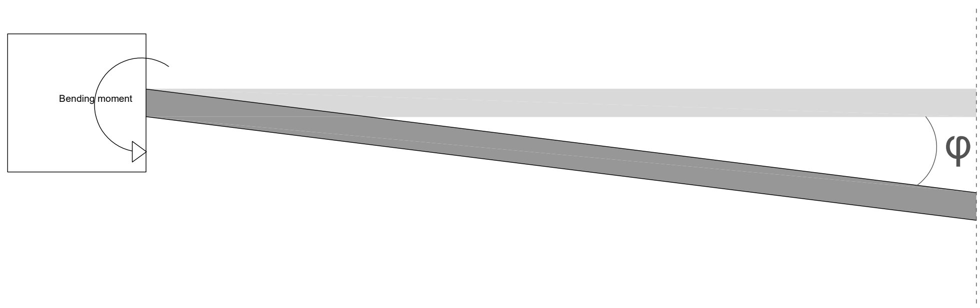
The first requirement for the connections in a plate shell is that they can withstand the loads they are subjected to. A connection in a plate shell has to transfer loads between the facets: primarily bending moments and in-plane forces. The amount of load transferred by the connection detail depends on the efficiency of the shell structure, the stiffness of the glass facets and the stiffness of the connection detail itself. [Bagger, 2010]
More detailed, the connections in a plate shell are subjected to the following stresses: [Aanhaanen, 2008]

1. Bending moments resulting from the stiffness of the joint itself
2. Out of plane shear forces (which are transformed into in-plane forces)
3. In-plane normal and shear forces (see figure 7.14)
4. Forces resulting from the uplift of corners (see figure 7.15)
5. Out-of-plane shear forces from the transfer of torsional moments

7.4.2.1 - Rotational stiffness of the detail

The first type of bending moments results from the stiffness of the joint itself. When the shell is well designed to equilibrate external loads into in-plane forces through shell action, these are the largest bending moments in the FRP connections. These bending moments mainly depend on the rotational stiffness K_m of the connection. When the rotational stiffness K_m of a connection detail is larger, the bending moment around the axis of the connection will generally also be higher. A high rotational stiffness will therefore restrain the plate from bending [Bagger, 2010]. This relation is given by the definition (see figure 7.17):

$$m = k_m * \phi$$



This behaviour can be explained by an example: the bending moments in a faceted arch (figure 7.18). When the arch has fixed connections (and is fixed on both ends) it will deflect less, but the bending moments in the plates will be higher. This means higher stress concentrations in the glass facets. It will also be sensitive to buckling: in a very rigid system the deflection will be minimal, followed by sudden collapse of the entire structure.
When the arch has hinged connections it will allow for rotation and as a result deflect more, but the bending moments will be lower. This system can, however, snap through when the deflection becomes too large.
The ideal system is therefore a semi-rigid system where the bending moments are low and the connections allow for a larger deflection.

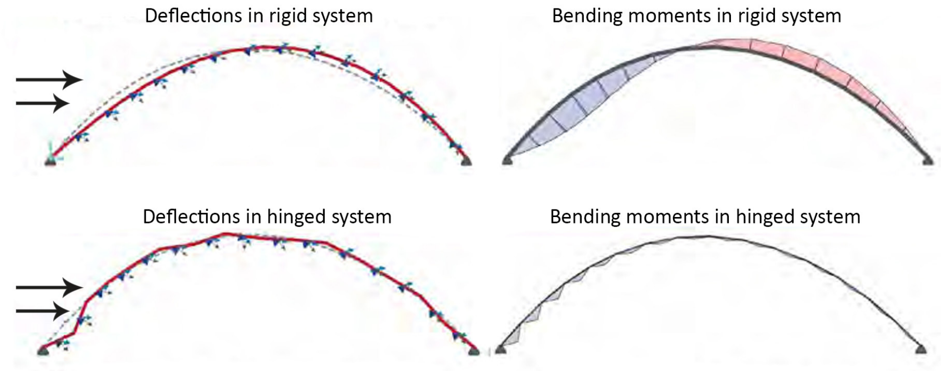


Fig. 7.18 - Structural behaviour (bending moments and deflection) of a faceted arch under a live load [Nikolao, 2017]

According to Bagger (2010) the appropriate stiffness for the connection of a semi-rigid system can be determined in relation to the bending moment of the plates. The largest bending moment in a plate will occur either in the middle or near the middle of one of the facets' edges. This bending moment can be estimated by determining the bending moments in a circular plate - supported by a rotational spring support - followed by an adjustment to polygonal geometry (the hexagon).

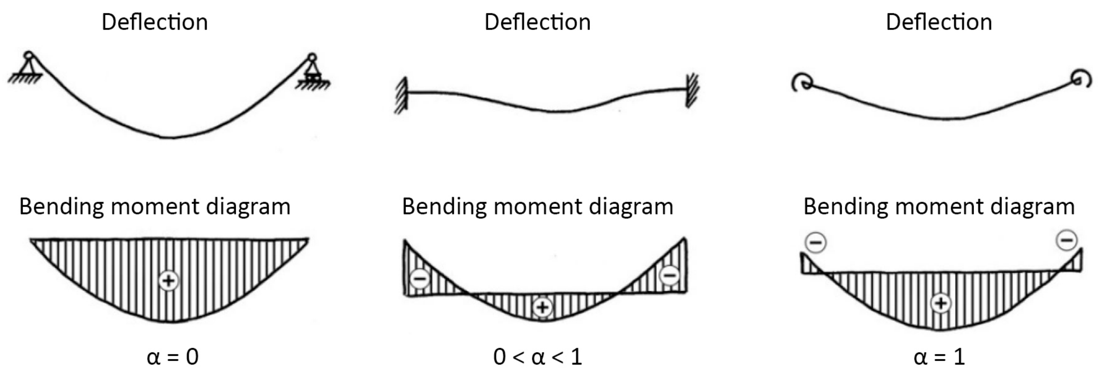


Fig. 7.19 - From left to right: the deflection and bending moment diagram of a fully hinged connection, fully rigid connection, semi-rigid connection. [Bagger, 2010]

Bagger introduces the rotational restraint factor α (figure 7.19). This factor defines the type of connection:

- α = 0 means a fully hinged connection
- 0 < α < 1 means a semi-rigid connection
- α = 1 means a fully rigid connection

With:

$$\alpha = \frac{k_m}{k_m + k_p} \qquad k_m = \frac{E\,t^3_{joint}}{6\,W_{joint}} \qquad k_p = \frac{E\,t^3_{plate}}{6\,l_{plate}(1-v)}$$

Research shows that the plate edge rotation, the deflection of the plate and both the bending moment at the support of a circular plate and in the plate middle varies linearly with α. This results in the following equations:

$$u = (1 - \alpha) u_s + \alpha u_c$$

$$m_{edge} = \alpha m_{edge,c}$$

$$m_{mid} = (1 - \alpha) m_{mid,s} + \alpha m_{mid,c}$$

$$\phi = (1 - \alpha) \phi_s$$

To calculate the above given bending moments (m), deflections (u) and rotation (ϕ) for both a hinged connection and a rigid connection the following terms, adjusted for a polygonal plate geometry, are given:

Plate shell facet with 4, 6 or more edges	
Edges hinged $(k_m = 0)$	Edges clamped $(k_m \longrightarrow \infty)$
$u_s = 1.1 \cdot \frac{5 + v}{1 + v} \cdot \frac{1}{1024} \cdot \frac{qd^4}{D}$	$u_c = 1.1 \cdot \frac{1}{1024} \cdot \frac{qd^4}{D}$
$m_{edge,s} = 0$	$m_{edge,c} = -1.4 \cdot \frac{1}{32} qd^2$
$m_{mid,s} = 0.9 \cdot \frac{1}{64} \cdot (3 + v) qd^2$	$m_{mid,c} = 1.3 \cdot \frac{1}{64} \cdot (1 + v) qd^2$
$\phi_s = 1.1 \cdot \frac{qd^3}{64D(1 + v)}$	$\phi_c = 0$

Fig. 7.20 - These equations can be used to calculate the bending moments, deflections and rotation of a plate after calculating the rotational restraint factor α.[Bagger, 2010]

7.4.2.2 - Axial stiffness of the detail

The axial stiffness K_n of the connection detail defines the in-plane movements when forces are transferred through shell action. It has an effect on the critical load for the shell structure: a higher axial stiffness generally means a higher critical load. [Bagger, 2010]
It will also have an effect on the tendency of the glass plates to curve upwards at their edges when they are loaded with out of plane loads. This can be explained by the changing distance between the plates when they curve upwards: this distance becomes larger. When the axial stiffness is high, the distance can not become larger, thus minimizing the curvature. The relation between in plane movements and the axial stiffness is given by the definition (see figure 7.21):

$$n = k_n \cdot \Delta y$$

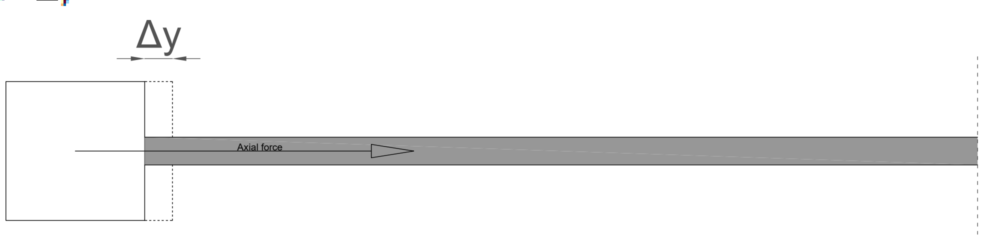


Fig. 7.21 - Definition of axial stiffness [Bagger, 2010]

7.4.2.3 - Uplift of corners

When a force is introduced on a simply supported hexagonal plate, the plate centre will deflect in a shape that resembles the deflection of a circular plate as much as possible, as this is the energetically most efficient. [Bagger, 2010] This will result in an uplift of the corners of the plate.
The connection detail will oppose this movement (depending on its axial stiffness) which will cause stress concentrations in the corners of the plate. This can be explained by the angle of the principle stresses to the edge: this should be at a 90 degree angle. However, the deformed plate has zero curvature in the direction of and perpendicular to the edge. The 90 degree angle is impossible in the corner leading to stress concentrations.
Combined with the higher fragility of the corner, a solution should be found for these stress concentrations. There are three possible solutions for this problem:

1. A clamped connection: this will result in no stress concentrations in the corners of the plate as the edge is restrained from both translations and rotations. The problems of a clamped connection are, however, shown in paragraph 7.3.2.2 and will therefore not be applied in this design.
1. The stress concentrations can be reduced by shortening the connections along the facets' edges: an area in the corner will be left free and thus free to lift. [Bagger, 2010] This has as second advantage the incorporation of a water drainage. Surplus water can escape via the free corners to make the bridge less slippery and heavy under rainy circumstances.
2. Rounding off the edges of the plates. This will somewhat reduce the peak stresses in the corners and will make these corners less fragile during transport and assembly. [Aanhaanen, 2008]

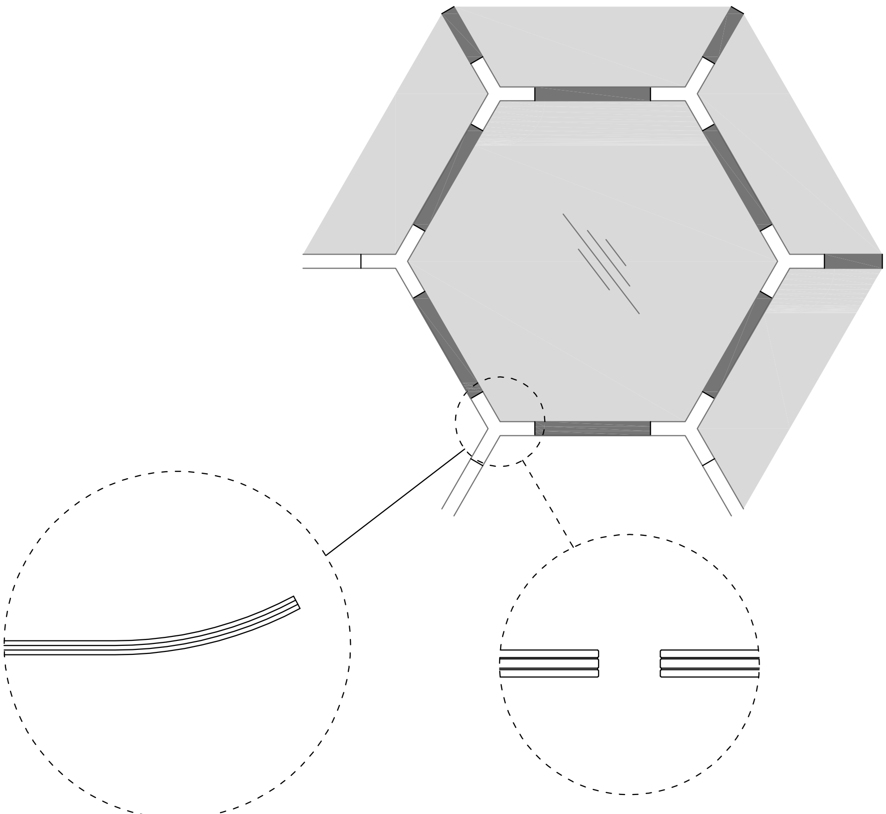


Fig. 7.22 - Uplifting of plate corners. By reducing the length of the connections the stress concentrations in the weaker corners are minimized, while providing water drainage.

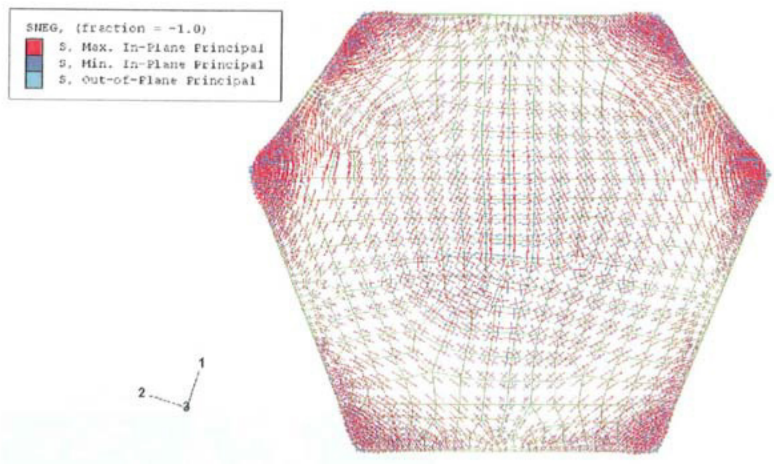


Fig. 7.23 - The stress concentrations in the weaker corners of a plate: simply supported plate with a evenly distributed load of 1,0kN/m2 perpendicular to the plane. [Isgreen, 2007]

7.4.2.4 - Functional requirements

The connection detail should be strong enough to withstand all the previously mentioned forces. Furthermore there are several functional requirements for a connection detail in a plate shell that apply to this bridge design. [Bagger, 2010].

1. The appearance of the detail should be slender and light to show that the facets are the basic structure: the connections merely transfer the loads between the facets.
2. The connection detail should be as simple as possible to assemble, to ensure connections that are visually homogeneous, and have the desired strength and stiffness.
3. Temperature movements in the connection detail should not induce significant stresses in the detail or in the glass. This means that materials with a different thermal expansion than the glass must not be fixed too rigidly to the glass.
4. When the detail would fail it is desirable that a certain yielding capacity, where forces are redistributed to relieve the detail for some of the load, is present.
5. If parts of the connection detail display time dependent behaviour, such as creep, the consequences must be assessed.
6. In case a facet needs replacement, it is preferable that the connection detail can be disassembled without harming the surrounding facets, so that the broken facet can be removed, and a new facet can be fastened.

7.4.3 - Overall geometry

According to Aanhaanen (2008) there are several factors that can lead to early design choices for the basic geometry of a plate shell:

7.4.3.1 - Direction of curvature

As mentioned in the material research, glass behaves best in compression. Microscopic cracks in the surface of glass make glass weak in tension. Therefore the shape of the shell should lead to compression in the structural members in most of the load cases. To create a shell which is loaded in compression the Gaussian curvature should be positive.

7.4.3.2 - Magnitude of curvature

In order to create a shell with an efficient load bearing behaviour it is necessary to refrain from having areas of low curvature in the shell. These areas are more ductile and it will therefore be tried to create a relatively high curvature for the entire shell. These areas can also invoke bending stresses in the shell, which is a very inefficient load carrying mechanism. Of course this also depends on the angle of the flat areas with the load and support.

7.4.3.3 - Free edges

The bridge design in this thesis will be a free-form shell shape. This shell will therefore have free edges. Such a plate shell has not yet been developed and tested. Previous research included dome-shaped shell designs.

The free edges of this new type of plate shell might therefore require stiffening the edges when the torsional moments are too large.

7.5 - Conclusion

The most efficient type of faceted shell - from the three types that can be distinguished - is the plate shell. This type of shell approximates the structural efficiency of the smooth shell, while no large stress concentrations occur in the glass due to the difference in stiffness between FRP and glass.

The best shape of the plate for a plate shell is the hexagon. This is the only plate shape where three way vertices are used. Due to this type of connection it is not possible for the system to transfer forces through the vertices. The system is forced to transfer normal forces through the edges of the plates: a plate shell.

The connection in a plate shell should be strong enough to withstand the loads it is subjected to. These loads depend on the shell behaviour, but also on the stiffness of the detail itself.

A high rotational stiffness attracts larger bending moments. This relation between bending moments and the rotational stiffness of the connection detail can be calculated with several equations provided by Bagger (2010).

A high axial stiffness results in a higher critical load, but also in higher stress concentrations in the corners of a plate, due to the restraining of the uplifting of these corners. When the connection detail is shortened and the corners rounded off, the stress concentrations in these corners can be minimized while also incorporating water drainage for the bridge.

Lastly, the connection detail has several functional requirements, namely an easy assembly, slender appearance, thermal behaviour of the used materials that is almost equal, good yielding capacity, account for creep and easy replacement.

The basic overall geometry of the shell depends on material properties and shell behaviour. First of all a plate shell made of glass plates should have a positive Gaussian curvature. When a plate shell would have negative Gaussian curvature this will lead to tension in the plates. Glass has weak tensile properties due to microscopic cracks in the surface, therefore the hybrid bridge design should have a positive Gaussian curvature.

Secondly, the curvature of the plate shell should be as high as possible in regards to the program of requirements. Low curvature can lead to higher bending stresses, which is a very inefficient load carrying mechanism.

Thirdly, a glass plate shell with free edges has not yet been researched. It is possible that the free edges of this shell should be stiffened, to account for high torsional moments.

8 | The hybrid faceted shell: Form-finding & optimization

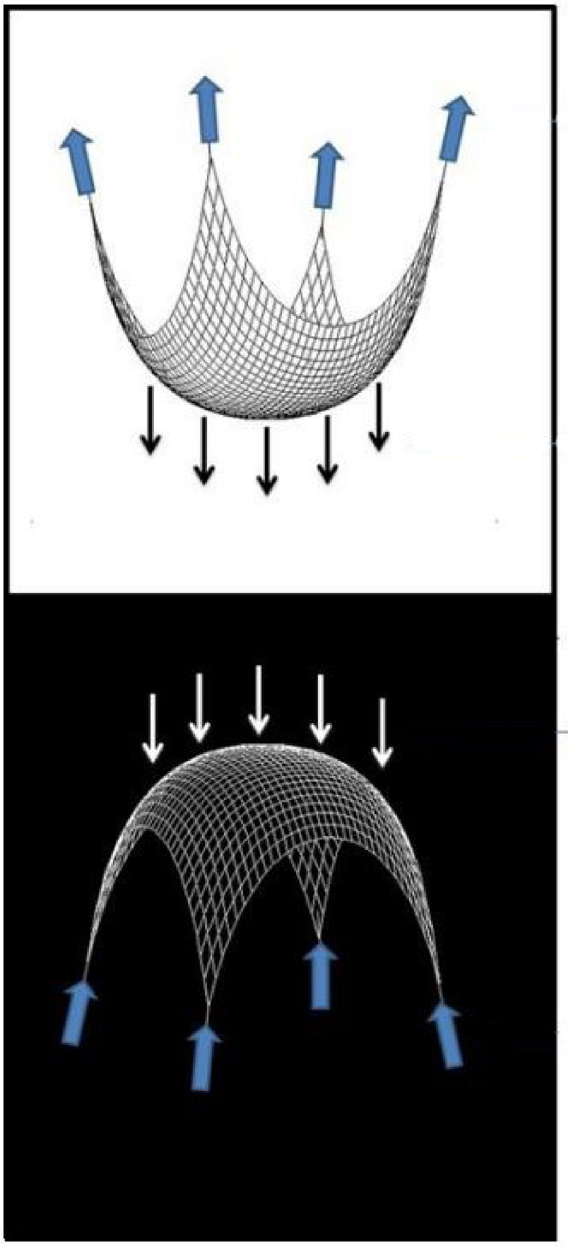


Fig. 8.1 - Principle of hanging chain models - first loaded in tension by its own weight, then reversed to be loaded in compression [Source: http://shells.princeton.edu/Mann2.html]

8.1 - Introduction

The shape and the sizes of the design can now be altered - considering the aforementioned shell theory - through a process of form-finding and optimization. The research question of this chapter is therefore:

What is the most efficient faceted shell in terms of shape and sizes of the shell?

The form-finding and optimization process should fit to the type of faceted shell that has been chosen in the previous chapter - the plate shell. The process will therefore consist of the following steps (figure 8.2):

- Defining boundary conditions
- Form-finding
- Geometric optimization
- Structural analysis
- Structural optimization

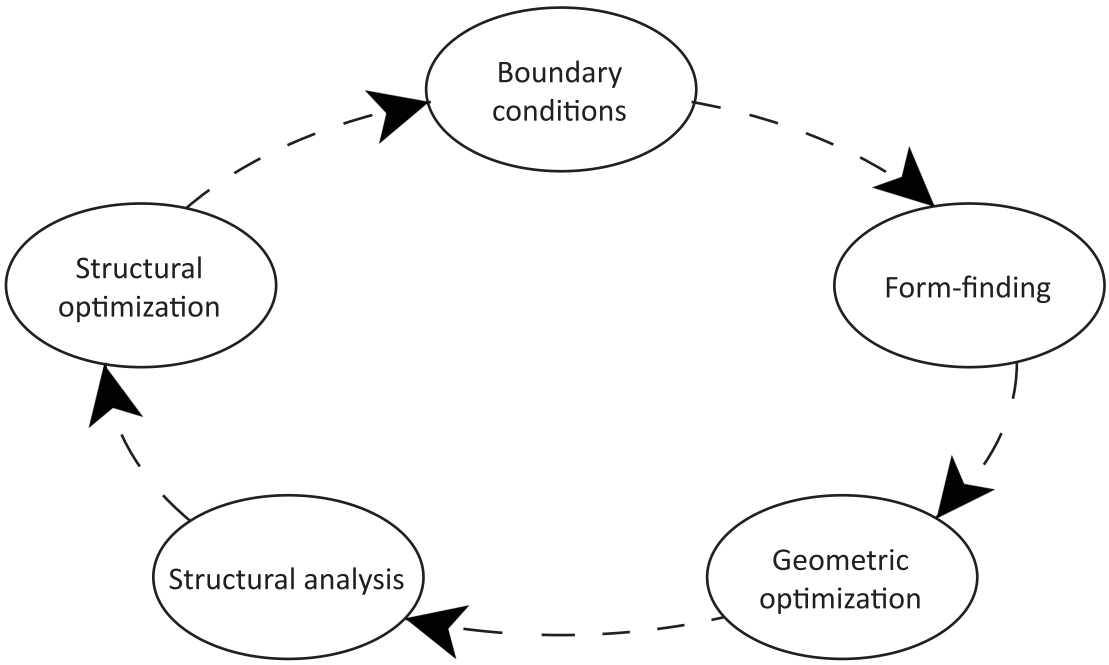


Fig. 8.2 - Overview of the to-follow process during the form-finding and optimization of the hybrid faceted shell bridge.

8.2 - Boundary conditions

The boundary conditions for the design of the hybrid bridge that are necessary for the form-finding and optimization process can be divided in four subjects:

- Dimensions
- Materials
- Basic geometry
- Connection type

The dimensions follow from the demands stated in chapter 1, the material choice follows from the theoretical framework created in chapter 2, 3, 4 and 5, the structurally most efficient topology is chosen in chapter 7 and finally the connection type is also based on the elaboration in chapter 9.

8.2.1 - Dimensions

The boundary conditions for this bridge design can be taken from chapter 1. The maximum and minimum dimensions of the bridge follow from the location analysis and the program of requirements (see chapter 1):

- The maximum width of the bridge is 10 meter
- The minimal width of the bridge (walkable surface) is 2,2 meter
- The total length of the bridge will be 33,8 meter
- The maximum inclination of the bridge will L/20 in the middle of the bridge, so 17050/20 = 853mm
- The vertical clearance of the bridge will have a minimal height of 2,60 meter over a width of 3,75 meter.

The parameters of the form-finding and structural optimization process will have to be adapted so the final shape does not exceed the maximum sizes of the bridge. The shell shape will then be optimal within the set of boundary conditions.

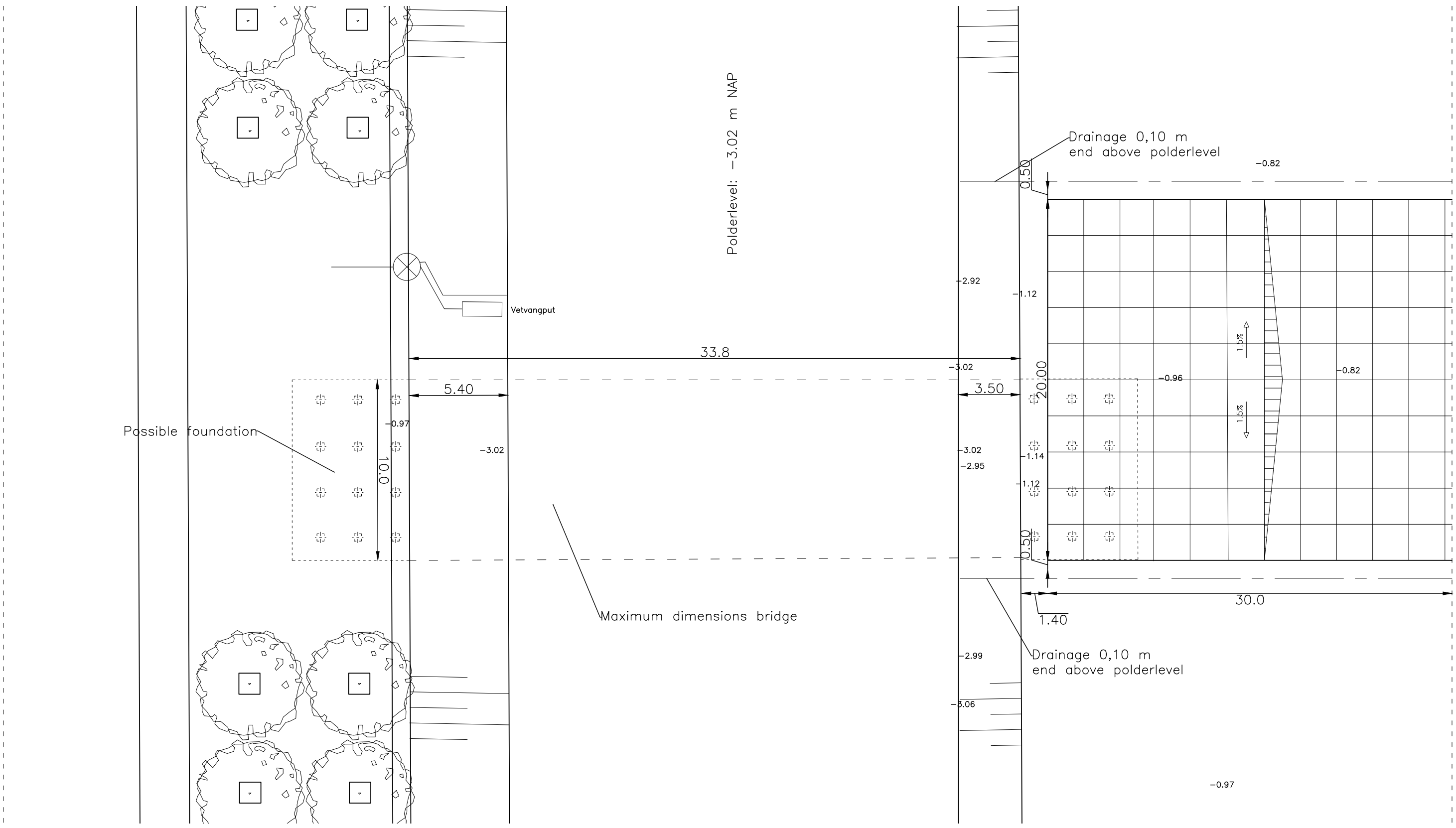


Fig. 8.3 - Boundary conditions location

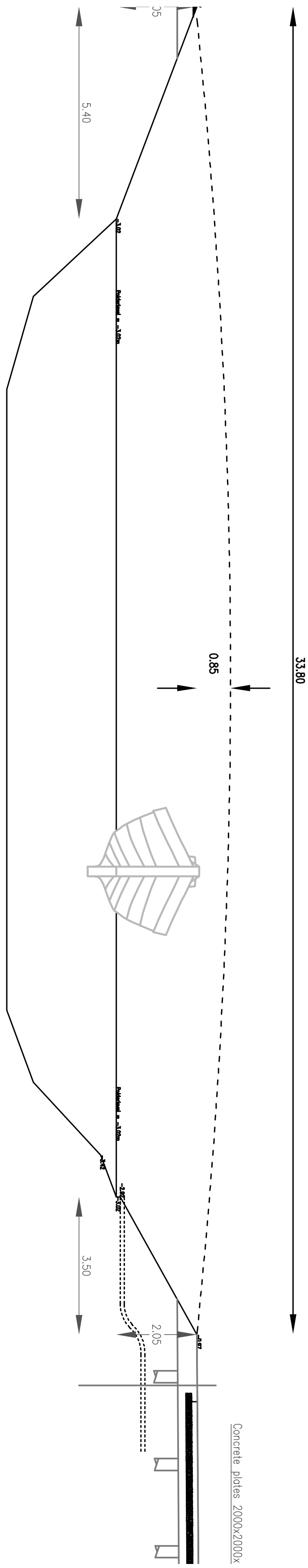


Fig. 8.4 - Boundary conditions location

8.2.2 - Material choices

During the material research a theoretical framework has been made to provide enough information to make the right material choices in this stage of the research. This material choice is defined here and used as input for the structural analysis and optimization phase.

8.2.2.1 - Heat strengthened glass (laminated - 5 layers with SentryGlas interlayer)

The plate shell will consist of flat glass elements. Flat elements are preferred over curved elements due to economic and tolerance related reasons.

From the four types of glass - depending on the amount of heat or chemical treatment - one type of flat glass has to be chosen to apply in this design. This will be heat-strengthened glass, due to its favourable breaking pattern combined with an elevated bending strength compared to the other glass types (figure 3.6 in chapter 3.4). The glass type related to the chemical composition will be soda-lime silica glass as this type of glass is most common and therefore economically most favourable.

The preliminary build up of the glass plates will consist of five layers of glass laminated with a SentryGlas interlayer material. This is the strongest type of interlayer material currently available.
One 6mm sacrificial top layer will be sandblasted to prevent slipping on the walkable surface of the bridge. This type of surface treatment will result in a semi-transparent surface. The bottom layer of the plate will also be a sacrificial 6mm glass pane.
The structural core consists of three layers of glass (8-10-8mm), with the middle layer being the thickest due to the FRP embedded sheet. The exact thickness of the glass plates can be altered during the form-finding and optimization phase, depending on the results.
The proposed composition of the (hexagonal) glass plates is shown below (figure 8.5):

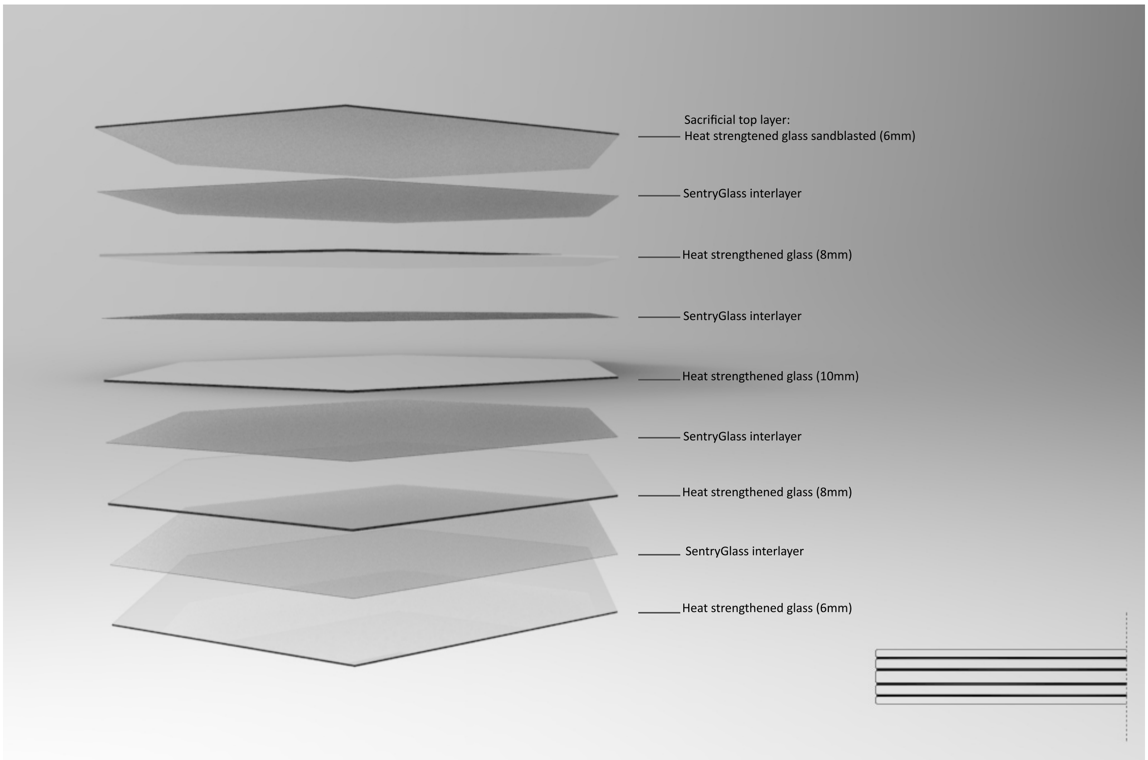


Fig. 8.5 - Initial build-up of the hexagonal plate with GFRP embedded sheet

8.2.2.2 - Quasi-isotropic glass-fibre reinforced polymers (60% fibre volume)

The purpose of the FRP connection detail is to transfer forces between the plates. These forces include bending moments, torsional moments, shear and compressive & tensile forces. The exact amount and direction of these forces will differ: people can walk over the bridge in all directions. Therefore it is necessary to compose a FRP material that can be loaded in all directions: the material should be quasi-isotropic. The proposed quasi-isotropic build-up of the material is (0, +-45, 90) (see figure 8.6).

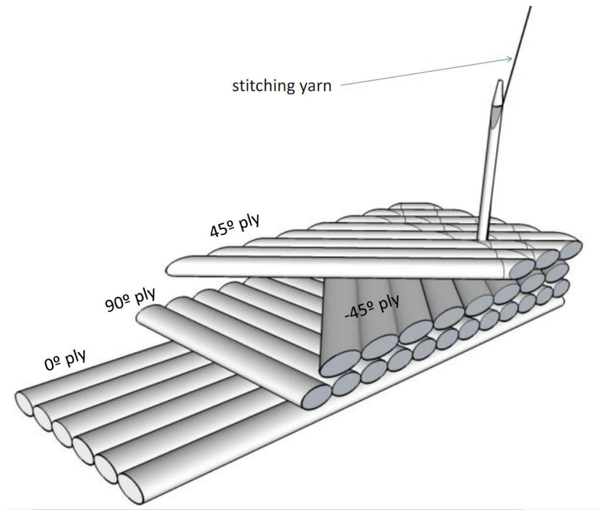


Fig. 8.6 - Quasi-isotropic build-up of the GFRP material chosen for the embedded GFRP sheet.

Glass-fibres will be used as they are the most commonly used and the cheapest fibre type, while still having relatively high strength. Glass-fibres also have the possibility to be translucent (figure 5.6 in chapter 5.3). Continuous glass fibres will be used, due to the higher mechanical performance than short or chopped glass fibres.

There are several kinds of glass-fibres: E-glass fibres, C-glass fibres and S-glass fibres. All have slightly different properties. Important is the large tensile strength and low thermal expansion coefficient of the fibre type. This results in a choice between E-glass fibres and S-glass fibres. S-glass fibres are the strongest and stiffest type, while E-glass fibres are the cheapest fibre type with relatively high stiffness and strength. Therefore E-glass fibres are chosen for this design.

There are several types of matrices in use for FRP materials, with each their own advantages and disadvantages. The most important demands for the properties of the matrix type for this bridge design are:

- Low thermal expansion coefficient
- High durability (high corrosion resistance)
- High fire resistance

An epoxy resin has the highest mechanical properties of all resin types (figure 2.11 in chapter 2.7.3), but also the highest costs. Because it is used in a innovative bridge design with a focus on structural strength and stability, the use of this resin type is substantiated.

The previous economic, structural and aesthetic reasons conclude in the use of quasi-isotropic glass-fibres and laminated heat-strengthened glass with SentryGlas interlayer material for this bridge design. These materials have the following material properties [CES, 2017] [Bos, 2009]:

Material properties	Heat strengthened glass (soda-lime silicate)	Epoxy + E-glass fibres (0,+-45,90)	SentryGlas interlayer (1,52 mm)
Density (g/cm^3)	2.5	1.75 - 1.97	0.92
Young's modulus (GPa)	70	15 - 28	0.256
Shear modulus (MPa)	-	6 - 11	86.6
Poisson's ratio	0,22	0.314 - 0.315	0.479
Yield strength (elastic limit) (MPa)		110 - 192	-
Tensile strength (MPa)	70	138 - 207	34.5
Compressive strength (MPa)	-	138 - 207	-
Bending strength (MPa)	70	345 - 483	-
Thermal expansion coefficient (mstrain/C)	5.4	8.64 - 33	10 - 15
Optical quality	Transparent	Translucent	Transparent (after treatment)

8.2.2.3 - SentryGlas interlayer material

Heat- strengthened glass will be produced in the standard way: float glass production, which is afterwards cut and then heat treated.

The GFRP elements will be produced in a pultrusion process. Due to the large amount of repetitive elements and the high precision that is needed, this production process will be the most efficient.

8.2.3 - Basic geometry

The basic geometry of the plate shell is based on the properties of the materials and the properties of plate shells (see chapter 7.3.3).

First of all it is necessary to create a shell with positive Gaussian curvature. Negative Gaussian curvature means tensile forces in the glass: this is not desirable.

Secondly, it is necessary to keep the curvature as high as possible while within the range of the requirements. A higher curvature generally leads to a better shell.

Thirdly, it is necessary to keep the geometric shape of the shell as simple as possible. A free-form plate shell has not yet been researched. By keeping the geometry simple it is possible to take the first step in this research and provide clear results.

8.2.4 - Connections

The connection between the plates of the plate shell will be linear to minimize stress concentrations in the glass at the connections. It will have finite rotational stiffness and a high axial stiffness: a semi-rigid connection.
The corners of the plates will be left free of connections. This is due to the large stress concentrations that will occur in these fragile corners.
The connection will also serve as a reinforcement for the glass edges: FRP has a thermal expansion coefficient that is close to glass.

The detail will therefore be modelled as a linear hinged connection protruding from the edge of the plates. It will not cover the entire edge of the plate, but three times the thickness of the glass elements will be left free from the edges (see chapter 9).

8.2.5 - Supports

The supports of the shell will be of the same nature as all the other connections in the shell. It will therefore be a linear semi-rigid connection. It will be connected using the FRP sheet embedded in the glass. The exact design of this connection will be given in chapter 9.

8.2.6 - Parapet

An important part of the bridge is the parapet or railing. Loads according to the NEN norms will be used (see chapter 1).

8.3 - Alteration of proposed design - form-finding

8.2.1 - Introduction to form-finding

The optimal plate shell can be found in a form-finding process, which can later serve as a basis for structural analysis and structural optimisation possibly resulting in a new form-finding process (figure 8.2). According to Adriaenssens (2014) form-finding can be defined as follows:

> *"Form finding is a forward process in which parameters are explicitly/directly controlled to find an 'optimal' geometry of a structure which is in static equilibrium with a design loading."*

There are several form-finding methods, ranging from physical methods to computational methods. Computational methods, which generally offer the most controllable parameters, can be divided in numerical methods and physical-method-simulating methods.

8.2.1.1 - Particle spring simulation

Particle spring simulation (PS) is such a physical-method-simulating method. This system consists of particles - objects with a mass, position and velocity, that respond to a force, but without spatial extend - that are connected through springs with a certain stiffness. [Witkin, 1997] PS is based on the physical form-finding with a network of hanging chains. It solves the problem of dynamic equilibrium to arrive at a steady state solution, equal to static equilibrium. Just like the physical hanging chain method it tries to find a shape where it is free of bending moments and where forces act in pure compression with minimized shear forces (figure 8.1).

The largest advantage of PS over other form-finding methods is that the user can change form and forces in real-time while the simulation is still running. This allows the user to really understand the effects of forces on the form. [Kilian & Ochsendorf, 2005] This form-finding method is also preferred over other methods when some initial dimensions are known. [Adriaenssens, 2014]
These properties and the availability of the parametric program "Kangaroo", which is a particle spring simulation program, leads to the use of this form-finding method in this thesis.

8.2.2 - Particle-spring simulation with "Kangaroo"

To create the optimal shell shape the parametric software program Grasshopper will be used in combination with its plug-in Kangaroo. This plug-in is a form-finding tool based on the simulation of a network of particles and springs. Kangaroo performs a virtual hanging-chain simulation of the structure in order to find the most efficient shape to carry the applied vertical loads. The simulation can be divided in two steps:

1. In the first step of particle spring simulation a flat surface corresponding with the boundary conditions is meshed and thereby divided into points and lines. The points are particles with a mass and the lines are springs with a certain length and stiffness connecting the particles. Each node is either free to move or fixed in each direction: the supports of the shell are defined. These particles are then subjected to a force. Due to the desire of the springs to reach a certain length (rest length), a shell shape that is in static equilibrium will form.
2. In the second step of the simulation this smooth shell shape is geometrically optimized by planarizing the hexagonal plates and scaling them to form the connections, resulting in a plate shell.

8.2.2.1 - Parameters

The sum of all forces and interactions in the particle-spring system will lead to a balance of forces and a shell shape that is in static equilibrium. [Adriaensens, 2014] To manipulate the resulting statically equilibrated shell it is possible to adjust several "tools": the parameters. The following parameters can be adjusted in the particle spring simulation with Kangaroo:

- The dimensions of the shell
- The meshing (refinement & topology)
- The parameters of the particle spring system, like the spring stiffness, mass of the nodes, rotation of the nodes and applied force on the nodes.

8.4 - Alteration of proposed design - optimization

8.4.1 - Introduction to optimization

The next step consists of analysing the form-found shapes and subsequently optimizing the best structural shape in a new form-finding and analysis process. According to Adriaenssens (2014) structural optimization can be defined as follows:

> *"Structural optimization is an inverse process in which parameters are implicitly/indirectly optimized to find the geometry of a structure such that an objective function or fitness criterion is minimized."*

The parameters that can be optimized depend on the type of optimization. Three types of structural optimization can be distinguished according to Adriaenssens (2014):

1. Size optimization: uses structural dimensions as input variables, for example cross section area.
2. Shape optimization: uses the shape of structural elements as its input variables, for example by tapering elements.
3. Topology optimization: changes the connectivity between finite elements to form load paths. In a discrete system this can be achieved by eliminating some elements from the calculation and possibly also changing the stiffness matrix by removing degrees of freedom.

8.4.2 - Goal of optimization

The goal of this optimization step is to find the most efficient plate shell, thus this process can be defined as **shape and size optimization**.

The most efficient smooth shell shape is defined here as a shell where energy and stresses have minimum local and global value and where stresses are mostly caused by membrane action (normal forces). For the first form-finding & optimization phase this leads to a comparison between different basic shell shapes. For the second phase, the shape of the planar facets and the size of the facets will be changed until the lowest deflection and stresses are reached.

8.4.3 - FEM analysis with "Karamba"

To analyse the shells that have been formed with Kangaroo, the grasshopper plug-in "Karamba" will be used. This finite element analysis tool is based on the visual interface of Rhino and Grasshopper, just like Kangaroo. Therefore this FE-tool is best integrated in the previously executed research. The shape of the shell can be changed real-time resulting in faster research possibilities.

8.4.4 - FEM analysis with "Diana"

Due to the limited possibilities of Karamba regarding plate shells, the geometry found during the geometric optimization (tessellation) will be analysed in TNO DIANA. This finite element tool uses a different interface, so exporting the geometry will be necessary.

8.5 - Phase 1 - Form-finding & analysis smooth shell

8.5.1 - Ground surface

The first phase of the Kangaroo form-finding process includes the definition of the flat surface. This surface is defined taking into account the maximum dimensions of the bridge.

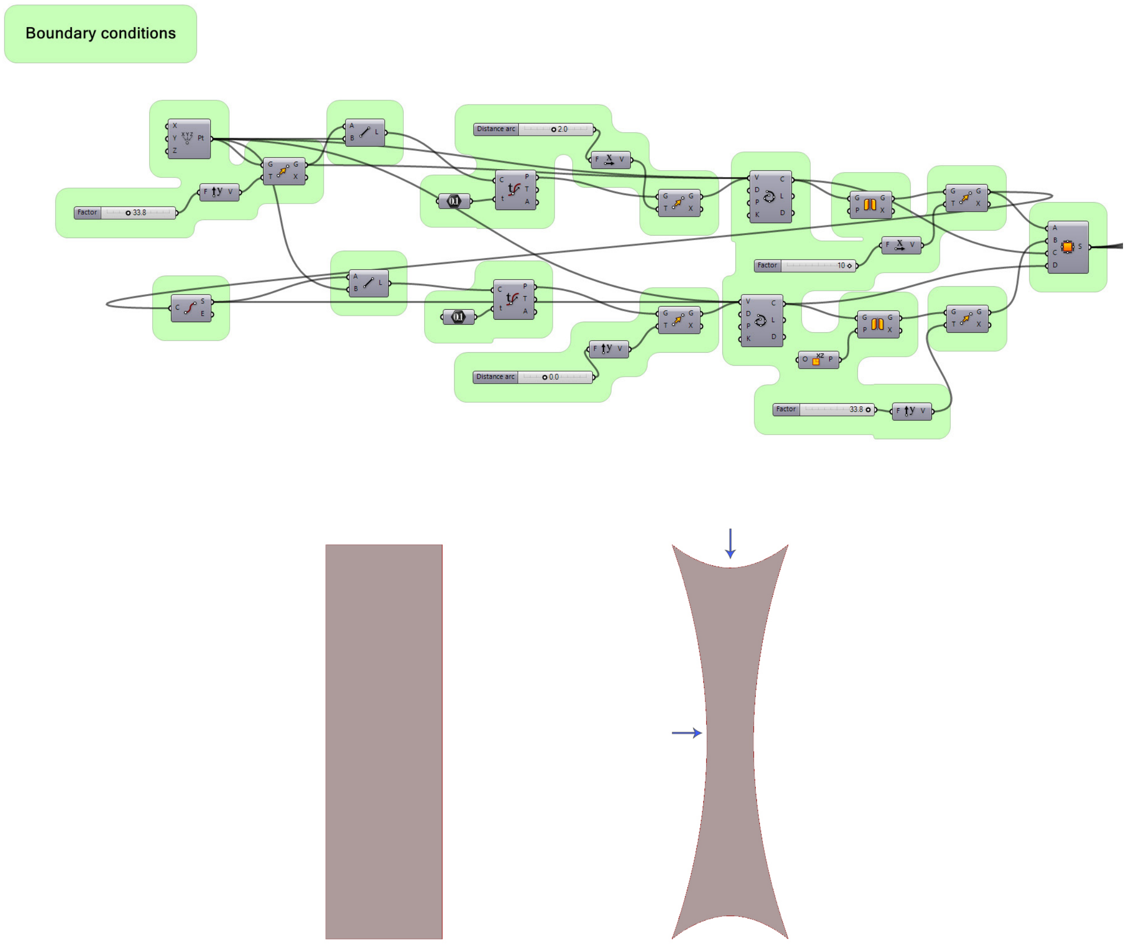


Fig. 8.7 - Grasshopper definition and Rhino interface of the flat ground surface

8.5.2 - Mesh definition

Secondly, the mesh of this surface is defined. Ideally the mesh would be hexagonal, as the glass plates will ultimately have a hexagonal shape. However, Grasshopper does not (yet) allow a hexagonal mesh to be created. Therefore the output from the Kangaroo plug-in can not result in a surface or hexagonal mesh.

The mesh will therefore be square with added diagonals to somewhat restrain the upward movement. When only a square mesh would be applied the resulting shell would have a very high curvature: too high to be walked on.

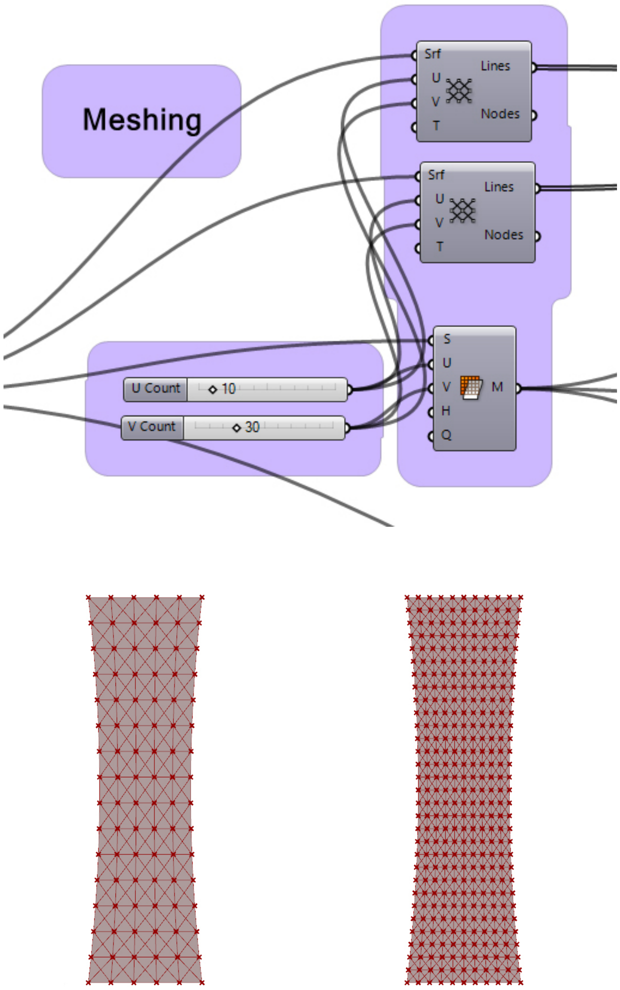


Fig. 8.8 - Grasshopper definition and Rhino interface of the meshing of the ground surface. Several sliders can be used to change mesh density.

8.5.3 - Particle spring simulation

The mesh is translated to particles and springs: the lines will become springs with a stiffness and rest length, while the intersection points of these lines become the particles with a mass. Several particles will be constrained: they will form the supports of the shell.
A unary force is then introduced in the positive z-direction perpendicular to the world axis, on all the particles of the mesh. This will result in the deformation of the surface: the springs are stretched while the unconstrained particles move up. The stiffness of the springs and the rest length of the springs ultimately stops this movement: a shell shape in static equilibrium has been reached.
The final shape of the shell depends on several parameters:

- The supports
- The force
- The rest length of the springs
- The mesh
- The stiffness of the springs

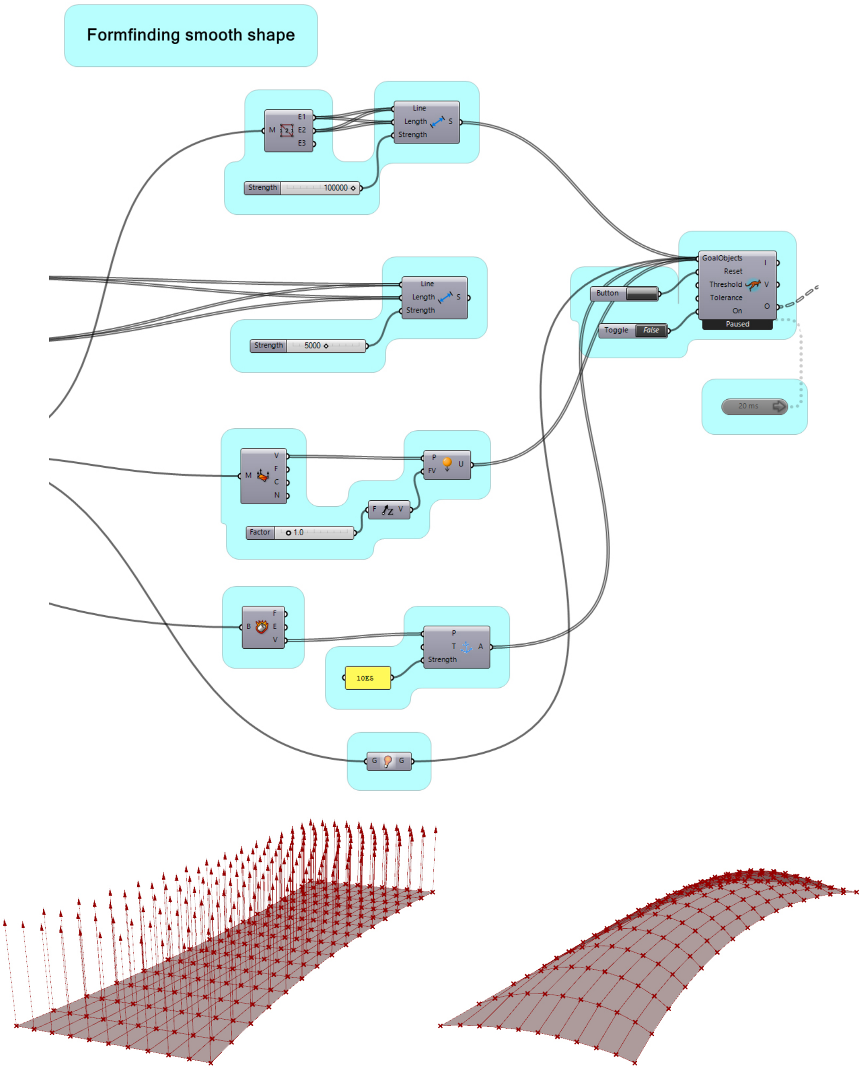
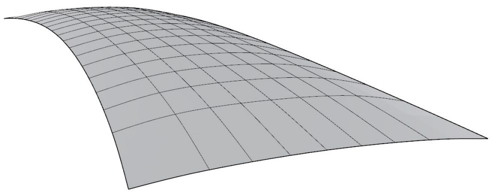
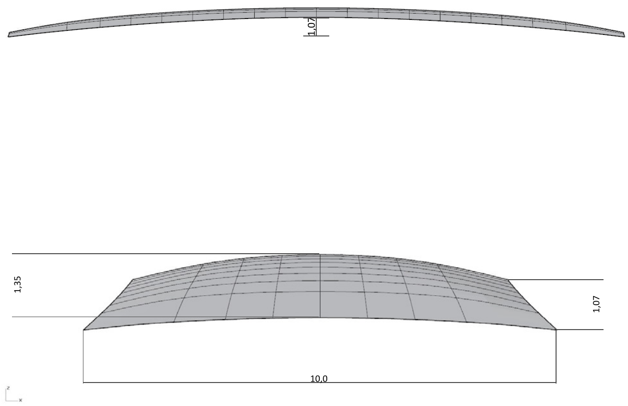
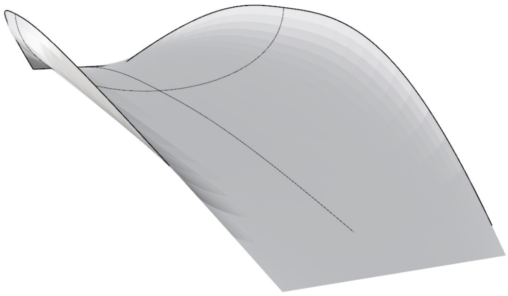
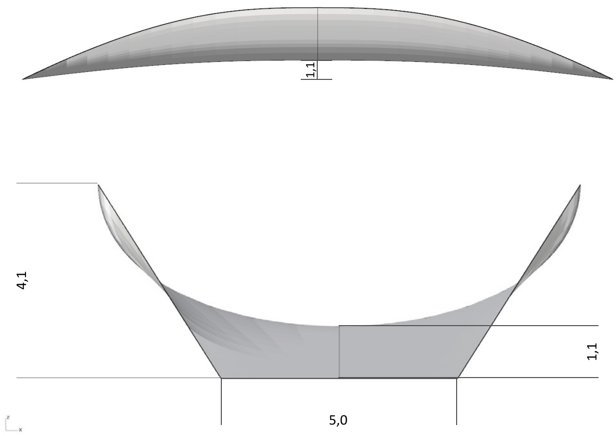
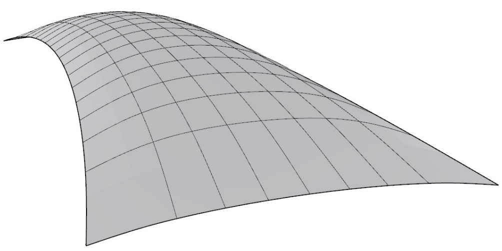
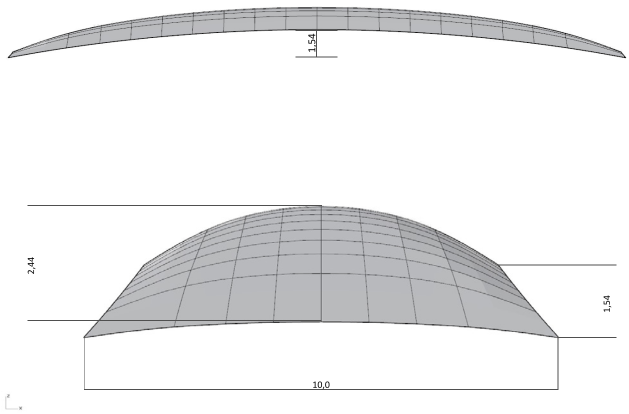


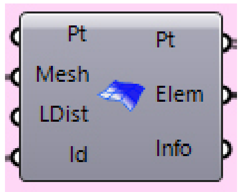
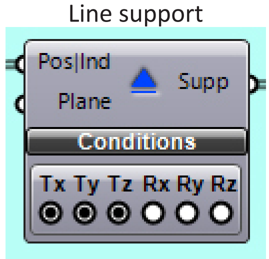
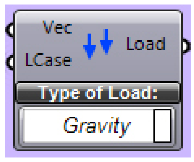
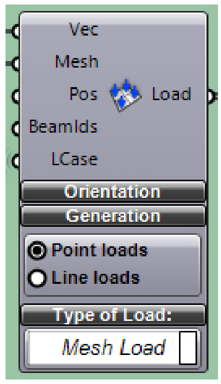
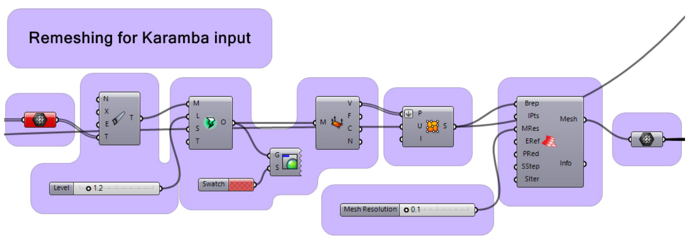
Fig. 8.9 - Form-finding with Kangaroo: Grasshopper definition & Rhino interface

8.5.4 - Structural analysis 1: smooth shell shape

Because it is possible to predict the stress distribution in a plate shell by analysing its corresponding smooth shell [Bagger, 2010] three shapes that meet the boundary conditions will be chosen to be further investigated: a convex shape, a concave shape and a second convex shape with different meshing and curvature.
These shapes will be analysed for their stress distribution and deformation due to dead load and a live load. The purpose of this analysis is to find the shape with the least (tensile) stresses and least deformation.

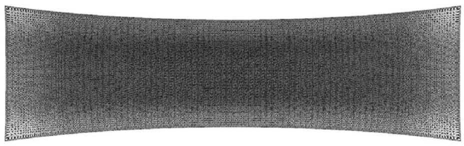
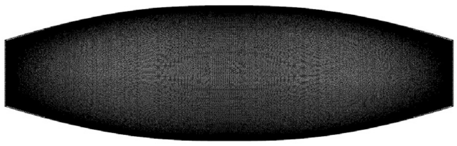
1. Convex shape 1: a convex shape with low curvature according to the boundary conditions. Most likely loaded in pure compression.
2. Concave shape: a concave shape according to the boundary conditions. Has a “natural” parapet, but will most likely be loaded in high tension.
3. Convex shape 2: a convex shape of higher curvature. Not according to the boundary conditions, but most likely better shell behaviour.

	Smooth shell variants		
Variant 1	Convex shape	 Square mesh strength: 50.000 Diagonal mesh strength: 200 Unary force: 1,5	
Variant 2	Concave shape	 Square mesh strength: 3000 Diagonal mesh strength: 1000 Unary force: 4,0	
Variant 3	Convex shape - higher curvature	 Square mesh strength: 50.000 Diagonal mesh strength: 150 Unary force: 4,0	

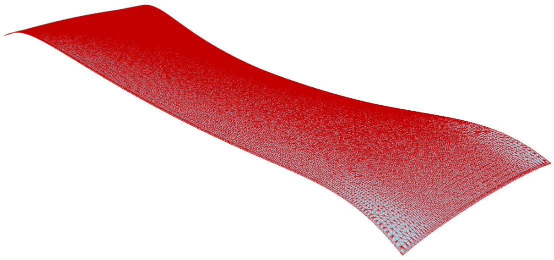
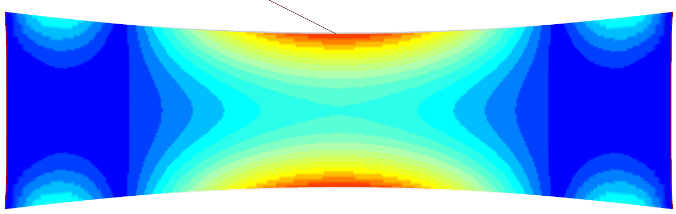
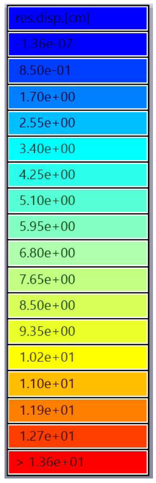
	Input for Karamba	
	Values	Definition
Material	<u>Heat-strenghtened glass (36mm)</u> Young's Modulus: 7000 kN/cm² Shear modulus: 2869 kN/cm² Poisson's ratio: 0,22 Specific weight: 24,5 kN/m³ Yield strength: 7 kN/cm²	Shell element 
Supports	Linear hinged	Line support 
Loadcase	<u>Loadcase 0 - Dead load & live load</u> Dead load: 258 kN Live load: $q_{rk} = 2,0 + \frac{120}{L + 30} = 3,9\ kN/m^2$	
Mesh	Mesh refinement: 0,1	

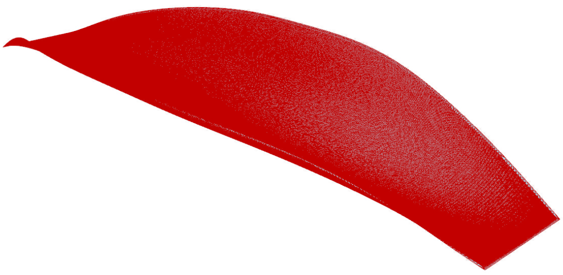
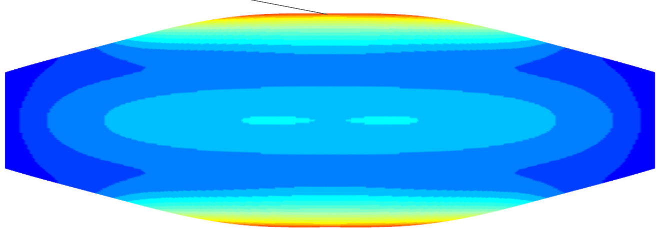
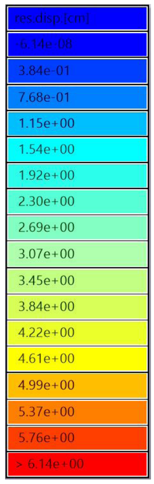
The shell will be simulated as heat-strengthened glass of 36 mm thickness. The corresponding material properties are taken from paragraph 8.2.2. The combination of loadcases - as presented below - are taken from chapter 1: according to the NEN norms.

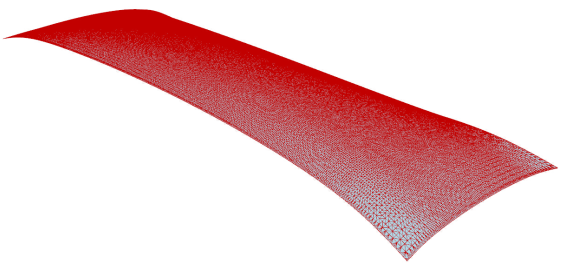
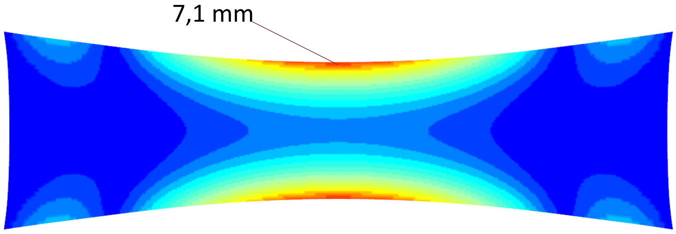
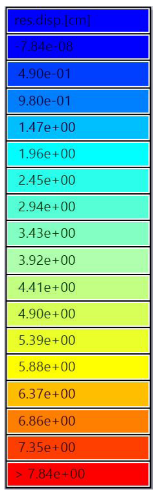
Loadcase 0	-	Dead load & live load
Loadcase 1	-	Dead load, live load & concentrated load
Loadcase 2	-	Dead load, live load & horizontal load

	Input for Karamba	
	Mesh (refinement factor 0,1)	Supports (linear)
Variant 1		
Variant 2		
Variant 3		

Karamba output: deformation

	Deformed shape (x10)	Legend
Variant 1	 Max.: 13,6 mm 	

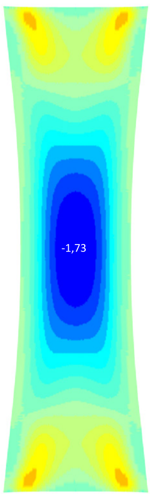
	Deformed shape (x10)	Legend
Variant 2	 Max.: 6,14 mm 	

	Deformed shape (x10)	Legend
Variant 3	 7,1 mm 	

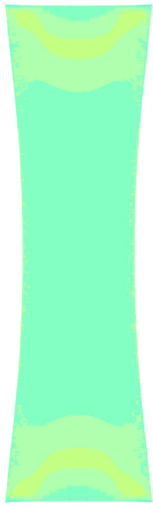
Principal stresses 1

Variant 1

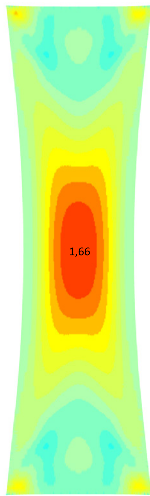
Top layer



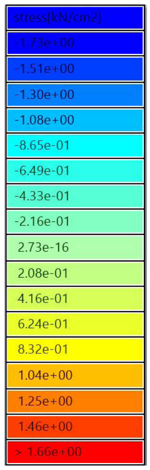
Middle layer



Bottom layer

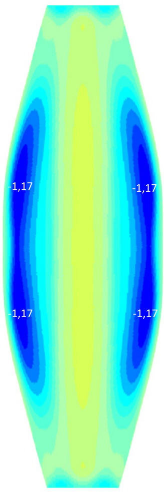


Legend



Variant 2

Top layer



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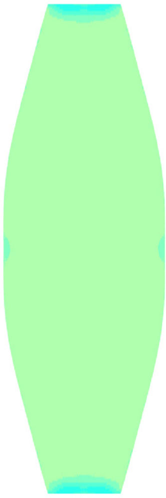

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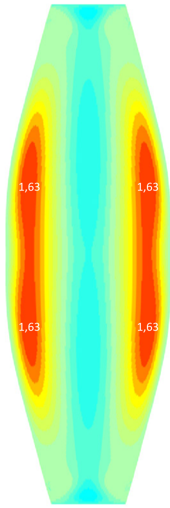

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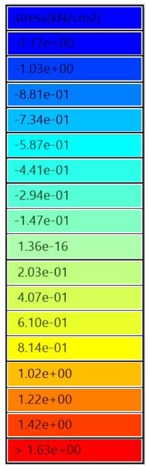

Variant 3

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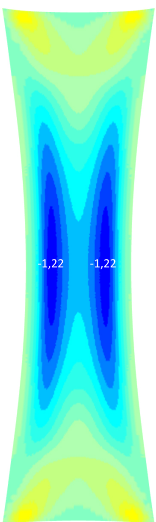

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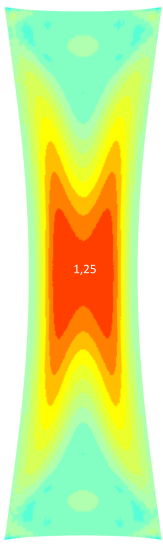
Bottom layer



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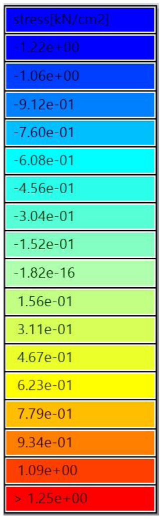
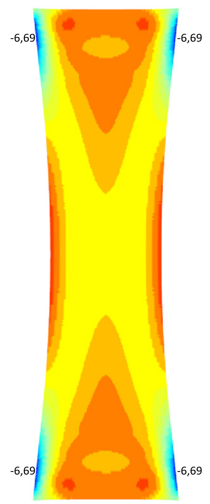


Principal stresses 2

Variant 1

Top layer



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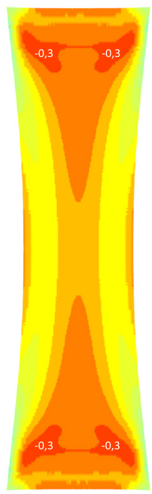

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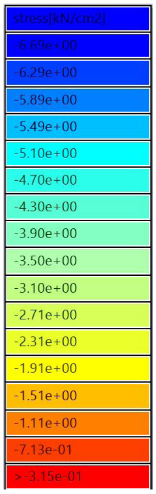
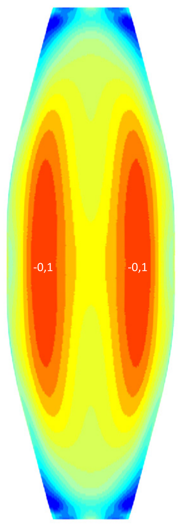
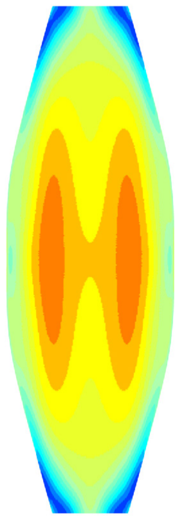


Variant 2

Top layer





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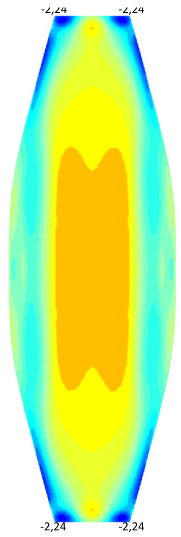
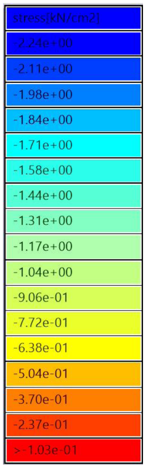
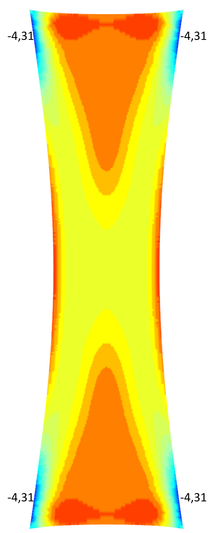


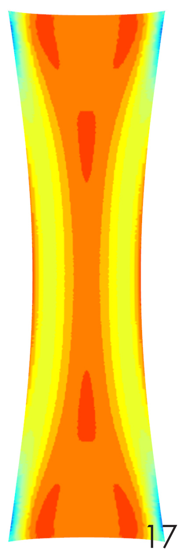
Legend



Variant 3

Top layer





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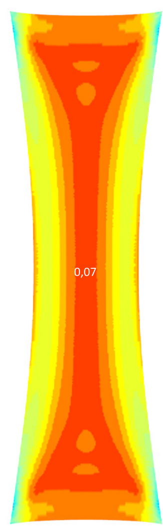

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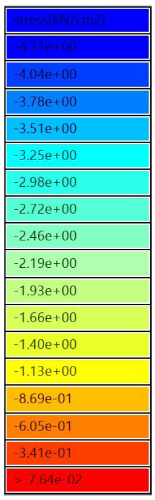


8.5.5 - Results

8.5.5.1 - Deformation

The deformation analysis shows the largest deflection in all variants at their free edges. These free edges are susceptible to in-extensional modes of deformation. By adding folds with negative Gaussian curvature to the free edges, stiffness will be provided to these edges preventing in-extensional deformation. However, when planar hexagonal panels are projected on the smooth surface, these folds will be flattened out by the planarization forces. This problem can be solved by adding a stiff beam (of FRP) to the free edges of the planarized and hexagonalized shell. The maximum deformation due to dead load and an equally distributed live load of 3,9 kN/m^2 amounts to:

- 13,6 mm for variant 1
- 6,14 mm for variant 2
- 7,10 mm for variant 3

8.5.5.2 - Principal stresses

The value for the total stresses in the shell is the result of the addition of stresses caused by bending of the shell and stresses caused by normal forces:

$$\sigma \text{total} = \frac{N}{A} + \frac{M}{I}$$

In the middle layer of the shell the stress due to bending is zero, while the normal stress is constant. This results in an approximation of the value of stress caused by bending (in-efficient shell behaviour) or stress caused by in-plane forces (efficient shell behaviour) and whether this stress is in compression or tension. The maximum allowed value of tensile stress for glass is 70 MPa (7,0 kN/cm^2). Because a plate shell generally has forces that are 2 to 3 times higher than the corresponding smooth shell [Bagger, 2010], the maximum allowed tensile stress in this phase is 7,0 / 3 = **2,33 kN/cm^2**.

Addressing the principal stresses in direction 1 for both convex shells (variant 1 & 3), large stresses can be witnessed in the middle of the shell. These stresses are almost entirely caused by bending, because the stress concentrations disappear in the middle layer of the shell (where bending stress is 0). For variant 1 the maximum tensile stress is 1,66 kN/cm^2 (where 2,33 kN/cm^2 is allowed in this phase). This value is lower for variant 3 (1,25 kN/cm^2) due to the higher curvature of this shell, causing more membrane action. Variant 2 shows its largest stresses to the left and right side of the middle. These stresses are also entirely caused by bending, because the stress in the middle layer is equally distributed over the surface. These bending stresses are, however, located just outside of the walkable area of the bridge. In practice these areas will therefore be part of the parapet of this bridge and will not be subjected to the same live load as is applied over the entire surface in this analysis. The maximum tensile stress in variant 2 is within limits and lower than variant 1: 1,63 kN/cm^2.
The stresses caused by normal forces in direction 1 are for variant 1 and 3 in compression (convex shells) and for variant 2 they are in tension (concave shell). This is due to the fact that the principal normal force directions are the principal curvature directions - positive for convex shells and negative for concave shells. [Ramos, 2013] However, the values of the normal stress are very low compared to the bending stresses.

The principal stresses in direction 2 show the largest compressive stresses of the shell: in all variants located at the supports. These stresses largely consist of normal stress: the difference in stress levels between middle layer and either top or bottom layer is very small. All the normal forces flowing to the supports follow the way of the highest curvature. This leads to the highest stress concentrations in areas of high curvature near the supports. The maximum compressive stress for the shell variants is not leading, because glass can handle much more compressive than tensile stress. The maximum compressive stresses in the shell are as follows:

- -6,69 kN/cm^2 for variant 1
- -2,24 kN/cm^2 for variant 2
- -4,31 kN/cm^2 for variant 3

8.5.5.3 - Conclusion

From this analysis it can be concluded that all three shells meet the requirements (maximum stress level and maximum deformation) under dead load and a live load of 3,9kN/m^2. In this light, variant 2 - the concave shell - can be seen as the most promising variant. This shell incorporates its sides of negative Gaussian curvature as "natural" parapet, while creating a railing on a convex shell variant (1 or 2) would mean compromising the thin shell layer. This would cause large forces on a small part of the shell, probably resulting in large bending stresses.

A disadvantage of variant 2 is the tensile stress in the glass in the direction of the negative Gaussian curvature. This tensile stress is, however, smaller than variant 1 which is the only other variant that has dimensions according to the boundary conditions. The tensile stress is minimal and can possibly be accounted for in the connection detail.

Therefore variant 2 - the concave shell - shows the most efficient shell behaviour, while meeting the dimensional and safety requirements. This shell will therefore be elaborated on in the next paragraphs of the form-finding and optimization process.

8.6 - Phase 2 - Geometric optimization & analysis in DIANA

8.6.1 - Hexagonal tessellation

Hexagonal panels will be projected on the concave smooth shell shape (found during the particle spring simulation) with a plug-in called Lunchbox. The resulting hexagonal panels will be curved and divided over the surface in relation to the Gaussian curvature of the surface.
The pattern of hexagonal panels can be adapted by changing the U and V ratio or with the use of attractor points.

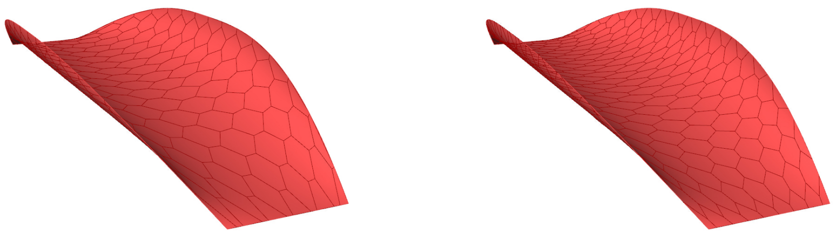


Fig. 8.10 - Hexagonal tessellation on the form-found smooth shell shape. The UV direction can be switched creating a different tessellation (right).

8.6.1.1 - Planarizing the hexagons

The plate shell will be made from planar hexagonal panels, so the hexagonal pattern on the surface has to be planarized. This is done in Kangaroo by subtracting the nodes from the curved hexagonal panels and subsequently planarizing these points. The length between the points is clamped between a minimum and maximum value to maintain a regular shaped hexagonal tessellation. The form-found smooth surface is used to pull the points, which will somewhat restrain the points from moving to far from their original location and thus forming a completely different shell shape.

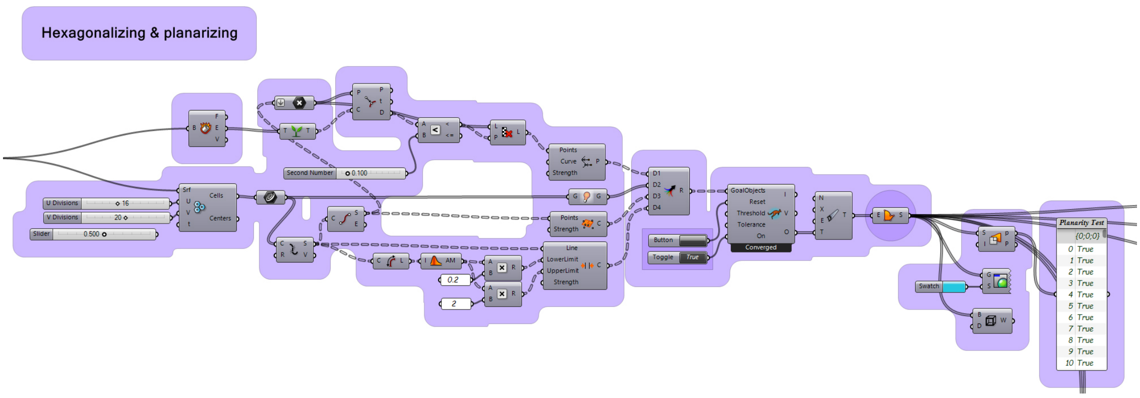


Fig. 8.11 - Grasshopper definition of planarization and hexagonalization of smooth shell

8.6.1.2 - Complications during hexagonal planarization

The research shows that hexagons on a concave shape are very complicated to planarize. Planarization of the form-found smooth shell shape results in heavy distortions and overlapping of the plates (figure 8.12). This is the case for both directions of the UV surface.

The plates also become concave instead of convex.

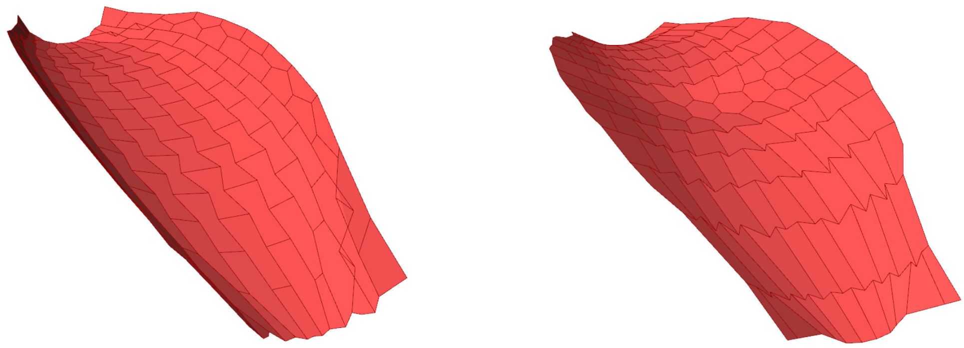


Fig. 8.12 - Overlapping and distortion of panels during hexagonal planarization. Left in normal UV direction, right in swapped UV direction.

The only concave shape that can be regularly tiled with a hexagonal mesh is the torus (of genus 1) [Wang et al., 2009]. The result of planarization of hexagonal panels on a part of a torus, however, is a concave plate shape (figure 8.14).

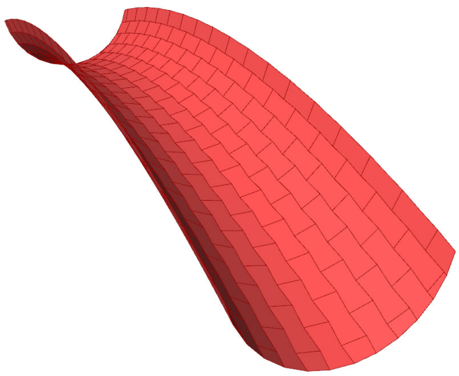


Fig. 8.13 - The torus can be regularly tiled with planar concave hexagonal panels. Part of it can serve as bridge.

This type of plate is not efficient when made of glass. The angles of the concave hexagon will be significantly larger than the convex hexagon: sharper corners in glass are not desirable due to economic and manageability reasons. Compared to both a quadrangular panel and a triangular panel, the production costs will be higher, while the panels will also be more vulnerable to damage.

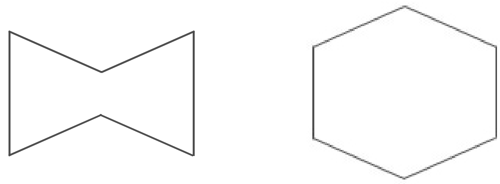


Fig. 8.14 - Concave (left) versus convex (right) panel

8.6.1.3 - Reconsideration other tessellations

A reconsideration of the quadrilateral and triangular plate shape is therefore necessary. Especially when considering that the advantage of the forceless vertices in a hexagonal plate shell no longer applies when the connection is shortened. This interrupts the continuity of the vertices in both the hexagonal, triangular and quadrilateral plate shell, resulting in stresses that are forced to move through the glass plate, regardless of the plates' shape.

In this light it is most efficient to use a triangular tessellation. This will result in the most regular shaped plates, while the form-found smooth shape is best approached.

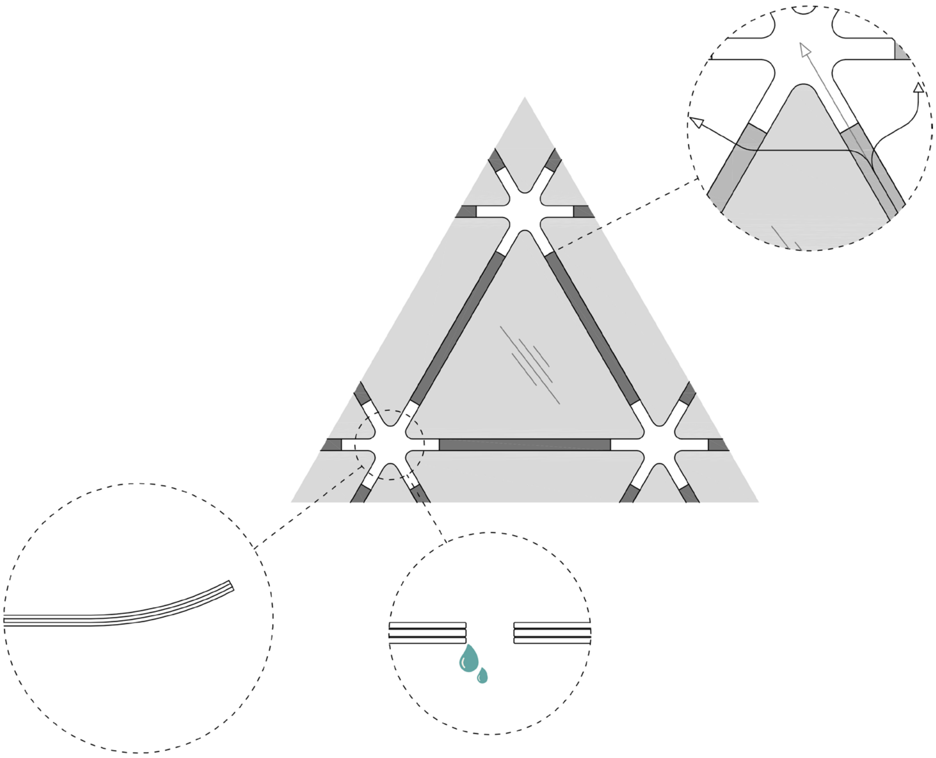


Fig. 8.15 - Shortened vertices leading to interruption of force flow through these vertices: the forces have to go through the plates

8.6.2 - Triangular tessellation

A triangular pattern (mesh) will be projected on the form-found smooth surface. The triangle is by definition planar, so extra planarization steps are not necessary.

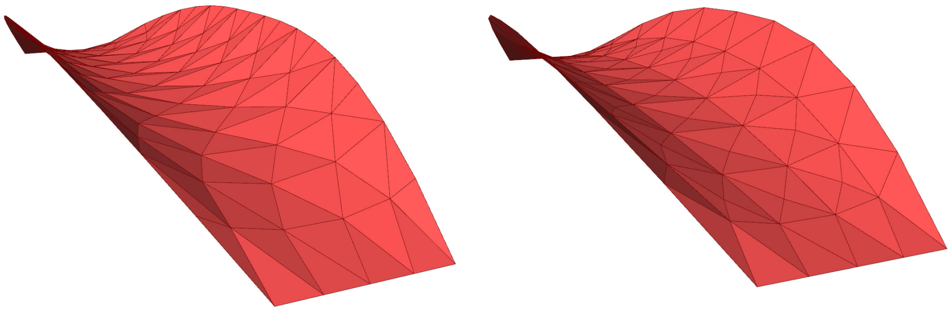


Fig. 8.16 - Triangular tessellation of the form-found smooth shell shape. Panels are already planar.

8.6.2.1 - Rounding off edges

Thereafter, the edges of the triangular plates will be rounded off in order to protect the weak corners of the glass plate. A fillet action is done in Grasshopper. The exact distance of this fillet is based on the thickness of the glass plate. An initial distance of 3x the thickness of the plate is chosen: 108mm.

8.6.2.2 - Creating the shortened connections

By shortening the length of the connection - and thus allowing the uplifting of the corners - the stress concentrations in the corners will be minimized, while also interrupting the continuity of the vertices (see chapter 7.3) and allowing water to escape.

The connections are created by scaling the triangular plates - creating a surface along each edge and in the same plane as the plate.

8.6.2.3 - Fixing the normal directions

Finally, the normal directions of the resulting surfaces of both the connections and the triangular plates themselves are checked. For further geometric optimization in DIANA these surfaces should all be oriented in the same direction.

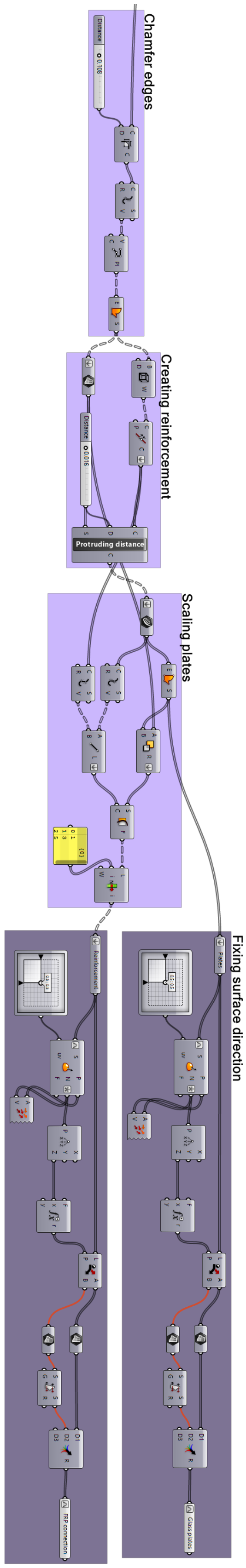


Fig. 8.17 - Grasshopper definition of the rounding of the edges, shortening of the joints and finally fixing the normal directions.

8.6.3 - Structural analysis 2 - Plate geometry

Before analyzing the entire plate shell, the design of the individual triangular plate will be optimized. Several assumptions have been made:

- Rounded edges for less stress concentrations in the corners
- Connection width of approximately 32mm
- Shortening the connections with a distance of 3x thickness plate (108mm)
- Plate composed of 5 layers of heat-strengthened glass (6-8-10-8-6)

These assumptions will be checked for an individual plate in a plate bending analysis in DIANA, to subsequently optimize the plate design.

8.6.3.1 - Nature of joint between plates

The joint between the plates will be created using an embedded GFRP sheet. Using this type of connection will distribute the stresses transferred from plate to connection detail over a larger area. This results in a higher capacity of the connection detail. More information about the type of joint between the plates will be given in chapter 9.

8.6.3.2 - Goal of analysis

Four types of plates will be analysed to find the influence of the of the length of the connection and the rounding of the corners to the level of stress concentrations in the glass plate and FRP embedded sheet. A solid glass plate, supported on its four edges will be used as a reference.

1. A plate with rounded edges, embedded sheet with a thickness of 10mm protruding 16mm from the edges with a distance of 114mm (3x thickness plate) from the corners of the plate.
2. A plate with rounded edges, embedded sheet with a thickness of 10mm protruding 16mm from the edges with a distance of 38mm (1x thickness plate) from the corners of the plate.
3. A plate with rounded edges, embedded sheet with a thickness of 10mm protruding 32mm from the edges with a distance of 114mm (3x thickness plate) from the corners of the plate.
4. A plate with rounded edges, embedded sheet with a thickness of 17,52mm protruding 32mm from the edges with a distance of 114mm (3x thickness plate) from the corners of the plate.

These models will be analysed in DIANA, simulated with hinged support conditions. The numerical models will consider all the construction layers of the glass composition (glass panes, SentryGlas interlayers and the GFRP embedded strip) and are composed of solids. The stresses in the plate will be analysed.

8.6.3.3 - Material input

The properties of all materials will be used according to chapter 8.2.2.

8.6.3.4 - Element types

The CHX60 element is a twenty-node iso-parametric solid brick element. It has an extra node on each edge and is based on quadratic interpolation and Gauss integration (figure 8.18).

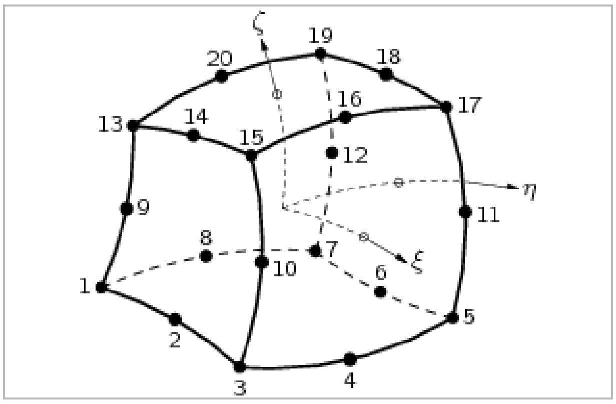


Fig. 8.18 - CHX60 brick element [TNO DIANA, 2012]

8.6.3.5 - Load

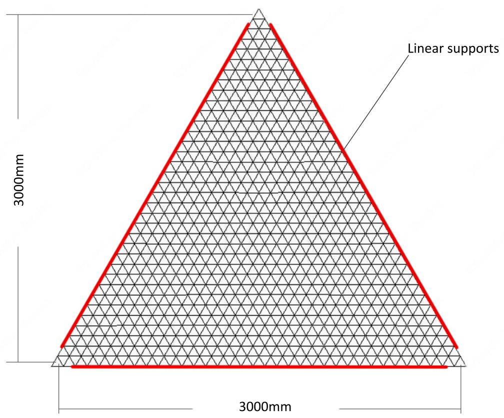
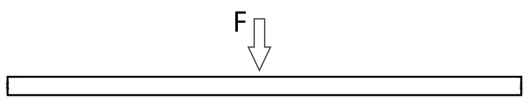
The load on the middle of the plate is 3,9 kN/m^2 in compliance with the required live load on the entire bridge according to NEN norms.

8.6.3.6 - Meshing

The triangular plate will be meshed with the TETRA/TRIANGLE mesh from DIANA (see table with input). The element size will be 0.1 meter.

8.6.3.7 - Boundary conditions

The plate is supported on all edges conform the length of the FRP embedded sheet. This connection is hinged (see supports as red line in table with input).

<table>
<tr><th></th><th>Plan (with meshing)</th><th>Section</th></tr>
<tr><td>Basic plate</td><td>
</td><td>
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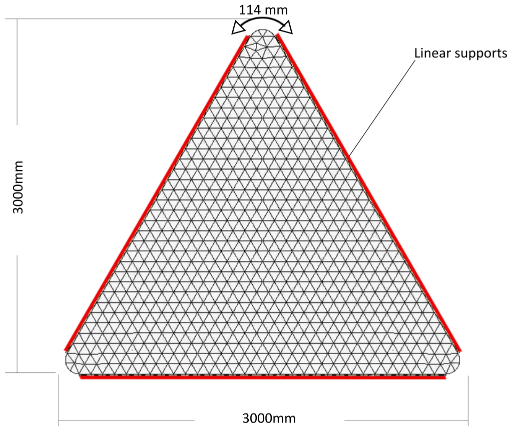
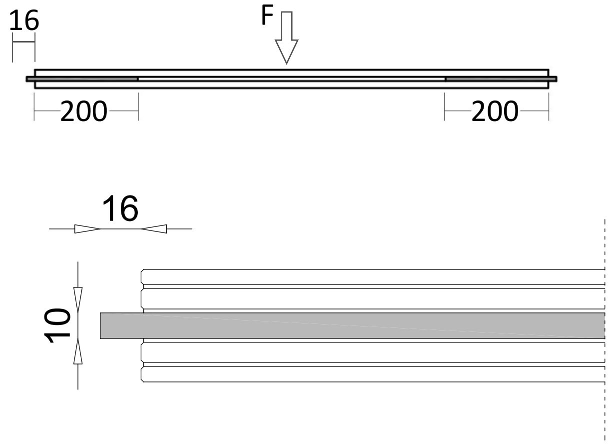
<table>
<tr><td></td><td colspan="3">Simply supported plate variants (clamped & hinged)</td></tr>
<tr><td></td><td></td><td>Plan (with meshing)</td><td>Section</td></tr>
<tr><td>Variant 1</td><td>Triangular plate with rounded edges
Distance to corner: 114mm</td><td>
</td><td>
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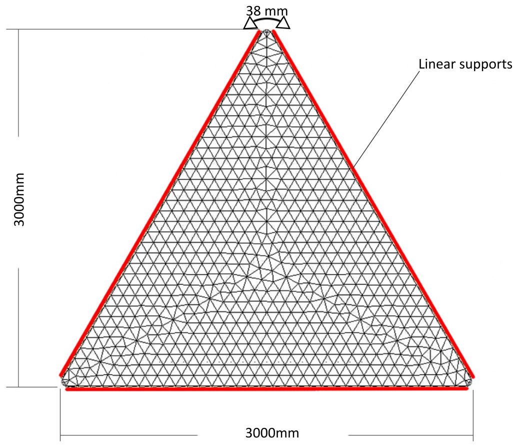
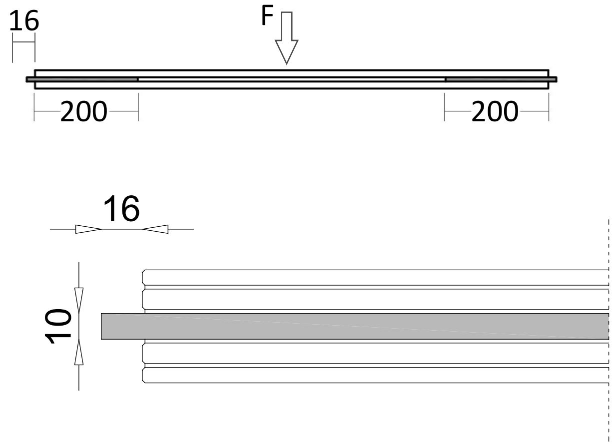
<tr><td>Variant 2</td><td>Triangular plate with rounded edges
Distance to corner: 38mm</td><td>
</td><td>
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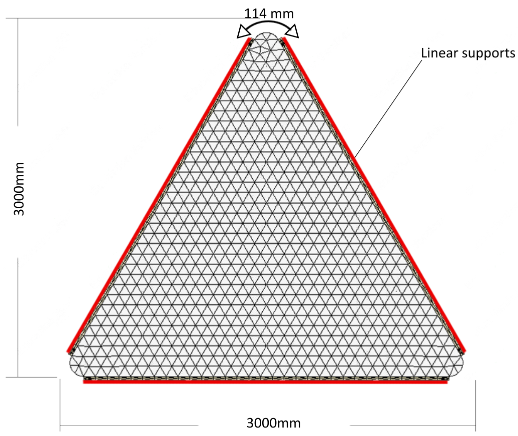
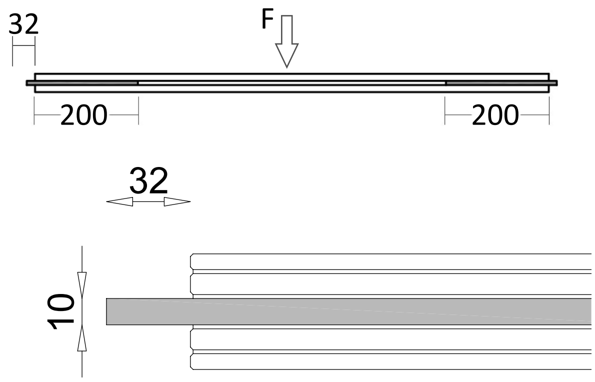
<tr><td>Variant 3</td><td>Triangular plate with rounded edges
Distance to corner: 114mm</td><td>
</td><td>
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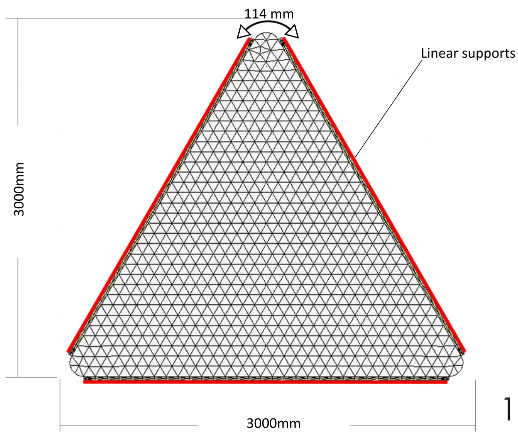
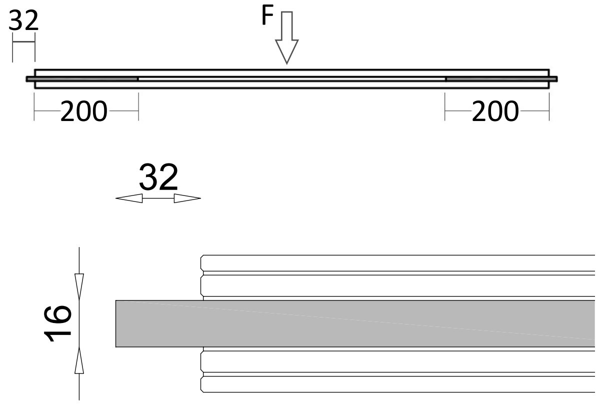
<tr><td>Variant 4</td><td>Triangular plate with rounded edges
Distance to corner 114mm</td><td>
</td><td>
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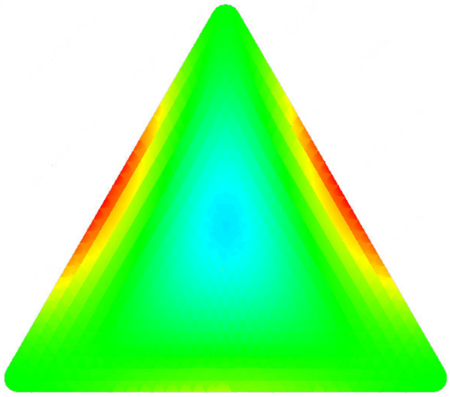
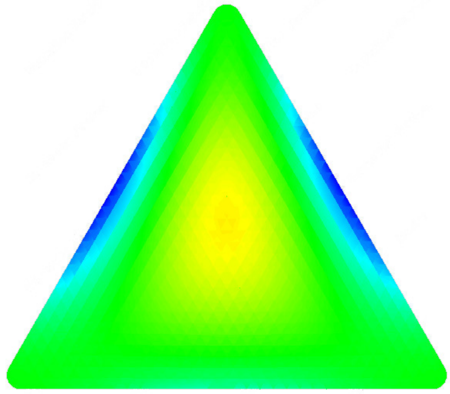
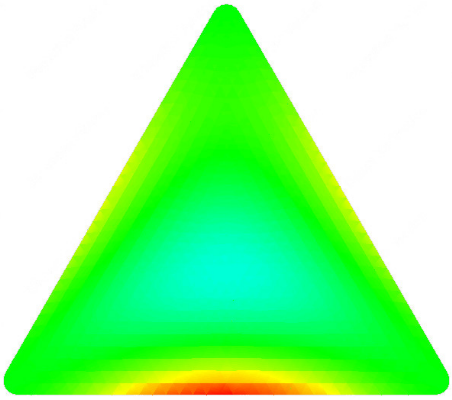
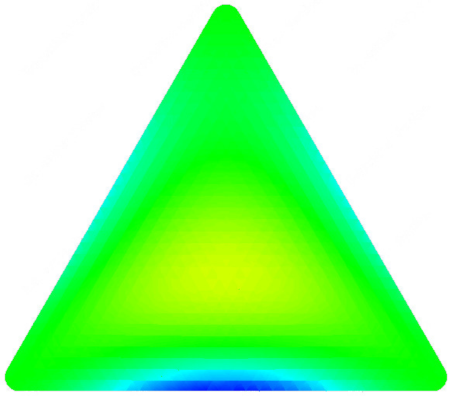
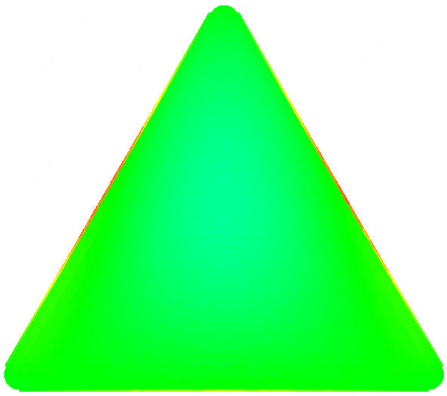
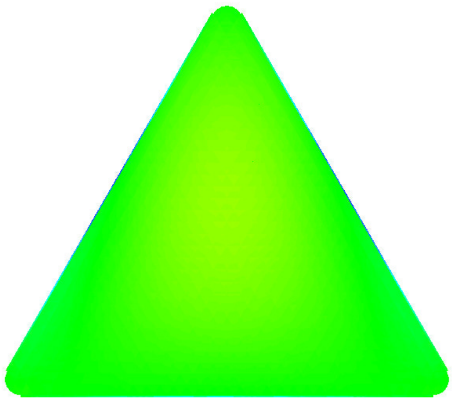
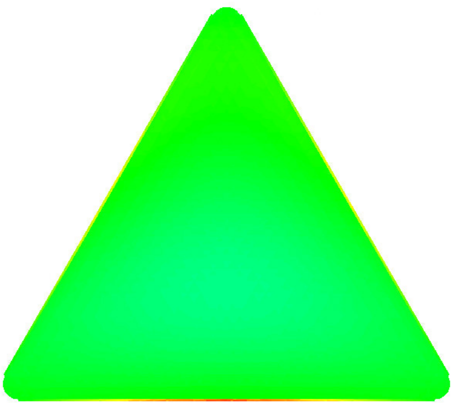
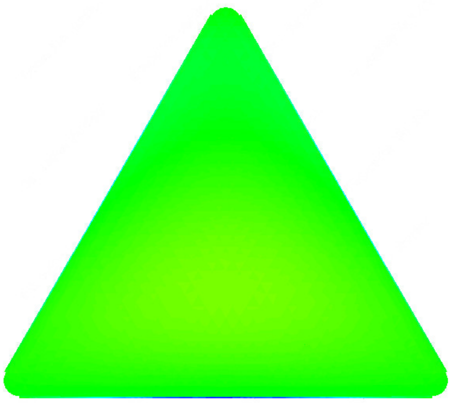
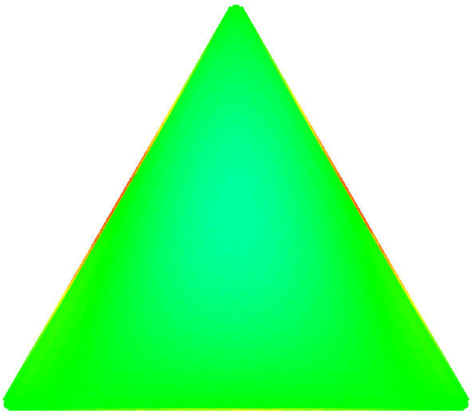
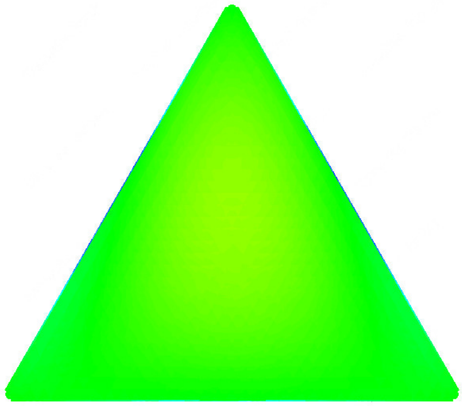
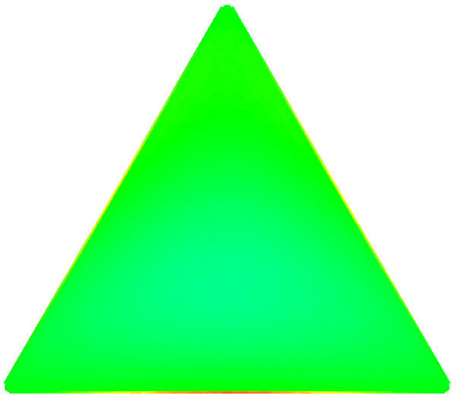
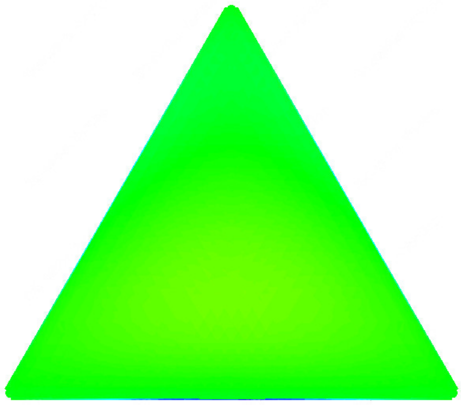
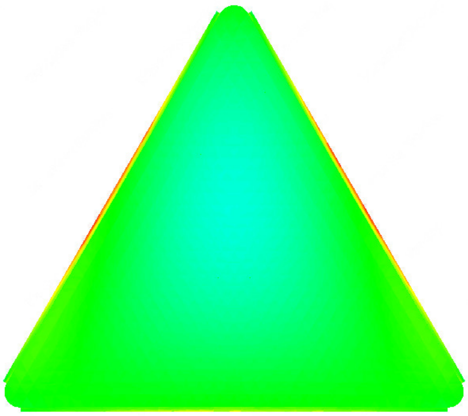
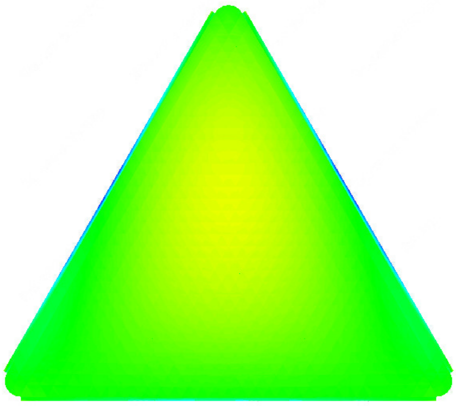
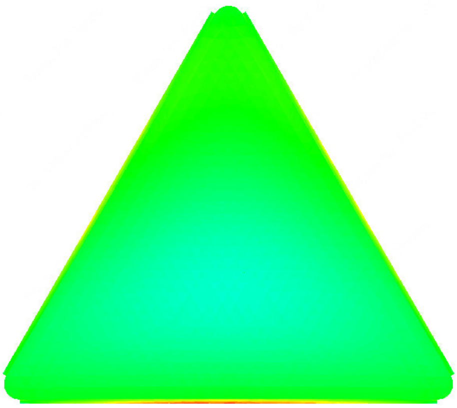
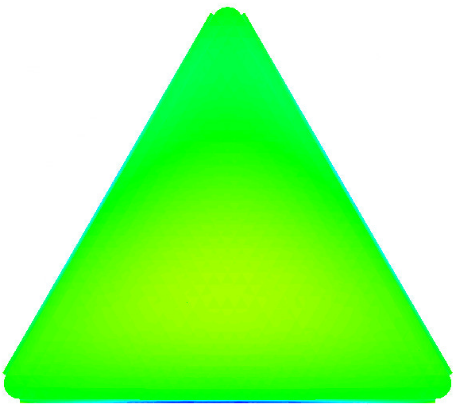
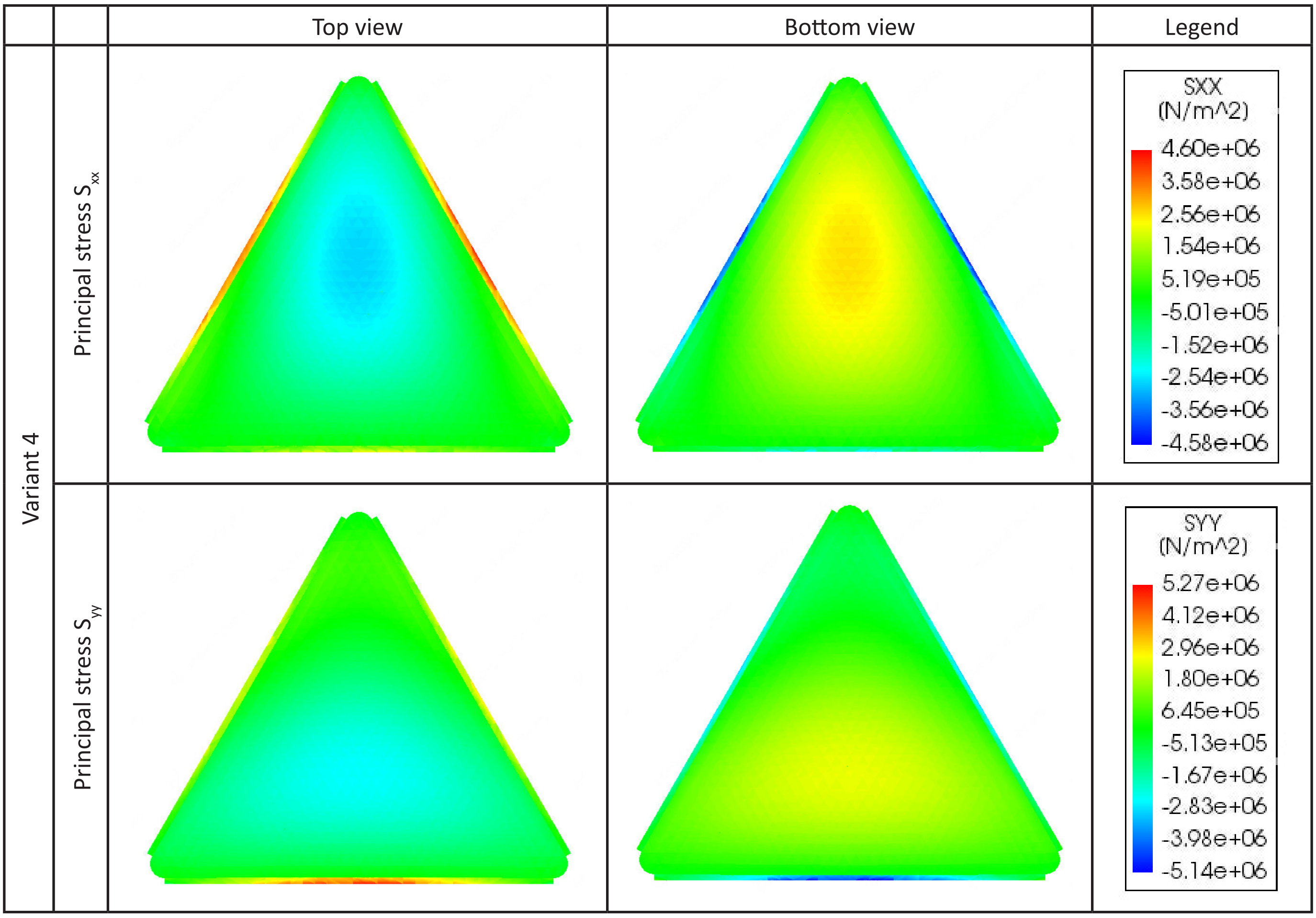
		Top view	Bottom view	Legend
Basic plate	Principal stress S_{xx}			SXX (N/m^2) 2.99e+06 2.32e+06 1.66e+06 9.96e+05 3.31e+05 -3.34e+05 -9.98e+05 -1.66e+06 -2.33e+06 -2.99e+06
	Principal stress S_{yy}			SYY (N/m^2) 3.70e+06 2.88e+06 2.06e+06 1.24e+06 4.17e+05 -4.05e+05 -1.23e+06 -2.05e+06 -2.87e+06 -3.69e+06
Variant 1	Principal stresses S_{xx}			SXX (N/m^2) 1.12e+07 8.72e+06 6.21e+06 3.70e+06 1.20e+06 -1.31e+06 -3.82e+06 -6.33e+06 -8.84e+06
	Principal stresses S_{yy}			SYY (N/m^2) 1.27e+07 9.89e+06 7.09e+06 4.29e+06 1.49e+06 -1.31e+06 -4.12e+06 -6.92e+06 -9.72e+06

		Top view	Bottom view	Legend
Variant 2	Principal stress S_{xx}			SXX (N/m^2) 1.10e+07 8.57e+06 6.14e+06 3.70e+06 1.27e+06 -1.16e+06 -3.60e+06 -6.03e+06 -8.47e+06 -1.09e+07
	Principal stress S_{yy}			SYY (N/m^2) 1.29e+07 1.01e+07 7.30e+06 4.49e+06 1.68e+06 -1.14e+06 -3.95e+06 -6.76e+06 -9.58e+06 -1.24e+07
Variant 3	Principal stresses S_{xx}			SXX (N/m^2) 8.06e+06 6.24e+06 4.41e+06 2.58e+06 7.52e+05 -1.08e+06 -2.90e+06 -4.73e+06 -6.56e+06 -8.39e+06
	Principal stresses S_{yy}			SYY (N/m^2) 9.65e+06 7.56e+06 5.47e+06 3.38e+06 1.29e+06 -7.95e+05 -2.88e+06 -4.97e+06 -7.06e+06 -9.15e+06



8.6.4 - Results

8.6.4.1 - Behaviour of basic plate

The simply supported triangular plate shows a concentration of forces in the middle of the plate and in the middle of each edge. The first is caused by plate bending, while the latter is caused by tensile forces due to stretching of the plate (strain).

8.6.4.2 - Shear force in FRP sheet

Variant 1 directly shows the largest disadvantage of the embedded FRP sheet: the large concentrated stress directly at the point where the FRP protrudes from the glass. This concentration of stress is a combination of the - in the basic plate witnessed - stress concentration along each edge with newly added shear stress. This shear stress is caused by the low stiffness of the FRP sheet compared to the glass plate.

In variant 2 this problem is not solved by creating a longer connection length to distribute the shear stress over a larger length. Variant 2 also shows that rounding off the edges of the triangular plate does not have much effect on the stress in the plate. Filleting the edges can therefore be dependent on the size of the gaps between the plates: this should not exceed the size of a foot.

Variant 3 shows that increasing the width of the protruding FRP sheet slightly lowers the stress concentration. A further increase of the width is not an option due to the desire to have a transparent bridge design. A wider embedded sheet - and corresponding wider connection detail - would result in less transparency.

In variant 4 the thickness of the embedded FRP sheet is increased. This results in a higher stiffness of the FRP plate while the stiffness of the glass plate is relatively less increased. The shear stress at the start of the protruding FRP sheet is therefore further minimized.

8.6.4.3 - Concluding new plate geometry

This research concludes in the need to redesign the initial plate geometry. The thickness of the FRP embedded sheet as well as the length of the protruding part of this sheet changes. The rounding of the corners depends on the size of the gap between the plate and the influence on the fragility of the corner. Therefore the fillet radius is significantly reduced to 20mm. The new plate design is given in figure 8.19.

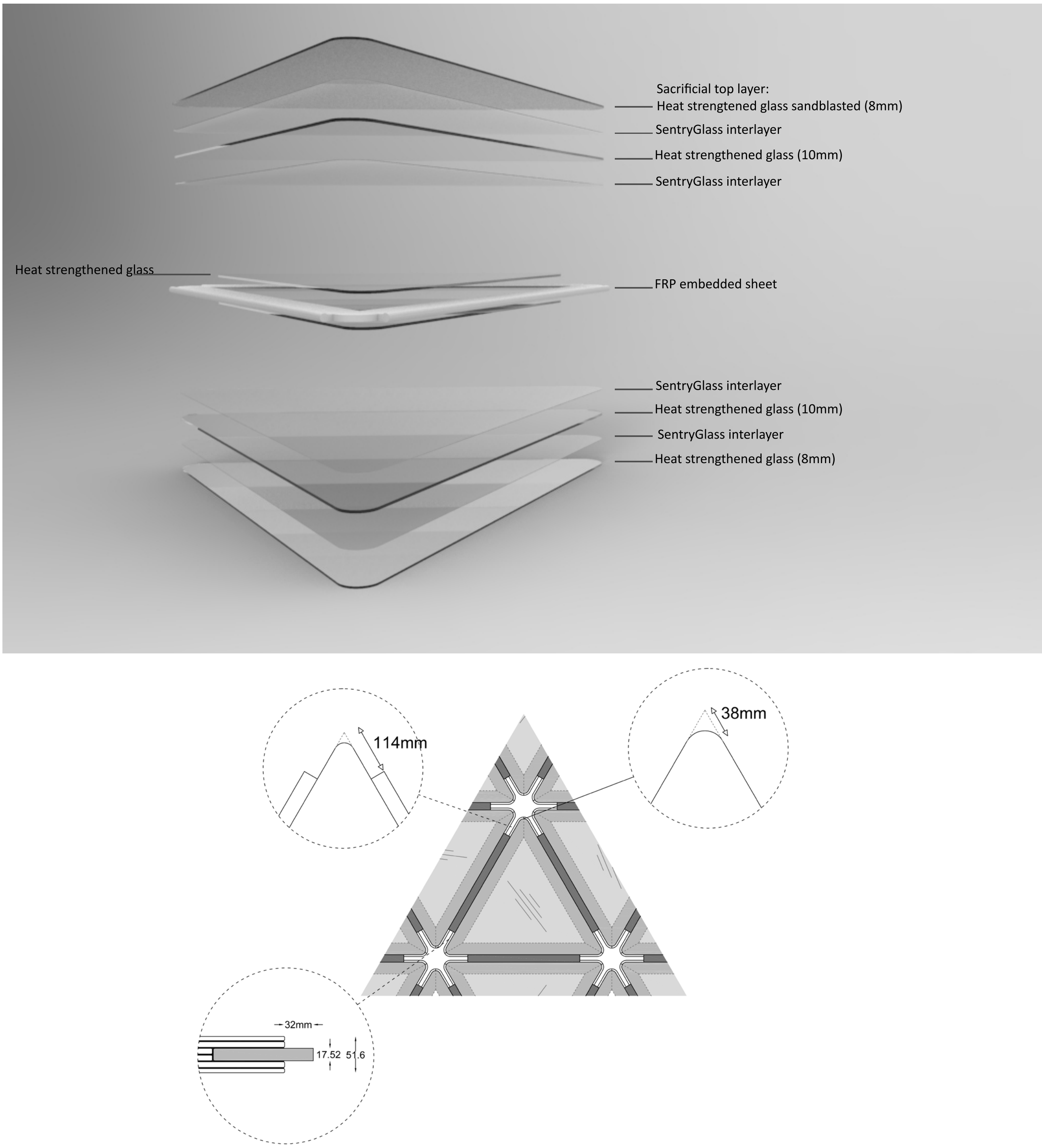
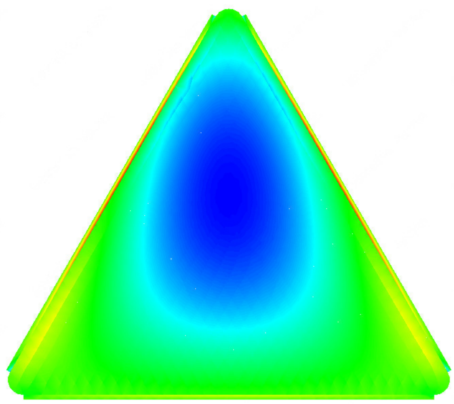
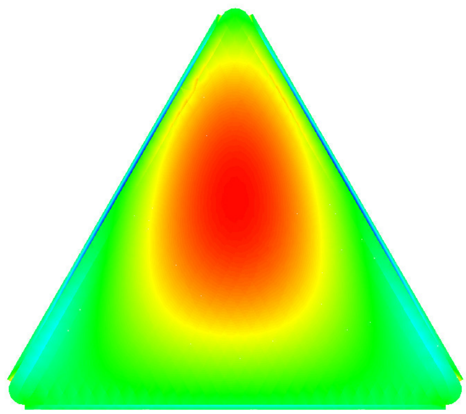
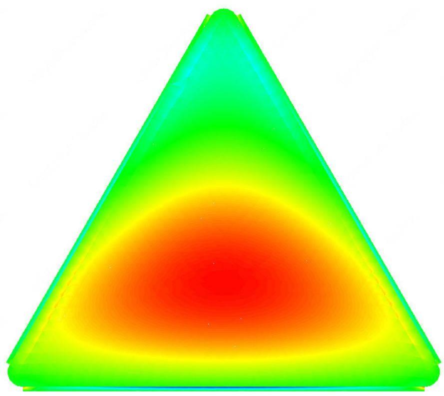
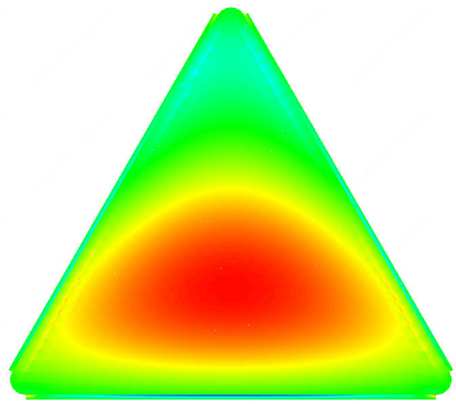


Fig. 8.19 - Build-up of the plate after geometric optimization of the plate and embedded sheet

8.6.5 - Flat shell analysis

The influence of the FRP embedded sheet on the plate behaviour has been shown in the previous research with the use of solids. However, to simplify the FEM analysis in DIANA - and save on computing time - flat shells will be used in the remaining geometric optimization phase.
The behaviour of the chosen plate geometry simulated as flat shell is analysed here to compare it with the behaviour of the chosen plate geometry simulated as solid.

		Top view	Bottom view	Legend
Flat shell	Principal stress S_{xx}			SXX (N/m^2) 2.21e+06 1.56e+06 9.08e+05 2.57e+05 -3.95e+05 -1.05e+06 -1.70e+06 -2.35e+06 -3.00e+06
	Principal stress S_{yy}			SYY (N/m^2) 2.84e+06 2.17e+06 1.49e+06 8.10e+05 1.33e+05 -5.45e+05 -1.22e+06 -1.90e+06 -2.58e+06

8.6.6 - Results

The behaviour of the flat shell is very similar to the behaviour of the solid. The largest bending moment is located in the middle of the plate, while the other concentration of stress (tension and shear) is located on the edges of the triangular plate.
The value of the bending moment in the middle of the plate is almost equal to the solid simulation. The forces at the edges (in the protruding GFRP) are, however, relatively lower than in the solid simulation.

An analysis with flat shells instead of solids will therefore result in comparable results. However, in the final stages it will be necessary to simulate the entire bridge using solids for more precision.

8.6.7 - Structural analysis 3: topology of plate shell (loadcase 1)

Three topologically different variants will be analysed. The purpose of this research is to find the topology which results in the least deformation (stiffest topology) and the least principal stresses in the bridge design. The three topologies are based on different methods of panelling the form-found shape.

1. Topology based on the equilateral triangle.
2. Topology based on a combination of the two.
3. Topology based on the isosceles triangle.

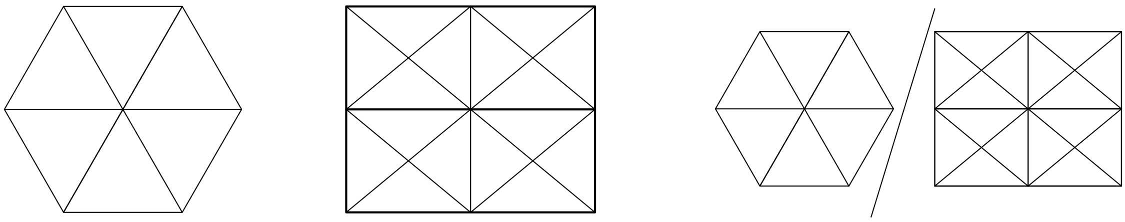


Fig. 8.20 - Types of triangular panels. From left to right: equilateral triangle, isosceles triangle and a combination of the two.

8.6.7.1 - Material input

Material properties are according to the earlier mentioned materials (paragraph 8.2.2). Glass panels of 44mm thickness and FRP connections of thickness 16mm according to the preceding structural analysis will be used.

8.6.7.2 - Element types

A quadrilateral iso-parametric curved shell element - the CQ40S shell element - is used for both the glass plates and the FRP embedded sheet. This element has an extra node on each edge, resulting in a total of eight nodes. It behaves as an iso-parametric curved shell element and is based on quadratic interpolation and Gauss integration over the ζ, η, ξ element area. [TNO DIANA, 2012]

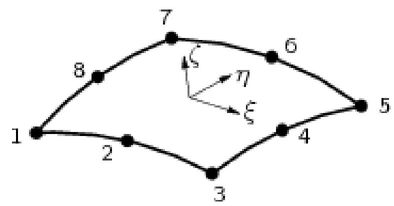


Fig. 8.21 - The CQ40S shell element [TNO, 2012]

The CL18B element is a three-node, three-dimensional class-III beam element. This element is used for the free edge beam (see chapter 9). [TNO DIANA, 2012]

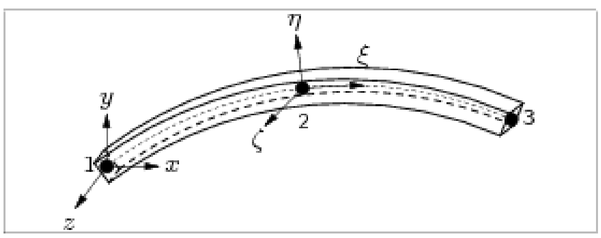


Fig. 8.22 - The CL18B three node, three dimensional class III beam elementCQ40S shell element [TNO, 2012]

8.6.7.3 - Loadcase

For this first analysis the load on the surface will consist of a dead-load and a live-load on the walkable area of the bridge according to the NEN norms (chapter 1). The value of the live-load will be 3900 N/m^2.

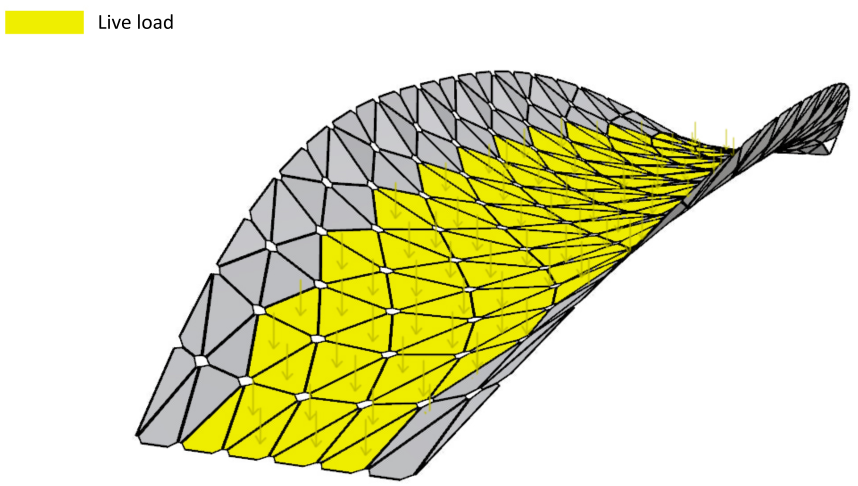


Fig. 8.23 - Loadcase 1: a live load of 3900N/m^2 on the walkable area of the bridge

8.6.7.4 - Meshing

Ideally the mesh division ratio per edge should be 1:1. However, the used educational version of DIANA does not allow this level of mesh refinement. Therefore the mesh is defined as follows:

- The triangular glass plates will be meshed with a triangular mesh (TETRA/TRIANGLE) with element size 0.2.
- The FRP connection is meshed with a quadrangular mesh (QUAD/HEXA) with element size 0.2.

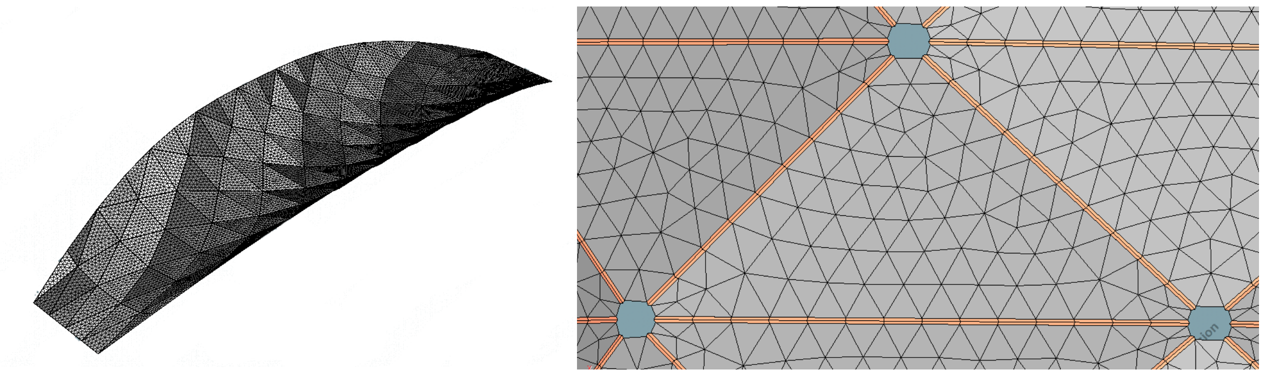


Fig. 8.24 - Meshing of the triangular plate shell in DIANA. Close-up shows the triangular meshing of the plate combined with the quadrangular mesh of the FRP connections.

8.6.7.5 - Boundary conditions

The model is supported along the two short opposite sides of the bridge. This joint is modelled as clamped (fixed translations and fixed rotations) and is connected to the FRP embedded sheet. Due to the low stiffness of the FRP embedded sheet this connection will behave as a semi-rigid connection.

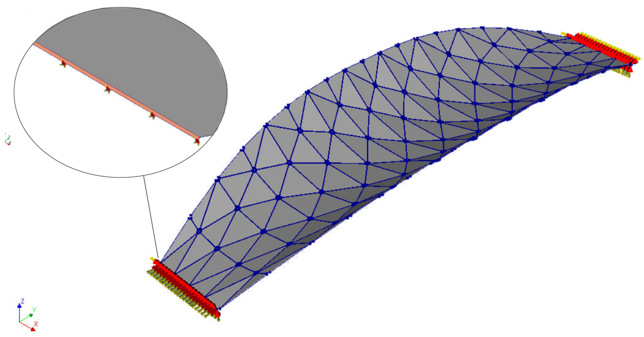
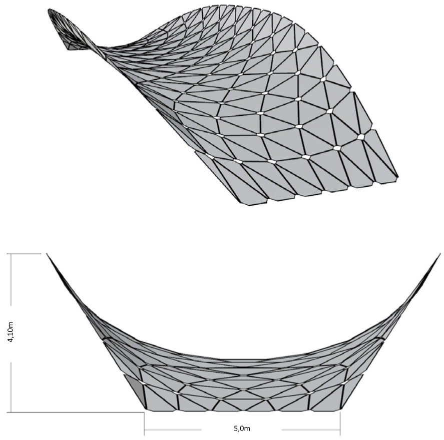
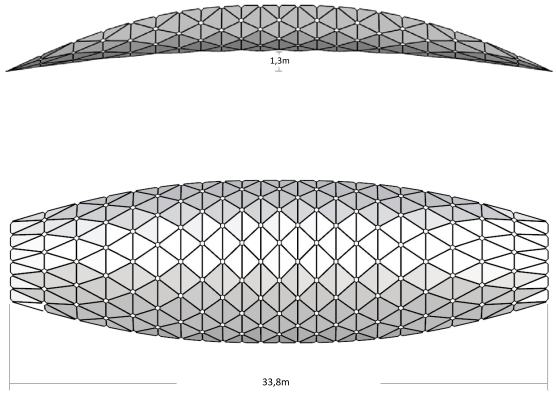


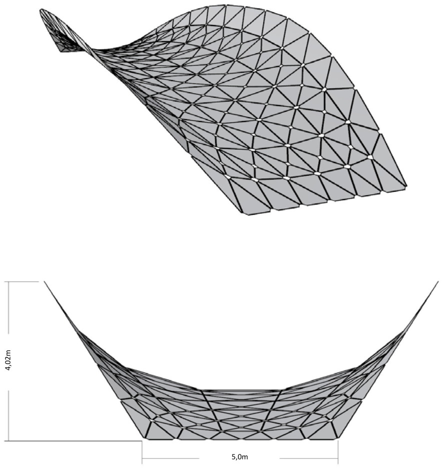
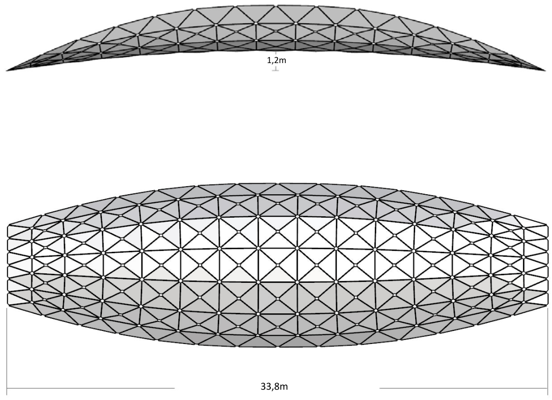
Fig. 8.25 - Location and nature of the supports: fixed supports at both ends of the bridge.

<table>
<tr><th></th><th colspan="3">Plate shell variants</th></tr>
<tr><td>Topology 1</td><td>
</td><td>
</td><td>Number of plates:
286

Average size of plates:
1.18 m^2

Max. edge length:
2.59 m

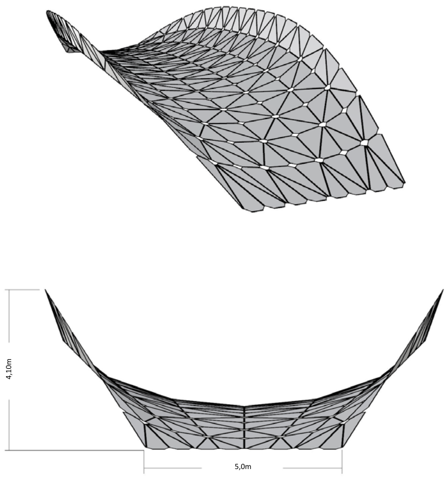
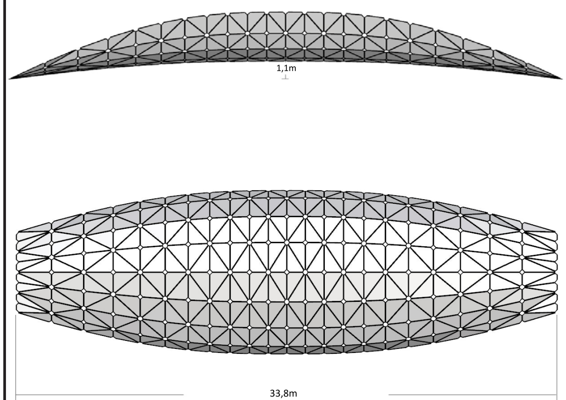
Min. edge length:
0.609 m

Estimated weight:
8402 kg
**</td></tr>
<tr><td>Topology 2</td><td>
</td><td>
</td><td>Number of plates:
336

Average size of plates:
1.00 m^2

Max. edge length:
2.55 m

Min. edge length:
0.823 m

Estimated weight:
8400 kg
**</td></tr>
<tr><td>Topology 3</td><td>
</td><td>
</td><td>Number of plates:
352

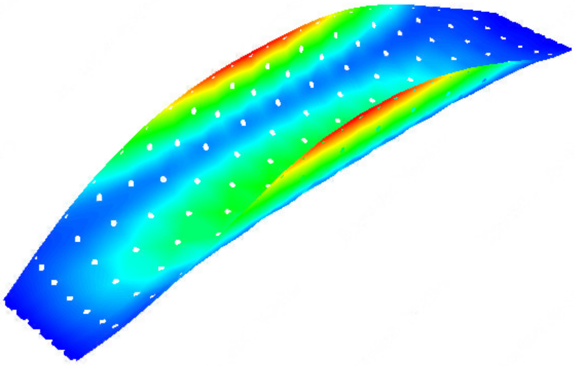
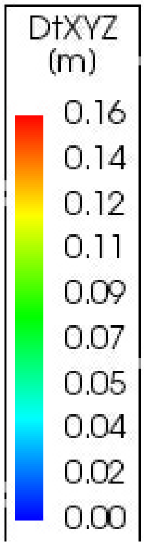
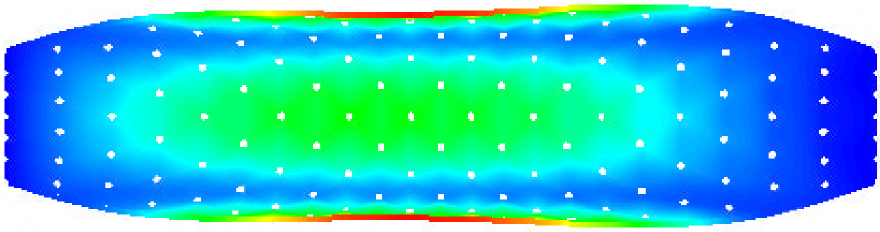
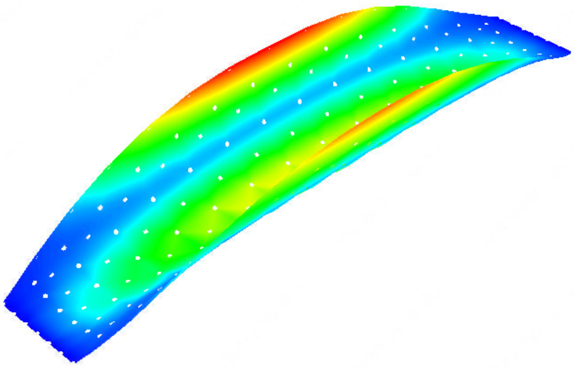
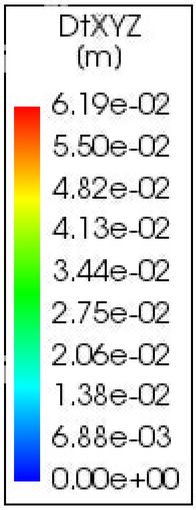
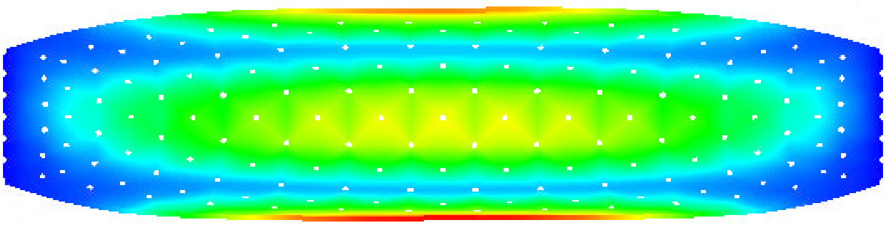
Average size of plates:
0.986 m^2

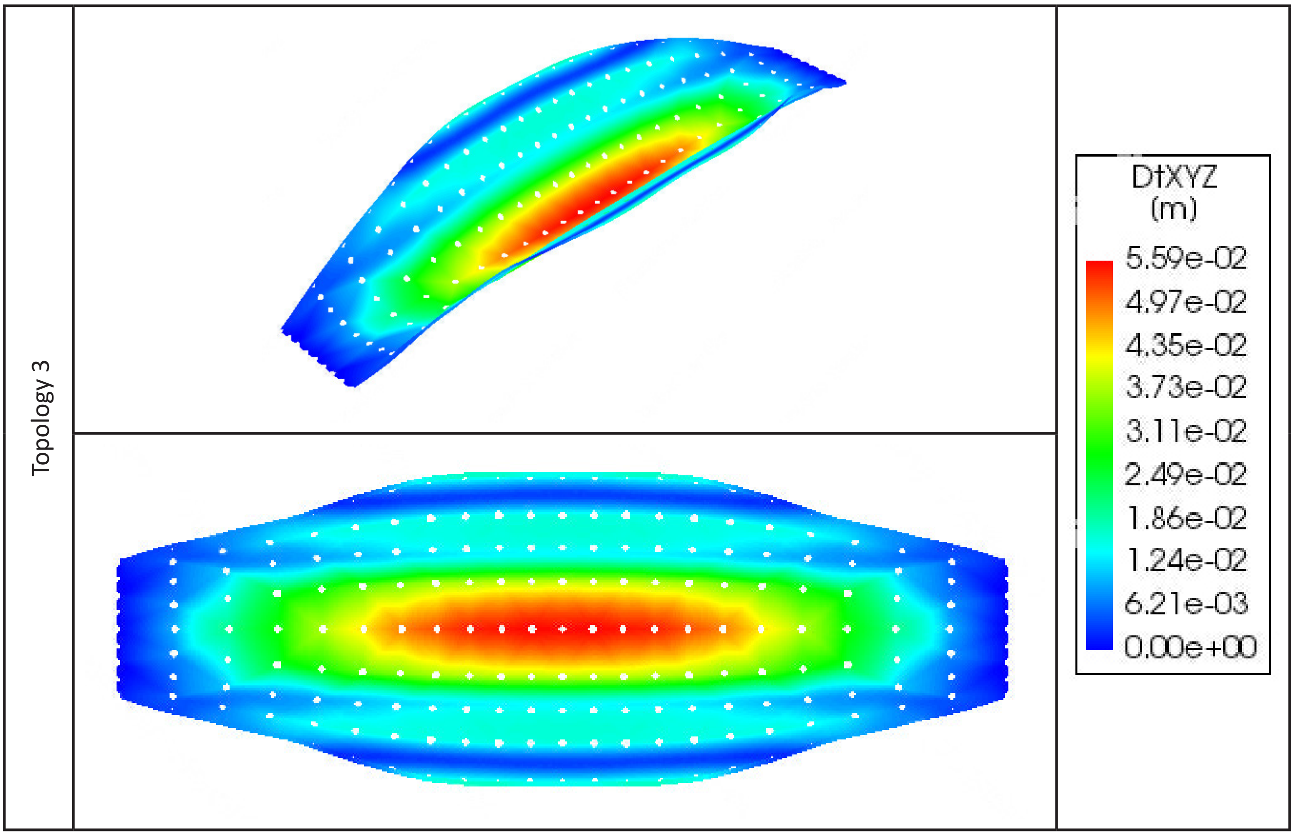
Max. edge length:
2.66 m

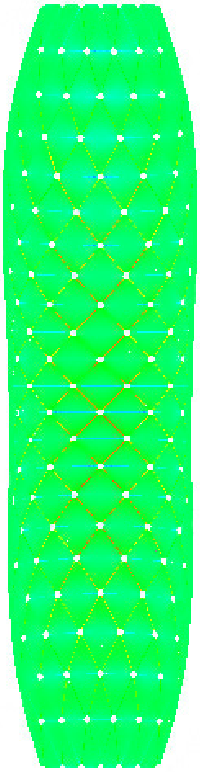
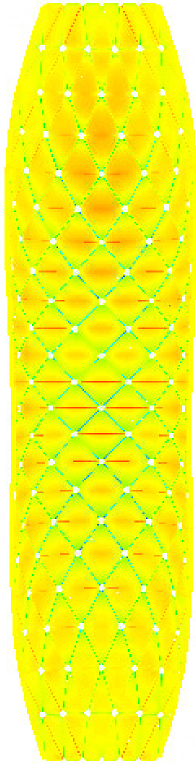
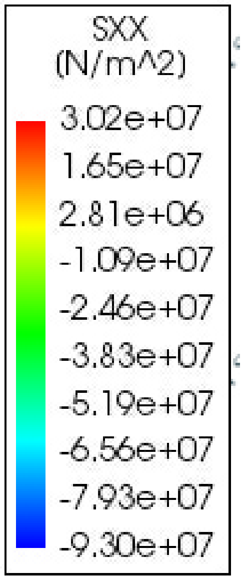
Min. edge length:
0.625 m

Estimated weight:
8676 kg
**</td></tr>
</table>

** For a more extensive comparison of the plate shells see appendix.

Deformation		
	Deformed shape (x10)	Legend
Topology 1		
		
	Deformed shape (x10)	Legend
Topology 2		
		
	Deformed shape (x10)	Legend


Topology 3
DtXYZ
(m)
5.59e-02
4.97e-02
4.35e-02
3.73e-02
3.11e-02
2.49e-02
1.86e-02
1.24e-02
6.21e-03
0.00e+00

<table>
<tr><td colspan="4">Principal stresses S_{xx}</td></tr>
<tr><td></td><td>Top layer</td><td>Bottom layer</td><td>Legend</td></tr>
<tr><td>Topology 1</td><td></td><td></td><td>
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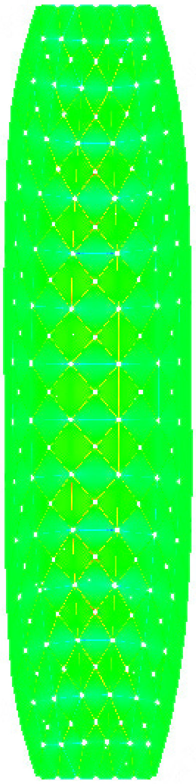
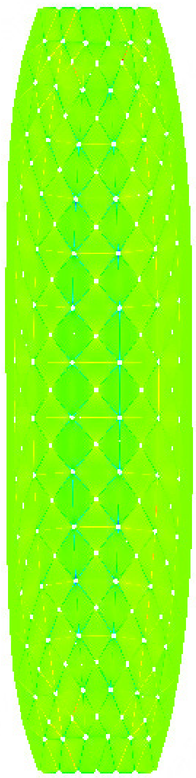
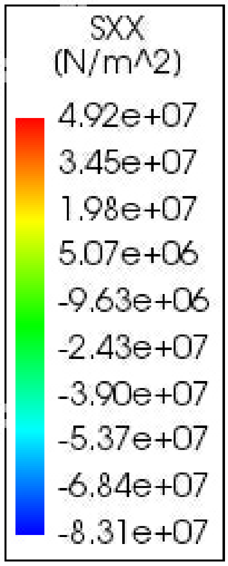
<tr><td></td><td>Top layer</td><td>Bottom layer</td><td>Legend</td></tr>
<tr><td>Topology 2</td><td></td><td></td><td>
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<tr><td></td><td>Top layer</td><td>Bottom layer</td><td>Legend</td></tr>
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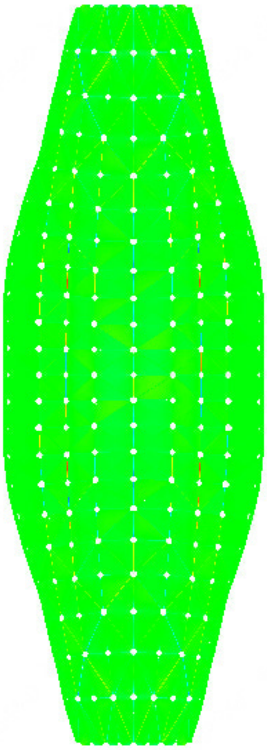
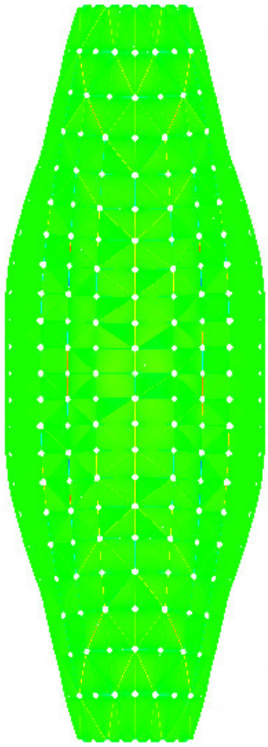
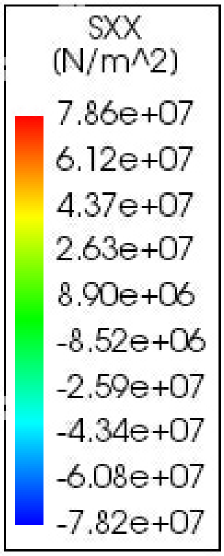
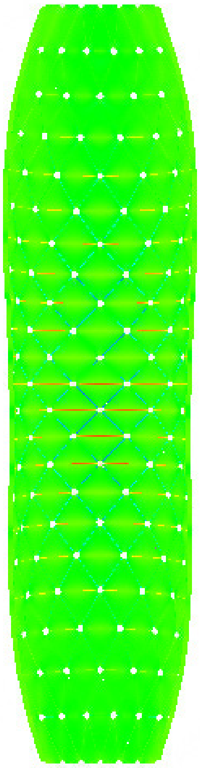
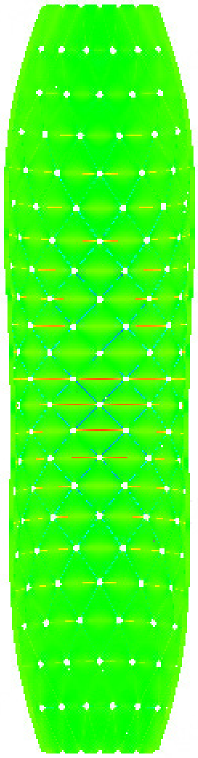
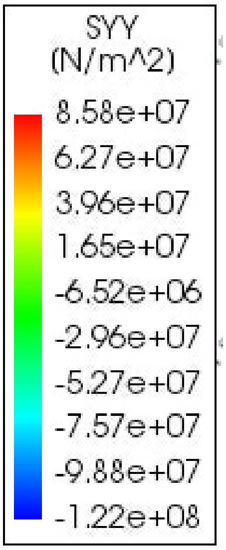
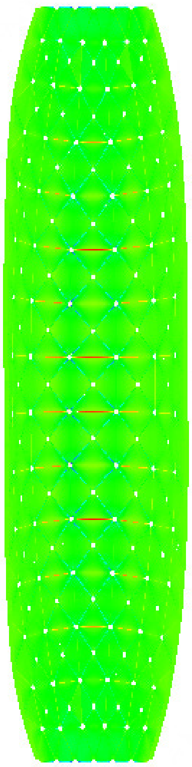
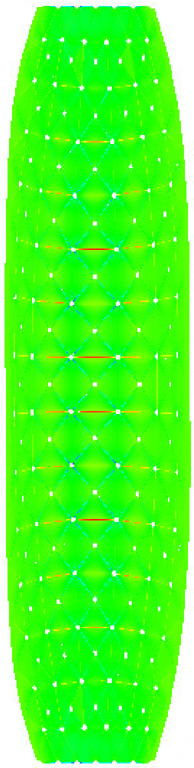
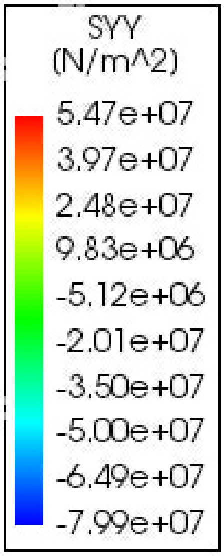
Topology 3			SXX (N/m^2) 7.86e+07 6.12e+07 4.37e+07 2.63e+07 8.90e+06 -8.52e+06 -2.59e+07 -4.34e+07 -6.08e+07 -7.82e+07

<table>
<tr><th colspan="4">Principal stresses S_{yy}</th></tr>
<tr><td></td><td>Top layer</td><td>Bottom layer</td><td>Legend</td></tr>
<tr><td>Topology 1</td><td></td><td></td><td>
</td></tr>
<tr><td></td><td>Top layer</td><td>Bottom layer</td><td>Legend</td></tr>
<tr><td>Topology 2</td><td></td><td></td><td>
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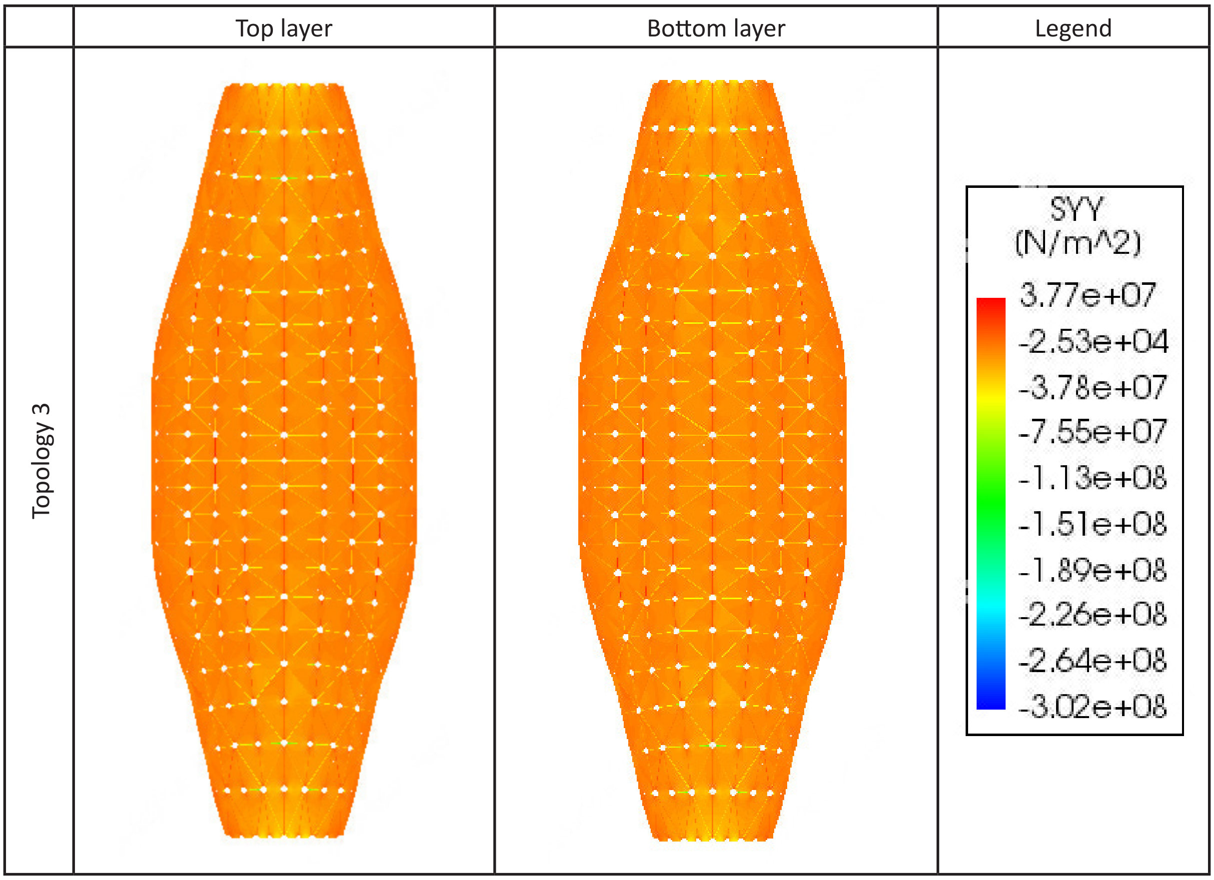


Loadcase 1	Sxx (Mpa)				Syy (Mpa)				Deformation (mm)
	Tensile		Compressive		Tensile		Compressive		
	Top layer	*Bottom layer*	*Top layer*	*Bottom layer*	*Top layer*	*Bottom layer*	*Top layer*	*Bottom layer*	
Topology 1	**92.7**	30.2	**-64.8**	**-93**	**61.4**	**85.8**	**-201**	-122	**160**
Topology 2	66	**49.2**	-58.2	-83.1	29.8	54.7	-141	-79.9	61.9
Topology 3	43	48.2	-51.4	-63.8	59.5	19.4	-124	**-218**	39.5

8.6.8 - Results

8.6.8.1 - Deformation

In the first two topology variants three zones of deformation can be witnessed:

- Zone 1: the middle of the plate shell deforms due to global bending of the plate shell bridge.
- Zone 2 & 3: the middle of the free edges of the plate shell deform due to a combination of torsion and global bending of the shell.

The highest value of the deformation can be found at the free edges of the shell. For variant 1 this deformation has a maximum of 160mm, while for variant 2 the maximum value is 61,9mm.
The third topology has only one zone of deformation: the middle of the shell. The deformation is the least of all variants: only 39,5mm.

This means that for a live load on the walkable part of the bridge, variant 3 will be the stiffest topology.

8.6.8.2 - Principal stresses

Variant 1 and 2 show very high compressive stresses in the X-direction of the plate shell. The highest tensile stresses are located in Y-direction. In the middle of the shell (zone 1 of the deformation) a pattern of large tensile stresses in the diagonal vertices and large compressive stresses in the vertices perpendicular to the Y-direction can be seen.
This behaviour is caused by the type of triangular panels that is used. In both variant 1 and 2 the centre point of the panel is moved downwards (along the z-axis). Normal forces will be forced to make a bend to move from plate to plate. This causes a bending moment which causes the high stresses in the vertices.

Variant 3 does not have these lower points in its panel, causing the stresses to flow smoother towards the supports of the plate shell. However, the angle between panels in X-direction is much larger than for variants 1 and 2. This causes the highest stresses to be located in one direction. When the parapet is loaded in a different loadcase this might cause higher stresses in variant 3 than in other variants.

8.6.9 - Structural analysis 3: topology of plate shell (loadcase 2 & 3)

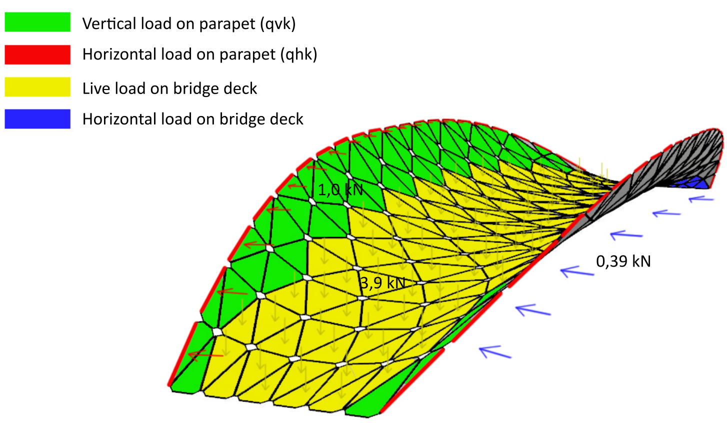
The first analysis only takes into account the live load on the walkable area on the bridge. However, in practice there will be many more types of loads on the bridge. Following the earlier mentioned NEN norms (chapter 1) the following loads have to be applied on this plate shell footbridge:

1. A live load of 3900 N/mm^2 working on the walkable area of the bridge.
2. A horizontal load of 390 N/mm^2 in x-direction on the walkable area of the bridge.
3. A dead load according to the dead weight of the structure.
4. A concentrated load of 10 kN working on the middle of the bridge
5. A horizontal load on the top of the parapet of 1000 N/mm^2.
6. A horizontal wind load on the parapet of 1000 N/mm^2
7. A vertical load on the parapet of 1000 N/mm^2

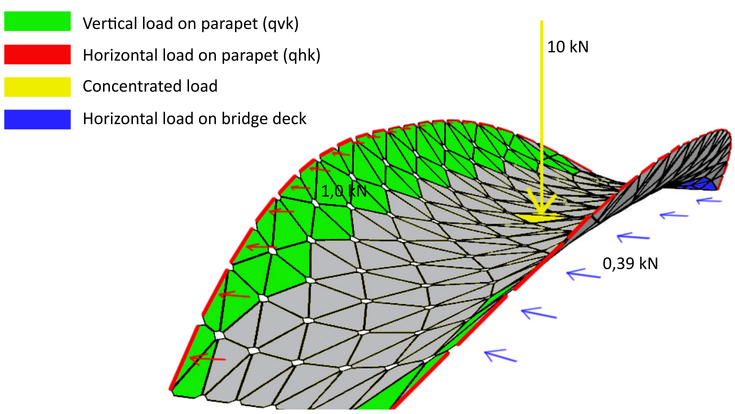
These loads will be combined in two loadcases:

1. Loadcase 2: dead-load + live load + horizontal load + loads on parapet
2. Loadcase 3: dead-load + horizontal load + concentrated load + loads on parapet

Loadcase 2



Loadcase 3



<table>
<tr><th colspan="3">Deformation loadcase 2</th></tr>
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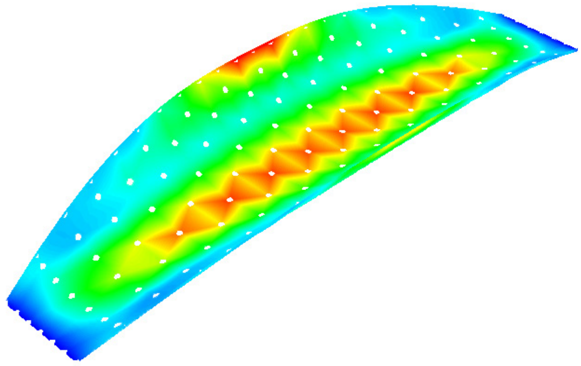
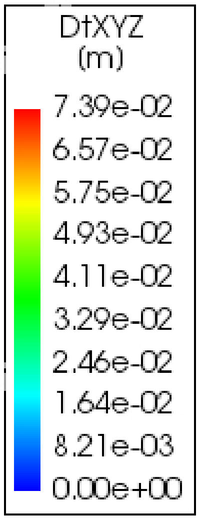
<tr><td rowspan="2">Topology 1</td><td></td><td rowspan="2">
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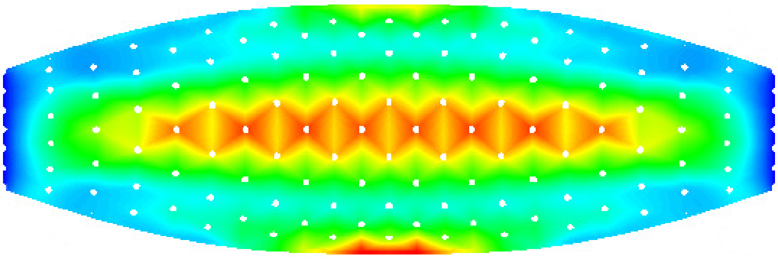
<tr><td></td></tr>
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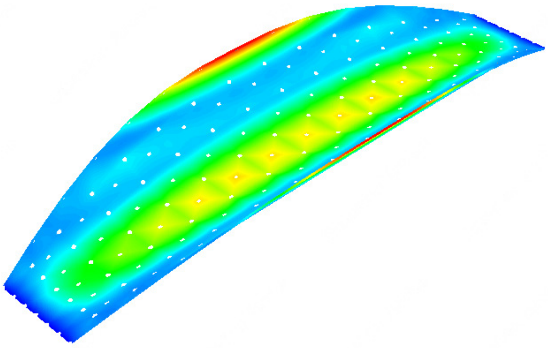
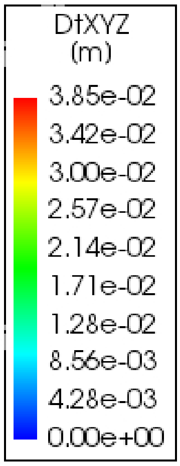
<tr><td rowspan="2">Topology 2</td><td></td><td rowspan="2">
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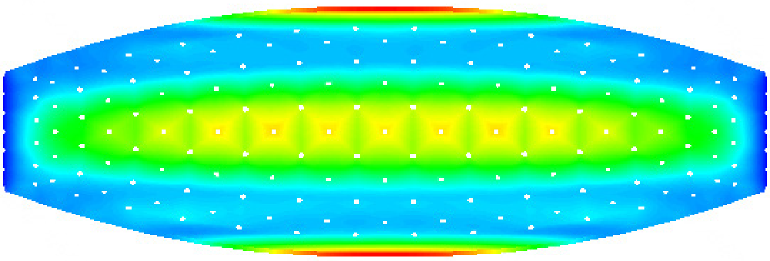
<tr><td></td></tr>
<tr><td></td><td>Deformed shape (x10)</td><td>Legend</td></tr>
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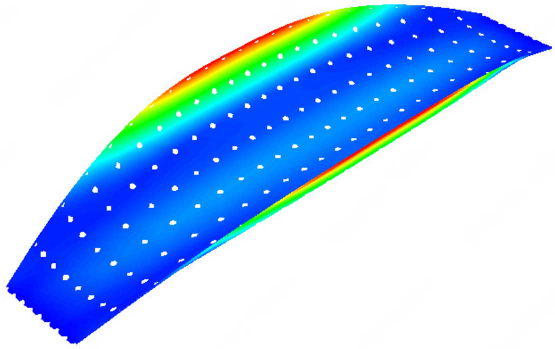
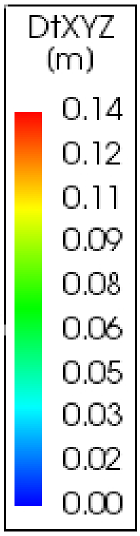
<tr><td rowspan="2">Topology 3</td><td></td><td rowspan="2">
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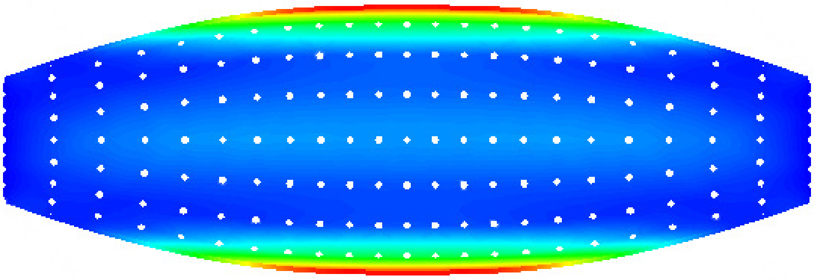
<tr><td></td></tr>
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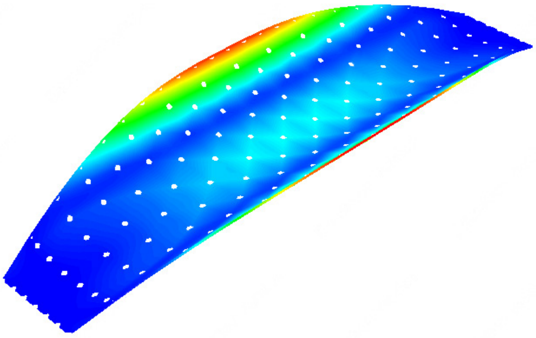
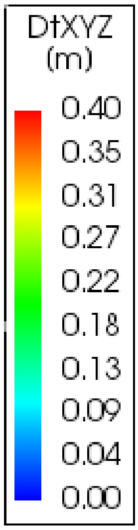
<tr><th colspan="3">Deformation loadcase 3</th></tr>
<tr><td></td><td>Deformed shape (x10)</td><td>Legend</td></tr>
<tr><td rowspan="2">Topology 1</td><td></td><td rowspan="2">
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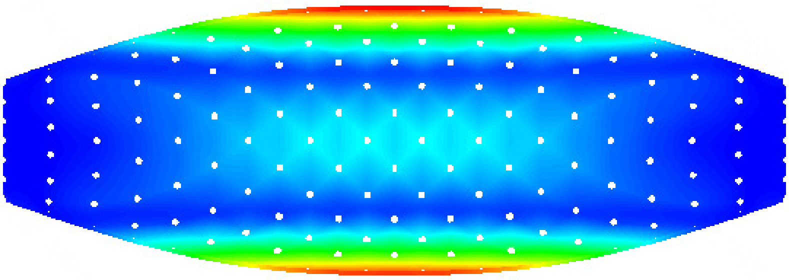
<tr><td></td></tr>
<tr><td></td><td>Deformed shape (x10)</td><td>Legend</td></tr>
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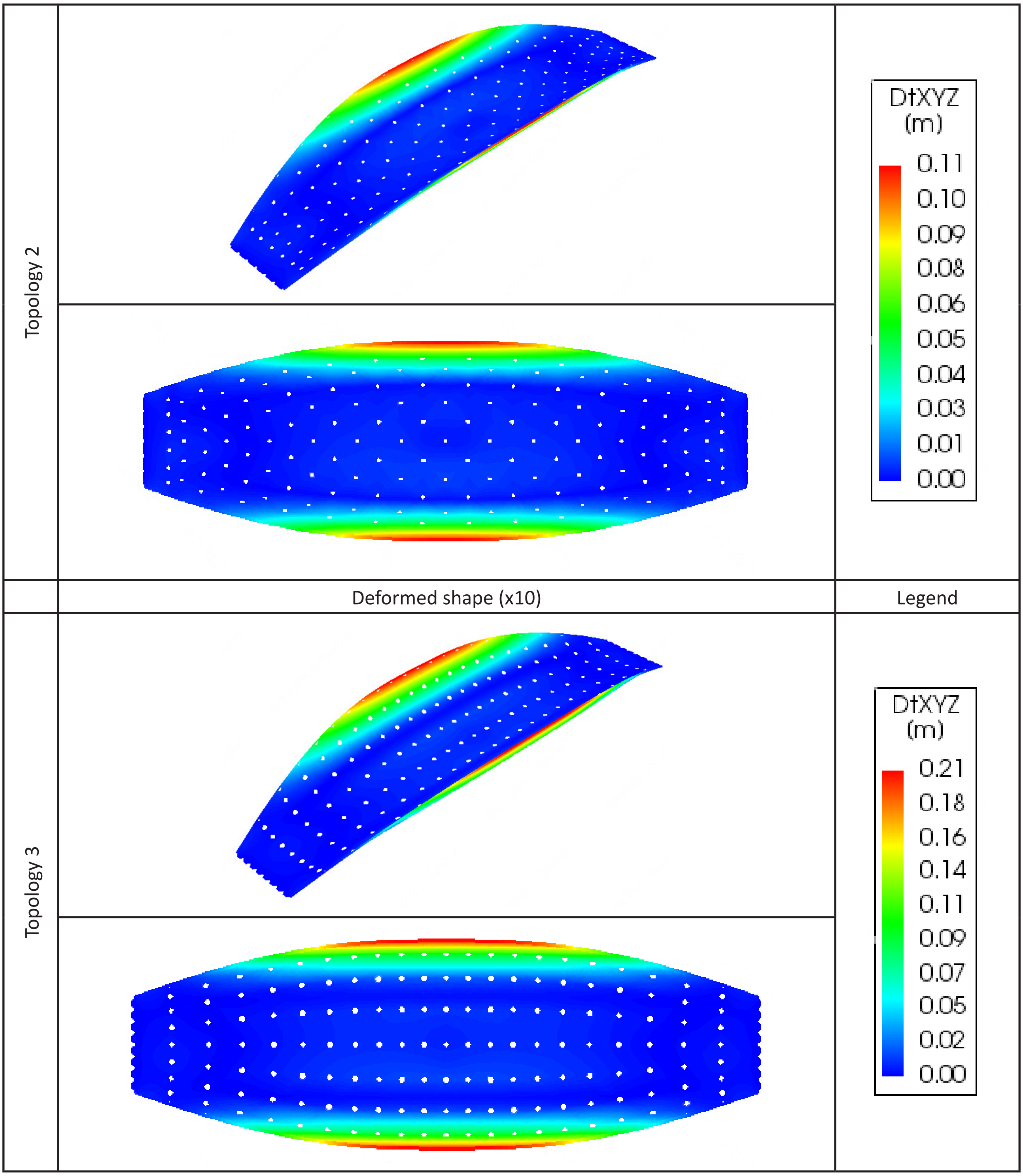


Loadcase 2	Sxx (Mpa)				Syy (Mpa)				Deformation (mm)
	Tensile		Compressive		Tensile		Compressive		
	Top layer	*Bottom layer*	*Top layer*	*Bottom layer*	*Top layer*	*Bottom layer*	*Top layer*	*Bottom layer*	
Topology 1	95	99.5	**-170**	-115	91.5	**243**	**-306**	-141	73.9
Topology 2	52.6	62.8	-67.4	-61.6	65.9	43.7	-111	-117	38.5
Topology 3	**140**	**140**	-137	**-138**	**158**	68.9	-133	**-208**	**140**

Loadcase 3	Sxx (Mpa)				Syy (Mpa)				Deformation (mm)
	Tensile		Compressive		Tensile		Compressive		
	Top layer	Bottom layer	Top layer	Bottom layer	Top layer	Bottom layer	Top layer	Bottom layer	
Topology 1	71.9	145	**-264**	-108	**171**	**223**	**-418**	**-275**	**400**
Topology 2	37	80.5	-97.7	-71.9	58.5	36.5	-82.8	**-195**	110
Topology 3	**155**	**155**	-156	**-157**	145	76.4	-98.5	**-230**	**210**

8.6.10 - Results

8.6.10.1 - Loadcase 2

The deformation of topology 1 and 2 shows a similar pattern. The highest deformation is located in the middle of the shell and in the middle of the free edges of the shell. In the middle of the shell this value is highest at the lower centre point of each panel, corresponding with the highest stress values.
In topology 3 the highest deformation is located at the middle of the free edges. As expected, this topology now has the highest deformation of all variants. The large angles between the plates in X-direction cause higher bending moments (and thus higher principal stress values) in this second loadcase. Especially the horizontal forces on both the bridge deck and the parapet cause larger deformation and stress values.

Topology variant 2 has the least deformation and the lowest principal stress values of all variants for loadcase 2.

8.6.10.2 - Loadcase 3

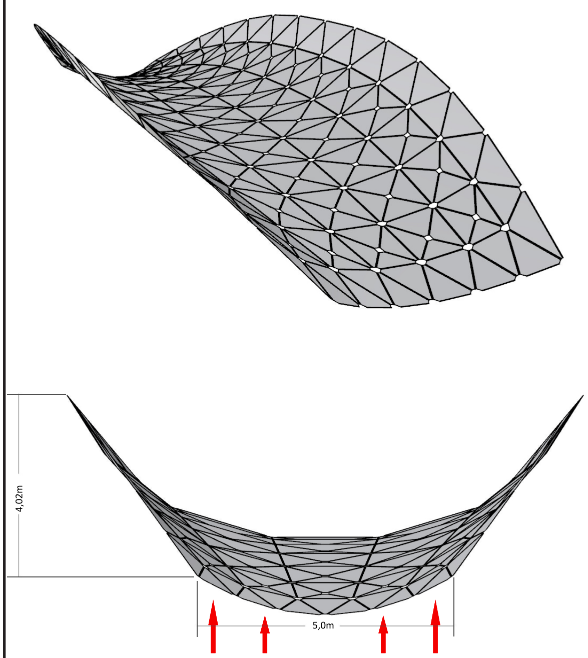
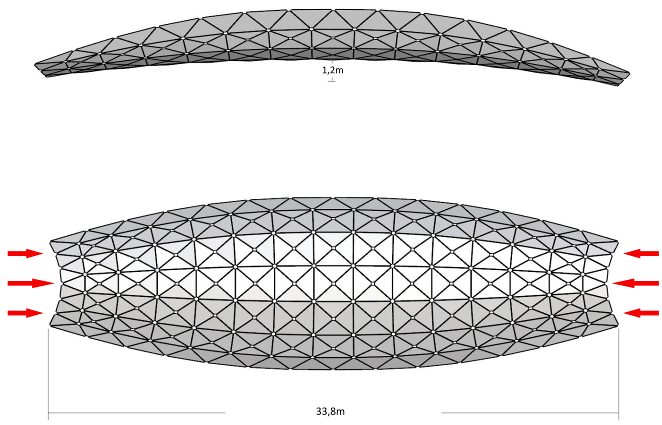
The deformation for loadcase 3 shows a similar pattern for all topologies. The highest deformation is located in the middle of the free edges, with a lowest value for topology 2.
The value of the deformation corresponds with the stress values in the topology variants. The highest stresses can be found in topology 1 - this topology has the highest deformation values. The lowest stresses can be found in topology 2: this topology has the lowest deformation values.

Overall, topology variant 2 is the most efficient plate shell design. It has, on average, the least deformation and the lowest principal stresses in all loadcases.

8.6.11 - Structural analysis 4: changing curvature at supports

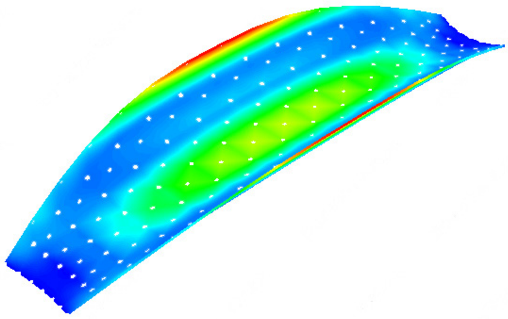
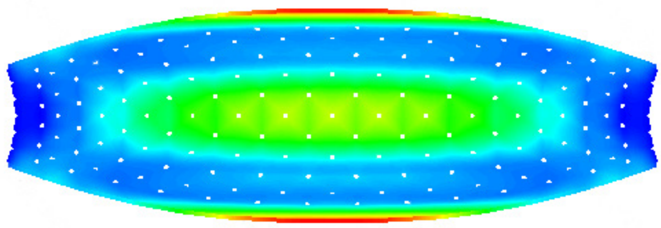
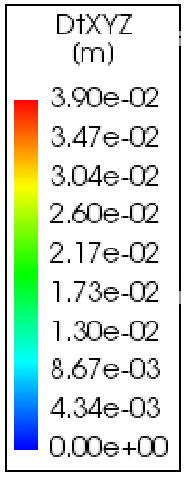
The results of the previous structural analysis shows that the highest stresses in the shell are located at the area near the supports. This is due to the straight line at the supports. This forces the shell to be single curved at the supports: the plate shell will therefore no longer behave like a shell, but more like a slab.

By changing the smooth shell shape to create a curved (concave) line at both ends of the bridge and subsequently repeating the tessellation process, a new triangular plate shell is created. The stresses and deformation of this plate shell (loaded with loadcase 2 according to the NEN norms) are compared to the previous plate shell.

	Plate shell	
Changed curvature		

The curvature is created by lowering the centre of both endings of the bridge by 0,5 meter. Furthermore the centre of both endings is moved inwards (towards the centre of the bridge) by 0,5 meter.
The curvature is limited by the requirements regarding the maximum inclination of the bridge. By creating a larger curvature the bridge would no longer meet these requirements.

Loadcase 2, as introduced in paragraph 8.6.9, is used to compare the shell with non-curved endings to the shell with curved endings.
The material properties, meshing, boundary conditions etcetera are equal to earlier FEM-analysis.

Deformation loadcase 2		
	Deformed shape (x10)	Legend
Changed curvature	 	

Loadcase 2	Sxx (Mpa)				Syy (Mpa)				Deformation (mm)
	Tensile		Compressive		Tensile		Compressive		
	Top layer	*Bottom layer*	*Top layer*	*Bottom layer*	*Top layer*	*Bottom layer*	*Top layer*	*Bottom layer*	
Topology 2	**52.6**	62.8	**-67.4**	**-61.6**	65.9	**43.7**	**-111**	**-117**	38.5
Changed curva	42.2	**63.6**	-56.1	-49.3	**79.5**	32.5	-89.7	-114	**39**

8.6.12 - Results

The stress values for the shell with changed curvature at the supports are - in almost all cases - lower than for the previous shell design without curvature. The maximum deformation rises with a neglectible amount: 0,5mm.

To create even lower stress values it is necessary to introduce higher curvature at the supports. However, this is not possible due to the program of requirements regarding the wheelchair accessibility of the bridge. However, especially the maximum compressive stress values are minimized in this new bridge design.

8.7 - Final conclusion

Form-finding the shell shape of the bridge according to the program of requirements, resulted in three types of shells. All these shells meet the requirement (maximum stress levels and maximum deformation) under dead load and a live load of 3,9kN/m^2. However, variant 2 - the concave shell - is the most efficient variant as this combines a natural parapet with the lowest bending stress.

After geometric optimization of the form-found concave shell shape several conclusions can be drawn regarding the individual plate shape and the topology of the plate shell.
First of all, hexagonal tessellation on a concave shell results in high distortion and overlapping of the panels. Only a triangular tessellation leads to relatively undistorted panelling of the smooth shell. The use of shortened vertices results in the disappearance of the disadvantage regarding concentrated forces flowing through the vertices of a triangular plate shell: the stresses are forced to flow through the plates. Therefore a triangular tessellation is applied in this case.

Several assumptions regarding the plate shape have been tested, resulting in an optimized collaboration between glass and embedded FRP sheeting. The corners of the plate have been rounded off for easier handling and production and less stress concentrations. The exact distance of this fillet is based on the size of the gap that will be created: a radius of 20mm is applied. The GFRP embedded sheet has been given the optimal thickness and width for the least stress concentrations. Further optimization for fewer stress is possible, given that the transparency of the bridge will be sacrificed. Therefore the end product of this analysis is given in figure 8.19.

Several types of triangular tessellation have been tested: topological variants. These have been tested in several loadcases according to NEN norms for deformation and stress values. The topological variant that showed the least deformation and stress in the material during all loadcases is variant 2. Therefore this variant is elaborated on.

Due to the shape of the arrival of the bridge, shaped as a straight line, the stresses at this location are highest. The shell is forced into single curvature leading to low stiffness at this point. By elevating the amount of curvature the stresses at the supports decrease significantly leading to a more efficient bridge design.

9 | The hybrid faceted shell: Connections

9.1 - Introduction

The connections have been modelled in the previous form-finding process as simple lines with infinite stiffness. However, these lines should be translated to a certain geometry. The research question for this chapter is therefore:

What is the most efficient connection between FRP and structural glass?

Efficient means in this case that the connection meets the functional requirements taken and adapted from Bagger (2010):

- Slender and light appearance (as transparent as possible)
- Easy assembly and replacement
- Minimal stress concentrations from temperature movements
- Yielding capacity when the detail would fail
- Taking into account creep

There will be three main types of connections between FRP and structural glass in this bridge design: the supports, the joint between the plates and the free edge beam. All have a different nature and therefore a (slightly) different design. The design of these connections will be treated in this chapter.

9.2 - Connection examples

Several connection types for plate shells have been developed. In this paragraph an overview of these connections, their advantages and disadvantages will be given. Together with the theory provided in chapter 7 this will result in a theoretical framework to develop and analyse a new FRP connection for the glass faceted shell bridge.

9.2.1 - Friction connection [Aanhaanen, 2008]

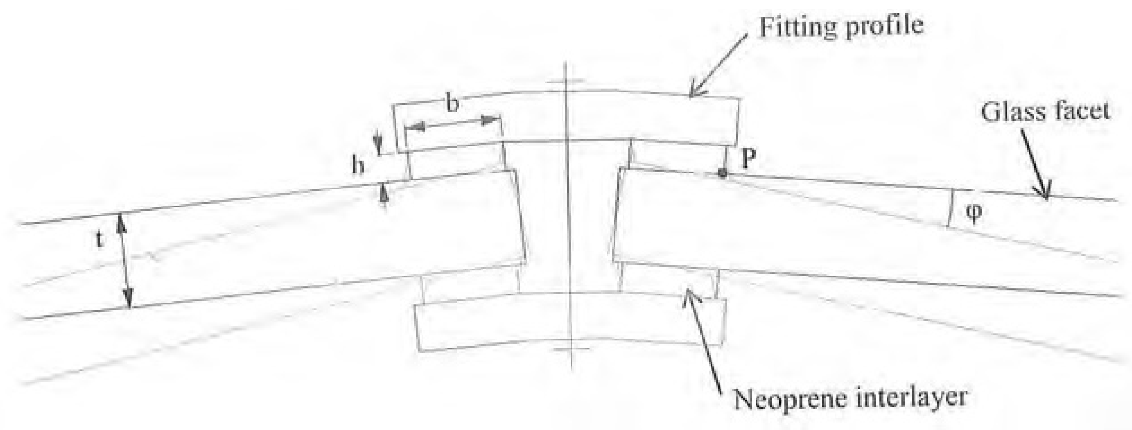


Fig. 9.1 - Frictional connection developed and tested by Aanhaanen (2008).

Aanhaanen (2008) proposed and analyzed a clamped connection consisting of two fitting profiles clamping the glass panes. A bolt pre-stresses the joint, while a soft neoprene strip, located between the fitting profiles and the glass, causes friction.

The analysis of a dome with this connection type showed that it does not fulfil the stability conditions: the deflections are too large and the lambda value too low. This is the result of low axial and shear stiffness of the joint. The glass panes can move over each other (figure 9.3). Several possibilities of redesign have been suggested by Aanhaanen:

- Increase the pre-stressing force exerted on the neoprene by the aluminium strips. The increased force will lead to more friction with resulting higher axial stiffness and out-of-plane shear stiffness of the joint. However, this effect is only limited and not likely to be enough to gain the desired stiffness. Furthermore the effect is very hard to predict or analyze because of non-linear behaviour of the neoprene due to relaxation and creep.
- Using thinner neoprene strips will have a large impact on the resulting axial and shear stiffness of the joint. However, the material should still be able to withstand the pre-stressing forces.
- Filling the openings between the glass plates with a rubber-like material. In this way the glass panels will be able to directly transfer the normal forces.

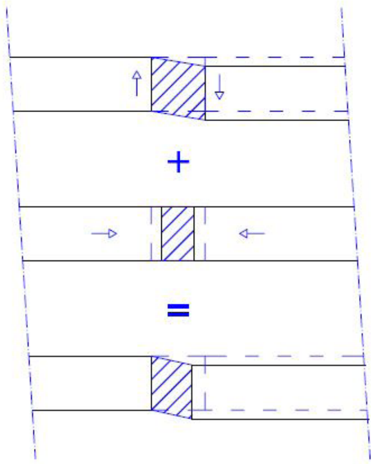


Fig. 9.2 - A combination of compressive forces and shear forces in the plates results in overlapping of the plates.

9.2.2 - Three connection types [Bagger, 2010]

The research of Anne Bagger (2010) concluded in three types of connection details for a faceted plate shell: the glued-in plate connection, the friction connection and the glued butt joint.

9.2.2.1 - Glued-in plate connection

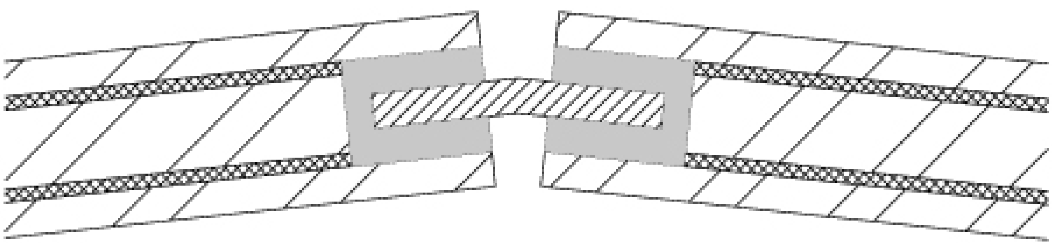


Fig. 9.3 - The glued-in plate connection proposed by Bagger (2010) seems to be the most promising connection type.

The glued-in plate connection detail consists of a plate (or another mechanical item), embedded into the glass facet edge using a structural adhesive. The glass plates consist of three layers of glass laminated together using SentryGlas interlayer material.
The edge of the middle glass pane is offset a small distance from the edge of the other two panes. The canal that is created is filled with a plate bonded with a structural adhesive. The rotational stiffness of this detail can be adjusted by altering the thickness and the material of the glued-in plate. The length of the plate depends on the edges it connects: to allow uplift of the facet corners, the plate length should be shorter than the connected edges. [Bagger, 2010]

The glued-in plate connection is deemed the most promising of the suggested connection details for large plate shell structures. The detail has several advantages:

- The connection will appear very slender (only 10-20mm without glass surface), without addition of extra height to the facet surface. The connection will not appear as the primary load-bearing system as it is very slender.
- The detail is ductile in bending, due to the yielding of the aluminium plate, while no apparent damage to the adhesive is inflicted.
- The connection detail can take up relatively large tolerances in all directions during assembly.
- The tendency form the detail to creep in the adhesive will reduce stress peaks at the connection ends. The creep rate appears to reduce quickly and become insignificant.

Drawbacks of this connection detail include:

- Assembly of the plate shell will be difficult: one half of each connection line can be glued in a workshop (so that the aluminum plate protrudes from the edge), but the opposing facet edge must be glued on site.
- Damage to the adhesive is not visible, unless it causes large deformations in the structure. This can lead to sudden collapse.
- It will be difficult to replace a broken facet.

9.2.2.2 - Friction connection

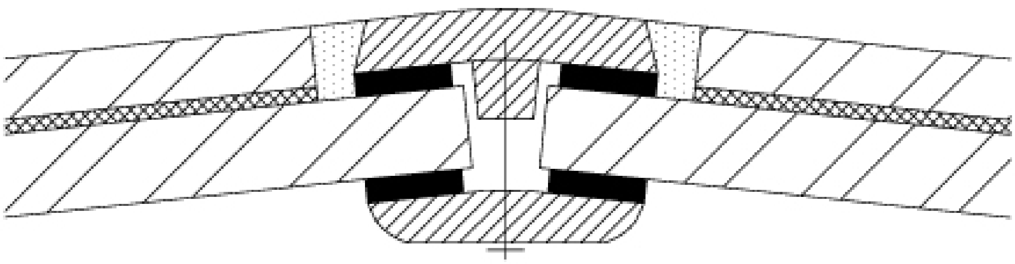


Fig. 9.4 - The frictional connection proposed by Bagger (2010). Improvement in relation to Aanhaanen is the use of a different friction material: Klingersil fibre sheeting.

This detail is very similar to the one developed by Aanhaanen (2008). Two continuous profiles made of aluminium, steel, GFRP or any other suitable material, are clamped around the edge of a single monolithic glass pane. A strip of softer material serves as interlayer between the profiles and the glass. This strip has multiple functions: it secures a good transfer of friction forces, it avoids stress peaks in the glass caused by uneven surface of the profiles, it allows differences in temperature movements between the glass and the profiles and it introduces a rotational compliance in the connection.
Pre-stress is applied by tightening screws to hold the profiles together. A second layer of glass is laminated on top of the clamped layer for a smoother surface.

An important advantage of this connection detail is the ease of assembly and disassembly. A drawback is the relative low axial stiffness of the detail: the pre-stress that is necessary to create very high friction (and therefore high axial stiffness) is too high to withstand for a soft interlayer material. The ideal interlayer material is relatively soft while having good friction.

9.2.2.3 - Glued butt joint

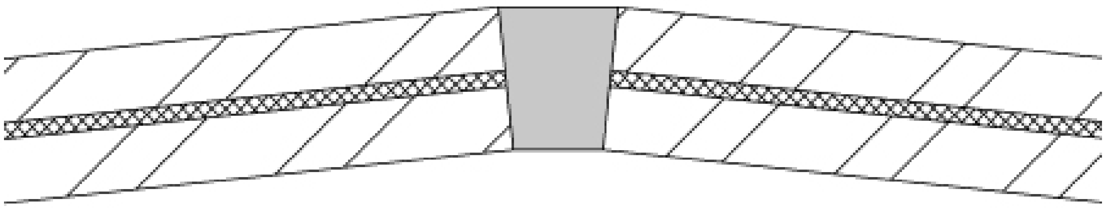


Fig. 9.5 - The glued butt joint connection: the most simple connection with the least structural capacity

A glued butt joint, as illustrated in figure 9.5, consists of two laminated glass panes connected with a structural adhesive. The design of this structural adhesive is very important. Before using the glued butt joint in a full scale plate shell structure, the capacity of the joint should be determined through experimental investigations, for varying temperature conditions, air moisture contents and load durations.

Analysis conducted on the ILEK faceted plate shell with a glued butt joint concluded that a plate shell using the glued butt joint should be relatively small, with a span of 3 - 4 m, with relatively thick facets (15mm or more) measuring roughly 0.6 - 0.8m in diameter. This is at the same time the largest disadvantage of this joint type: the size of the plate shell is very limited.

The largest advantage of this connection type is the slenderness and transparency that can be achieved.

9.2.3 - Semi-rigid hybrid connection [Nikolao, 2017]

The research of Nikolao (2017) resulted in a semi-rigid hybrid connection for the design of a glass faceted shell with quadrilateral plates (figure 9.6).

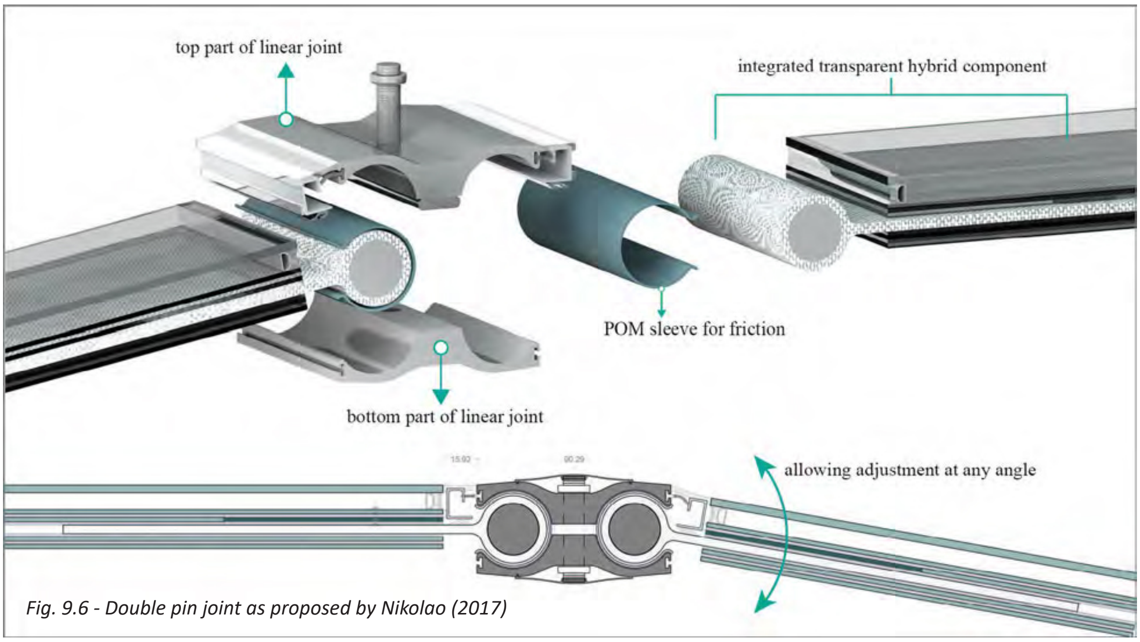


Fig. 9.6 - Double pin joint as proposed by Nikolao (2017)

It is a double hinged system that links the glass plates. An embedded reinforcement strip - made of E-glass fibres and phenolic resin - is extended outwards of the glass plate and placed into a linear strip-like joint. The strip-like joint is composed of a bottom and top part. When these parts are assembled they will lock the glass plates at the desired angle. In this way, direct contact between the glass plates is avoided.

Research has been conducted to:
1. Find the influence of the extended part on the boundary stresses in the plate in relation to the nature of the connection: either clamped or hinged.
2. Find the influence of the extended reinforcement on the bending moments in the glass plate. Thus, it would give a clue about the spectrum of the joint behaviour where the joint is rigid, semi-rigid or flexible.

The first analysis resulted in several conclusions:

- The embedded reinforcement causes a more uniform stress distribution at the boundaries of the plate.
- An increased length of the embedded reinforcement negatively influences the behaviour of the plate (50mm instead of 16mm). The increasing eccentricity from the plate to the support as well as the reduced stiffness of the extended part are likely causing for this effect.
- High levels of stiffness of the extended part and a small length (16mm protruding from the edge) can lead to a better plate performance.

The second analysis resulted in the following conclusions:

- The embedded reinforcement makes the connection behave like a hinge; even when the connection is a rigid connection the embedded reinforcement causes a semi-rigid overall behaviour.
- Clamped boundary conditions (rigid connection) result in lower bending moments in the plate.

The detail combines a large axial stiffness with a low rotational stiffness. Furthermore it combines the reinforcement of glass plates with a connection - the reinforcement plays an active role in connecting the glass elements. The material choice - GFRP - provides good implementation during the glass lamination process and a thermal expansion coefficient that is very close to that of glass.
A disadvantage of this detail would be the large amount of parts necessary for the detail.

9.3 - Proposed connections

The previously mentioned connection principles and structural behaviour of a plate shell joint should be translated to a connection design. The most efficient (see 9.1 - introduction) connection detail will be chosen and elaborated on.

The connection detail proposed by Nikolao (2017) showed great potential: a linear, semi-rigid, repetitive joint causing low stress concentrations in the glass, while offering the possibility to be disassembled. The embedded GFRP sheet is ideal due to the combination of a low thermal expansion coefficient and an easy laminating process, while giving the glass edges ductile post-breakage behaviour and providing a better distribution of forces.

The challenge is to translate this detail to a triangular plate shape. Subsequently, the detail can be further optimized by improving and analysing several facets of the joint, plate and reinforcement design.

9.3.2 - Joint between plates

Two types of joints between the plates will be proposed. They are graded on their efficiency as introduced in the introduction of this chapter.

9.3.2.1 - Proposed joint 1 - double pin connection

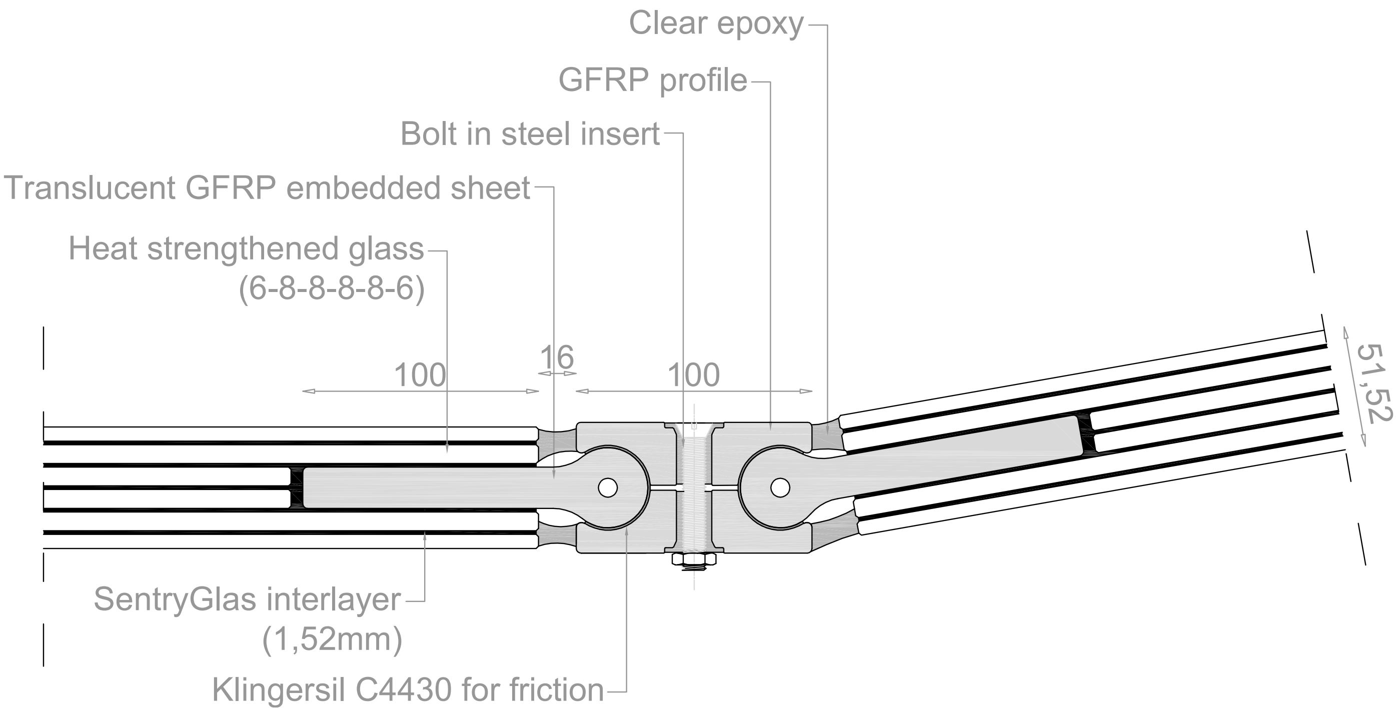


Fig. 9.7 - Double pin connection

This joint is based on the proposed joint by Nikolao (2017). It is composed of two GFRP profiles that are connected through a bolt. The plates are connected to the joint through their reinforcement: a GFRP plate embedded in between the glass. The reinforcement has a thickened and rounded edge which is placed between the GFRP profiles: a double pin connection. Klingersil C-4430 compressed fibre sheeting is placed between the GFRP embedded sheet and the GFRP profiles for extra friction. This material is a combination of rubber, glass fibres and synthetic fibres. It can handle higher pressures (up to 31MPa) than for example EPDM, due to which higher clamping pressures are possible, while still having a relatively low density (1,75 g/cm^3.

9.3.2.2 - Proposed joint 2 - clamped connection

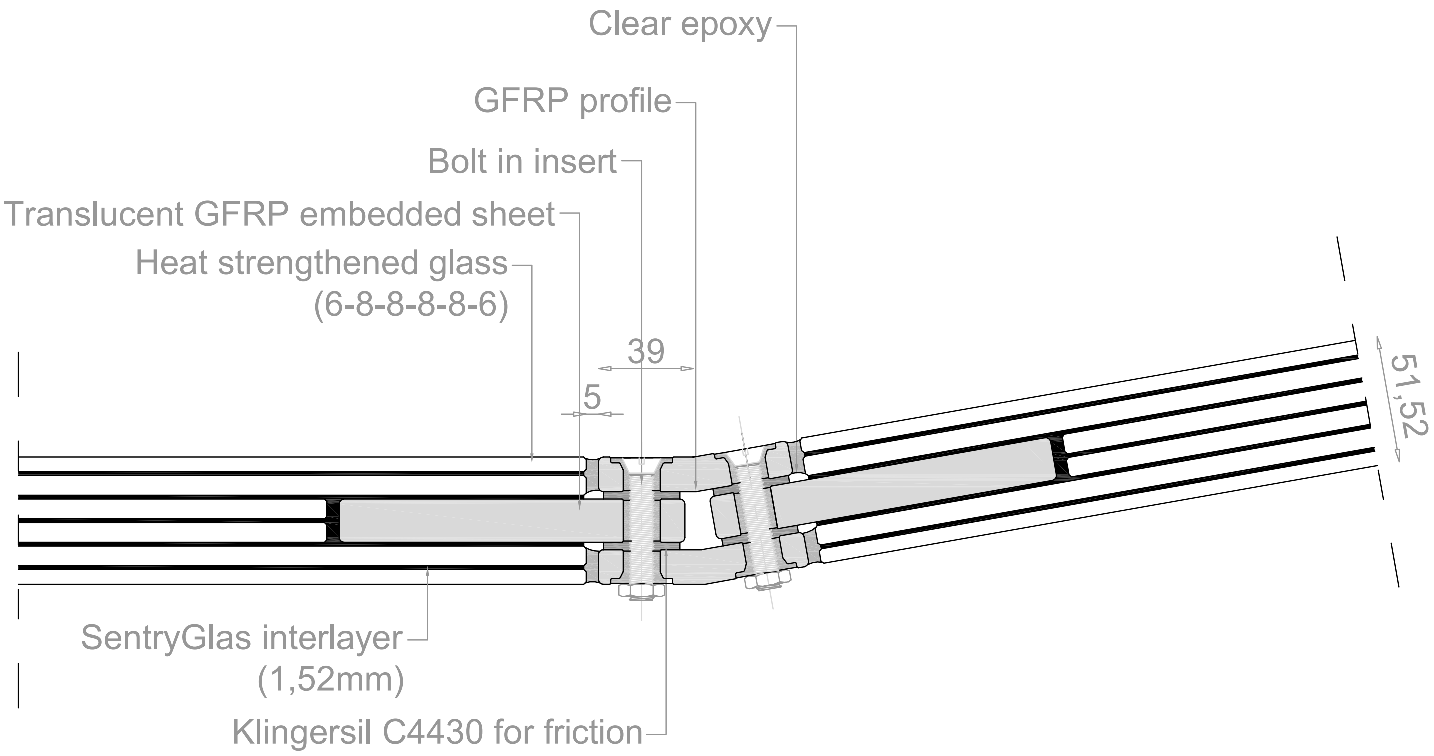


Fig. 9.8 - Clamped connection

The second joint is based on the clamped joint proposed by Bagger (2010). However, it clamps the GFRP embedded sheet instead of the glass panes, thus allowing for more pressure. The bolts are drilled through the GFRP embedded sheet allowing for even more - direct - pressure and friction. To resist this pressure and create more friction, Klingersil is used instead of a softer friction material.
The top and bottom profile are tailor made to fit the angle between the plates.

9.3.2.3 - Comparison connections

Both connections have their advantages and disadvantages. The most important efficiency criteria that the connection has to meet are as follows:

- Slender and light appearance (as transparent as possible)
- Easy assembly and replacement
- Minimal stress concentrations from temperature movements
- Yielding capacity when the detail would fail
- Taking into account creep

Both details meet all criteria. Both details are very slender: joint 1 being 132mm and joint 2 being 88mm. They are easy to assemble and disassemble, having a top and bottom profile that are clamped together using bolts. Temperature movements are minimal due to the use of GFRP and glass (which have an almost equal thermal expansion coefficient).

However, the biggest difference between the two joints is in the fabrication process. The first joint is uniform - every angle can be made with the same profile. The second joint has to be tailor made for every angle, which will increase the costs significantly.
Secondly, the clamped joint uses bolts that are drilled through the thin FRP embedded sheet. This might lead to creep and plastic deformation in the drilled hole and ultimately failure when tensile forces in the plate shell pull on the embedded sheet.

Due to these economic and structural reasons the first joint: the double pin connection - is chosen to be elaborated on.

9.3.4 - Supports & foundation

The supports of the bridge will have the same nature as the connection details. It will therefore be a semi-rigid connection attached to a steel base plate. This baseplate is connected with concrete anchors to a concrete foundation.

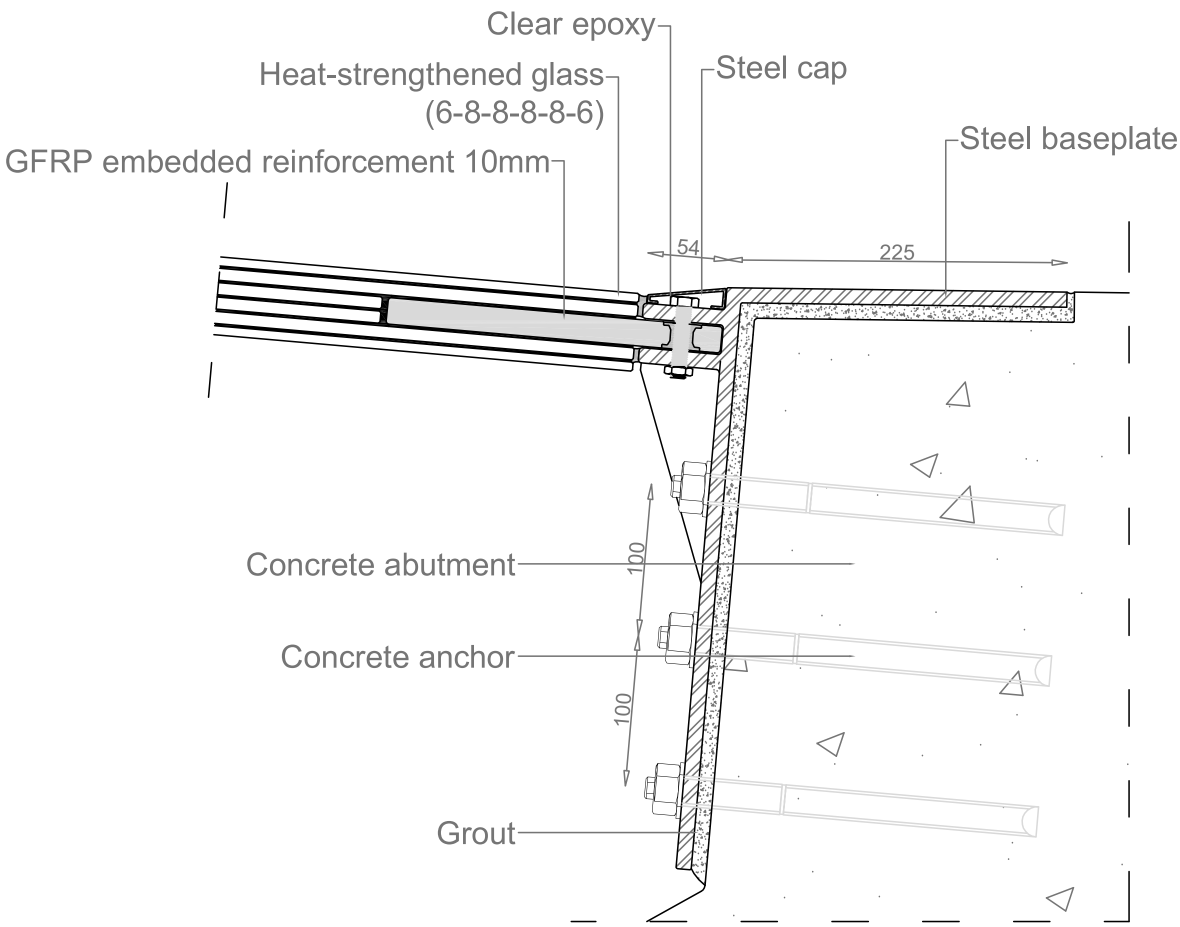


Fig. 9.9 - Supports

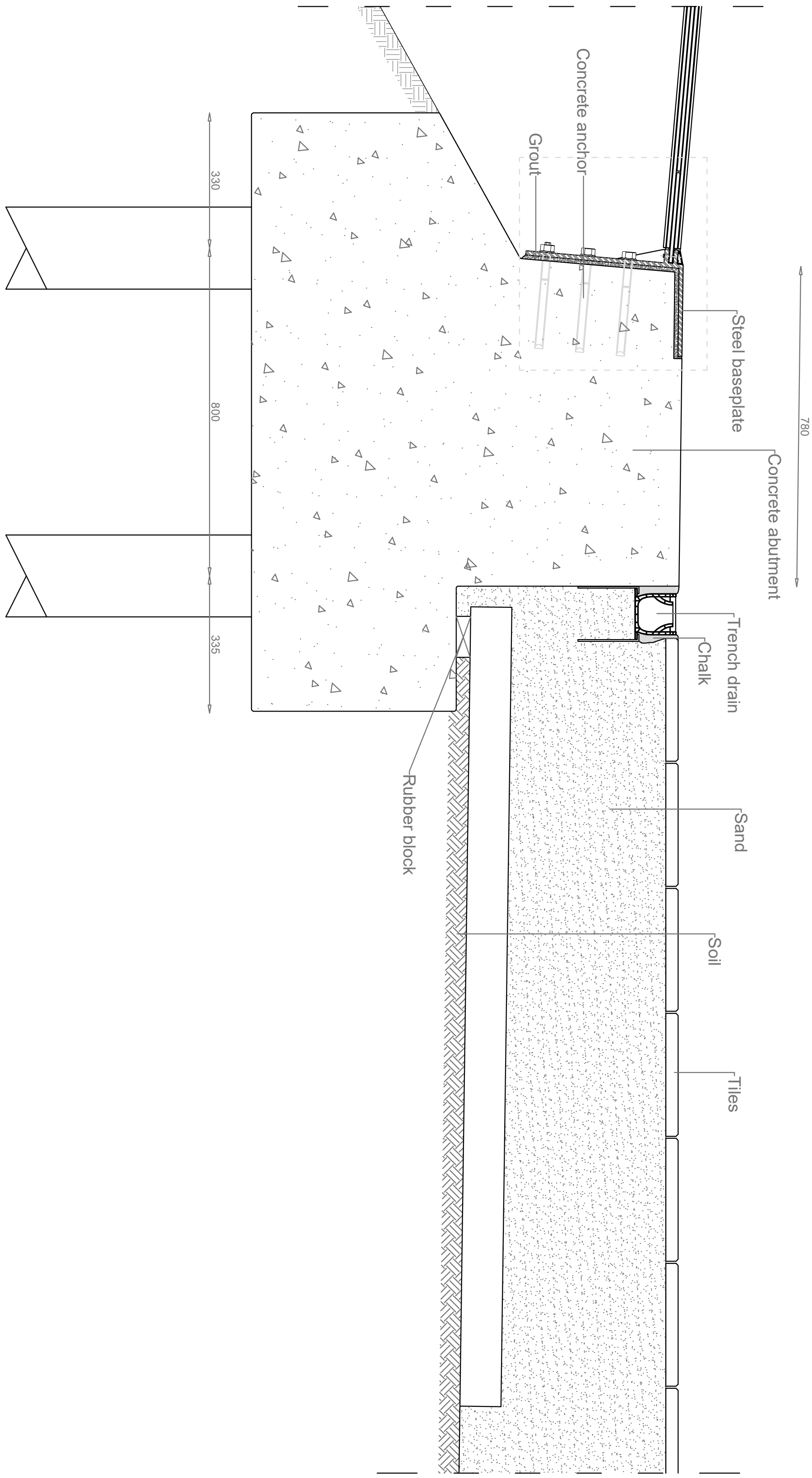


Fig. 9.10 - Supports overview

9.3.5 - Free edge beams

The free edges are the weakest part of the plate shell. The deformation is in all loadcases the largest near these edges.
Because of this structural reason and aesthetical reasons (a nice finishing of the plates and parapet) a GFRP beam will be placed on the free edges. This beam will somewhat restrain the edges from bending as it resists translations of the adjacent plates.

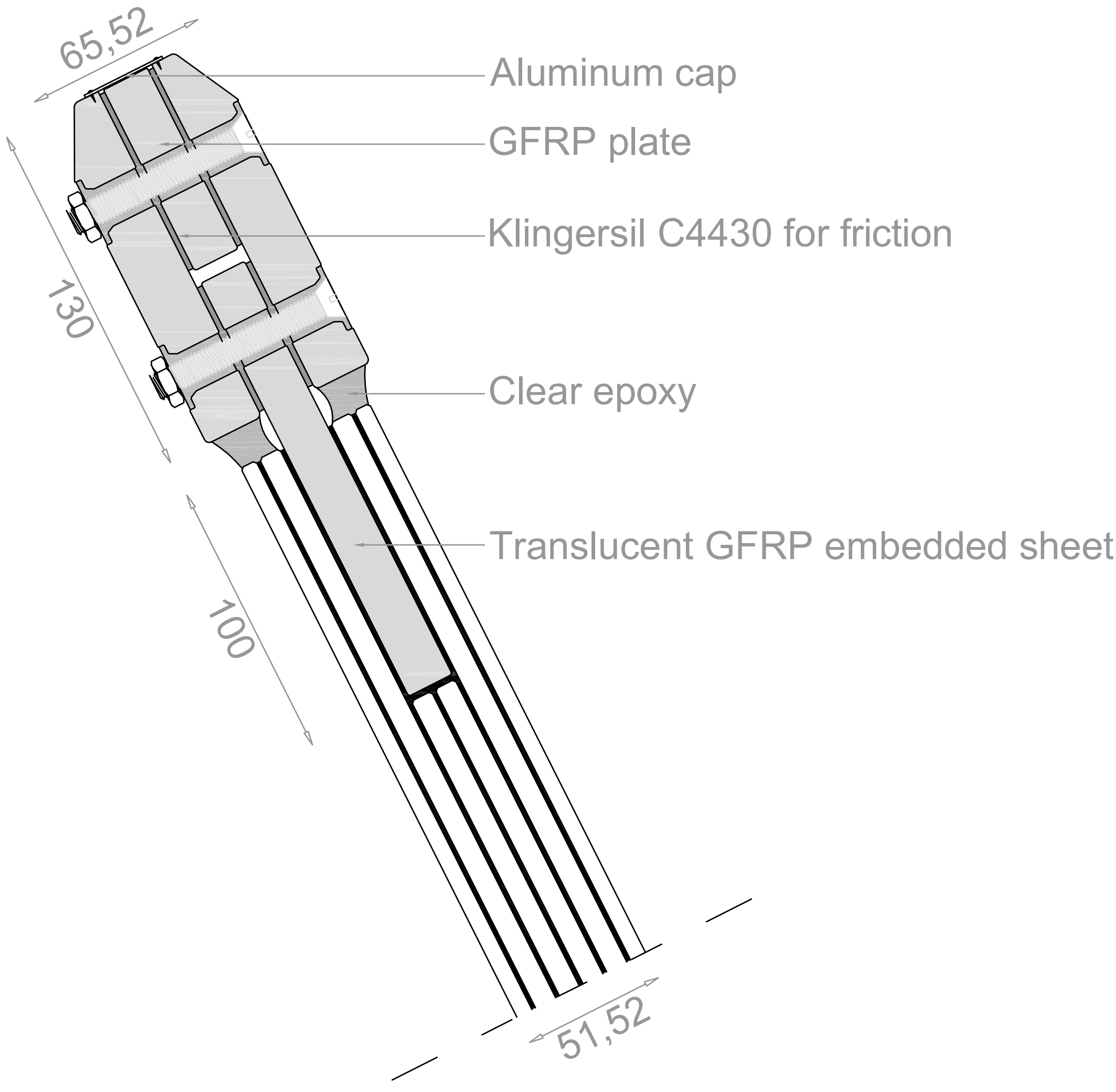


Fig. 9.11 - Free edge beam detail

9.4 - Fabrication

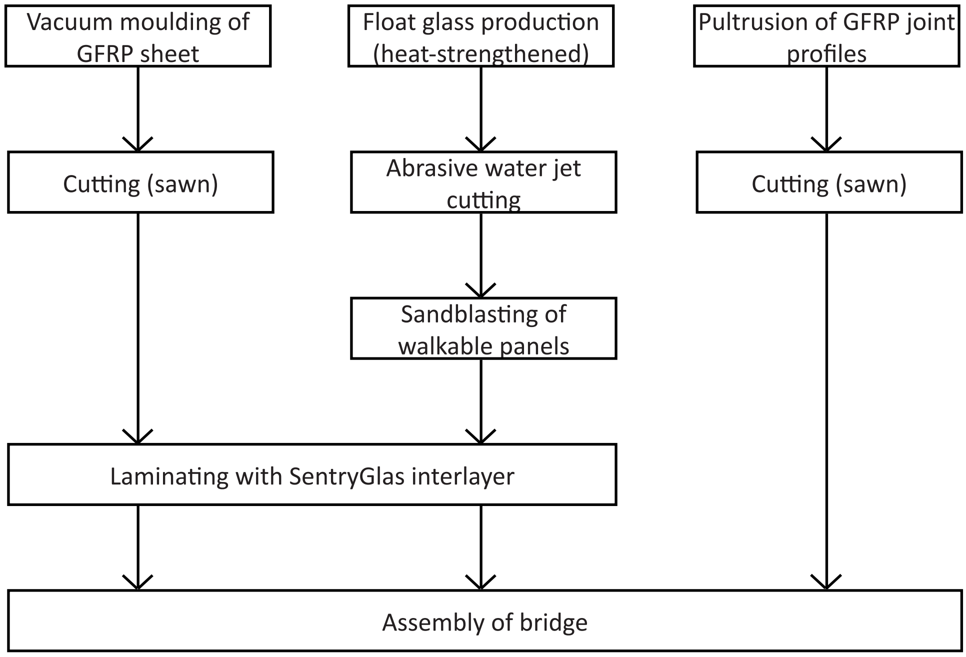


Fig. 9.12 - Overview of fabrication

9.4.1 - Glass plates

The triangular glass plates are produced in the float glass production process as square panels. They are later cut in shape using abrasive water jet cutting, where the edges are also rounded for less fragility.
The top (walkable) panels are subsequently sandblasted to create more grip on the slippery glass surface. The coated and sandblasted glass panes as well as the GFRP sheet are then laminated using SentryGlas interlayer material. The interlayer material will take up some of the tolerances in glass. For every meter the glass plates can differ 1 to 2 mm. This difference should be taken into account when laminating and cutting the glass (see paragraph 9.5: "Uncertainty analysis").
Finally the glass plates are assembled and connected using the embedded GFRP sheet.

9.4.2 - GFRP embedded sheet

The GFRP embedded sheet is vacuum moulded to ensure a quasi-isotropic behaviour of the material. The build-up of the mould is given in figure 9.13.

Mats with reinforcement pointing in different directions (0, 45, -45, 90) are placed in the mould. The mats are placed around a steel rod on one side of the mould to create the curving at the end of the GFRP sheet. Subsequently vacuum is created by subtracting the air under the B-side mould using tubes at the side of the mould. Resin (epoxy) is then inserted at the centre of the workpiece, which flows over the entire reinforcement due to the vacuum.

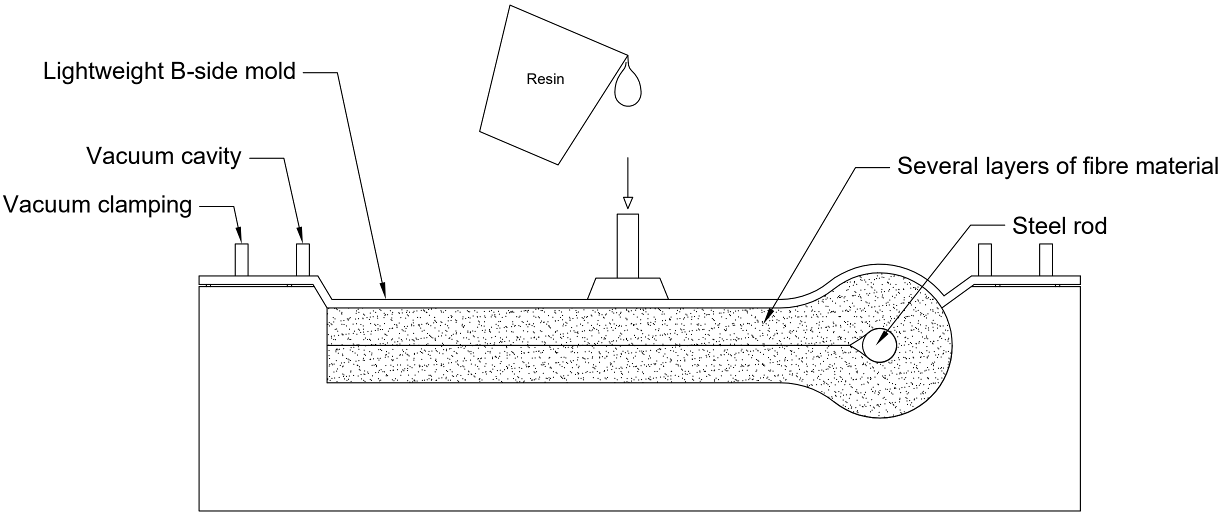


Fig. 9.13 - Proposed mould for fabrication of embedded sheet (vacuum moulding)

9.4.3 - Joint

The most important reason to choose the double pin joint is the uniformity of the connection profiles. The top and bottom profile are interchangeable and uniform throughout the entire design. Therefore the profiles will be produced using a pultrusion process. The profiles will be made quasi-isotropic by using continuous strand mats during the pultrusion process (see figure 9.14).

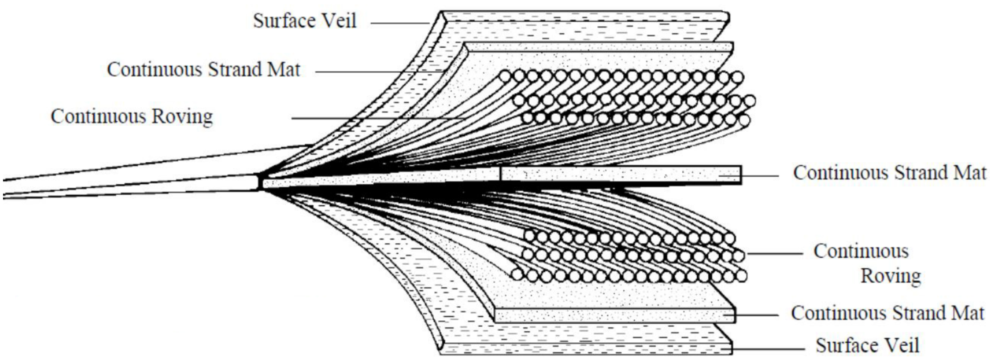


Fig. 9.14 - Build-up of pultruded profiles for the joint

9.5 - Uncertainty analysis

During both fabrication of glass plates and the laminating process an error margin should be taken into account. The size of glass panels can differ 1 to 2 mm per meter fabricated glass [Veer, 2017]. This amount of deviation can be enlarged during the lamination process when glass panels can slightly move over the viscous interlayer material. Therefore tolerances of approximately 4 mm should be taken into account for the double pin connection detail.
To find whether this might be a problem for the proposed connection detail an uncertainty analysis is performed in this chapter.

9.5.1 - Possible deviating alignments

Several situations are sketched where the glass panels do not align with the proposed detail. The possible areas where higher stress will occur are pointed out. The situation with most problematic points is chosen and will be elaborated on in the next paragraph. During this analysis both a bending moment and transversal shear force will be considered.

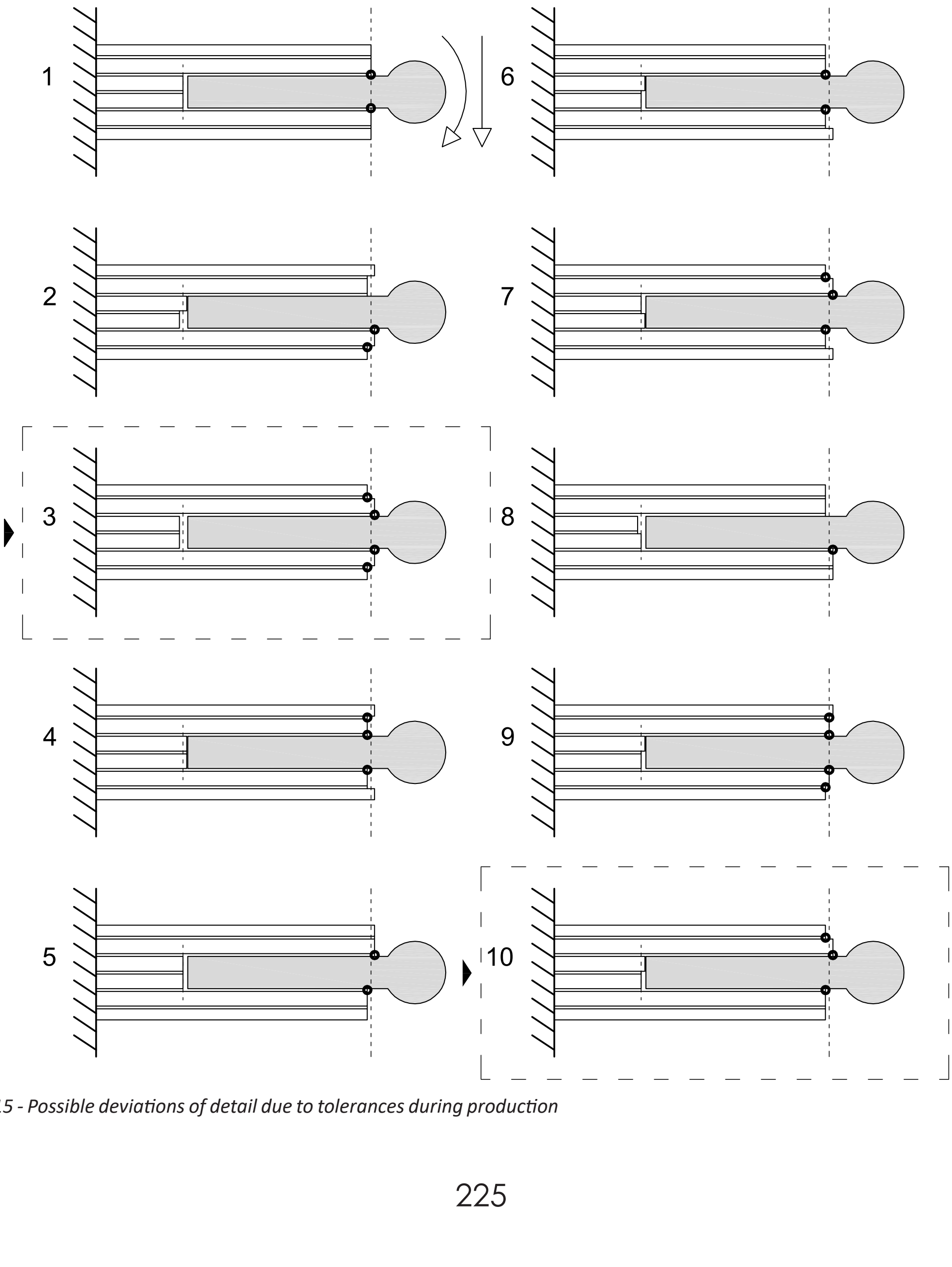


Fig. 9.15 - Possible deviations of detail due to tolerances during production

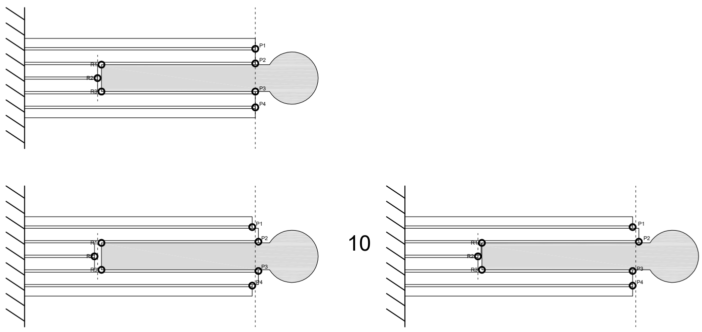
The third situation seems to introduce 4 points where stress levels will increase. Situation 9 also introduces 4 points of attention, but the deviation of these glass panels is less than in situation 3: 4 mm versus 3 mm. These two alignments will therefore be analysed in the next paragraph.

9.5.2 - FEM analysis

The previously found situation will be analysed in DIANA as a 2D strain analysis. Only a small part of the connection detail will be analysed as this is the part where most problems will occur. Adding a larger part of the connection detail will not lead to more and better information.

9.5.2.1 - Goal of analysis

The purpose of this FEM-analysis is to find the influence of deviating glass panels on the stress in the connection detail. The situations with the highest expected stress levels (situation 3 & 10) are analysed. A few areas are hereby focused on, as shown in the figure below:



9.5.2.2 - Material input

Both the material properties of heat-strengthened glass, SentryGlas interlayer material and quasi-isotropic E-GFRP with an epoxy resin - as introduced in chapter 8.2.2 - will be used.

9.5.2.3 - Element type

The used type of DIANA element is a plane strain element. This type of 2D element only considers strain in the direction of the element. Strain components perpendicular to the element face are zero. [TNO DIANA, 2012] This type of element approximates the real situation, where a plate is restrained and surrounded by adjacent plates.

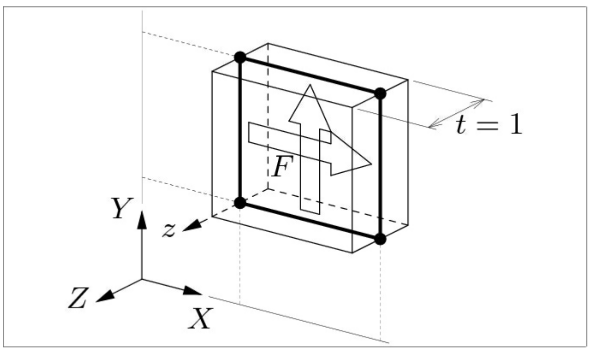


Fig. 9.16 - Plane strain elements in DIANA: the thickness is always t = 1 [TNO DIANA, 2012]

The exact type of plane strain element that is used is the CQ16E element. This type of element is an eight node quadrilateral iso-parametric plane strain element. This means it has an extra node placed in the middle of each side. It is based on quadratic interpolation and Gauss integration. [TNO DIANA, 2012]

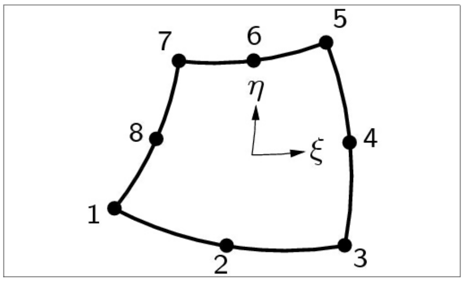
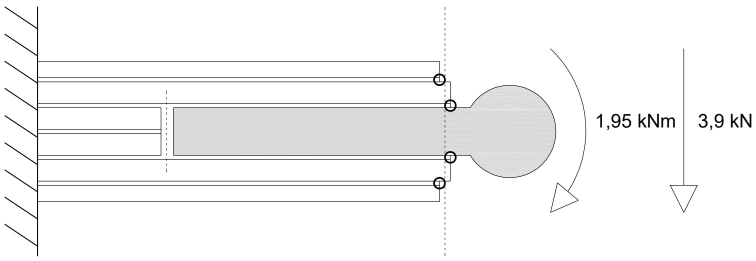
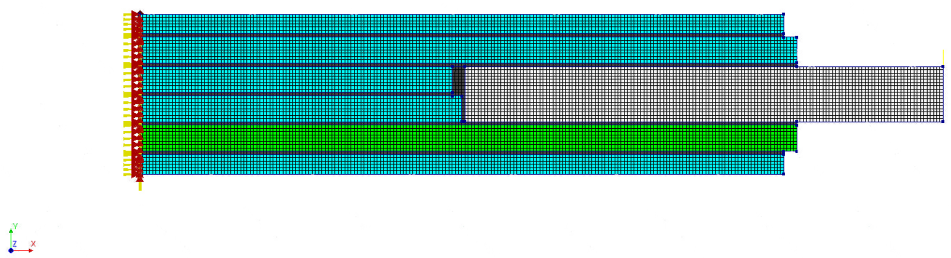


Fig. 9.17 - Plane strain elements CQ16E: an extra node is placed on each edge. [TNO DIANA, 2012]

9.5.2.4 - Load

Both a bending moment and a transversal shear force will be introduced on the connection detail. The value of the bending moment is based on a force of 3,9 kN (required live load - see chapter 1) working on a plate of 1 m^2. The maximum bending moment will then be approximately 0,5 m x 3,9 kN = 1,95 kNm. The transversal shear force working on the connection will be 3,9 kN.



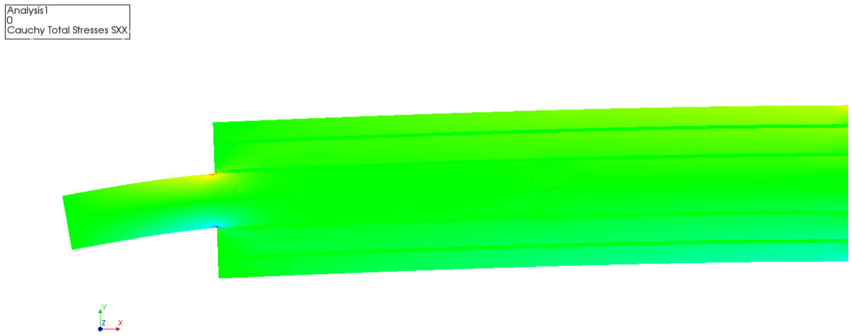
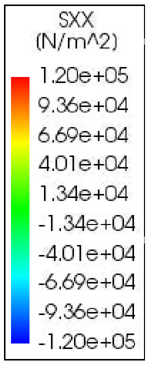
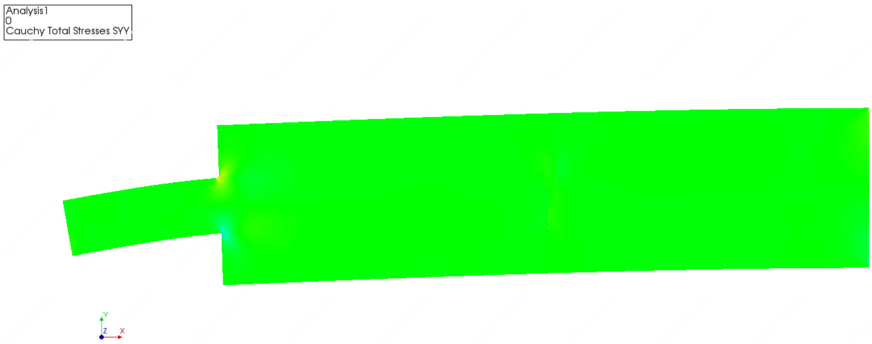
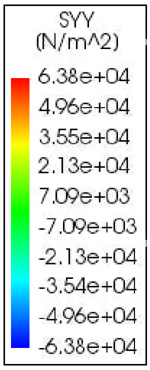
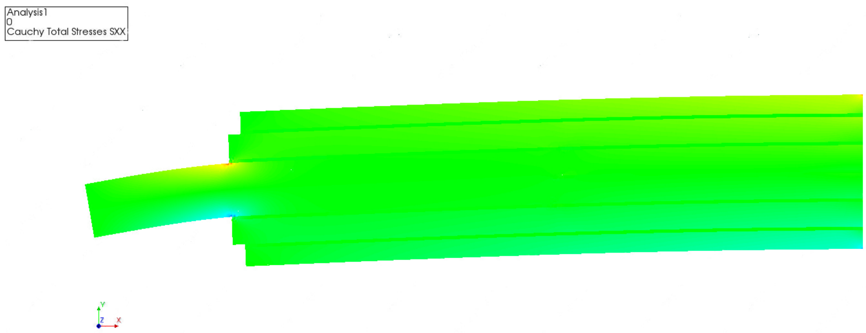
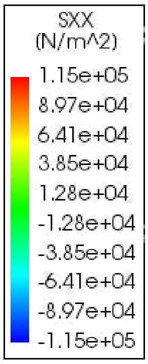
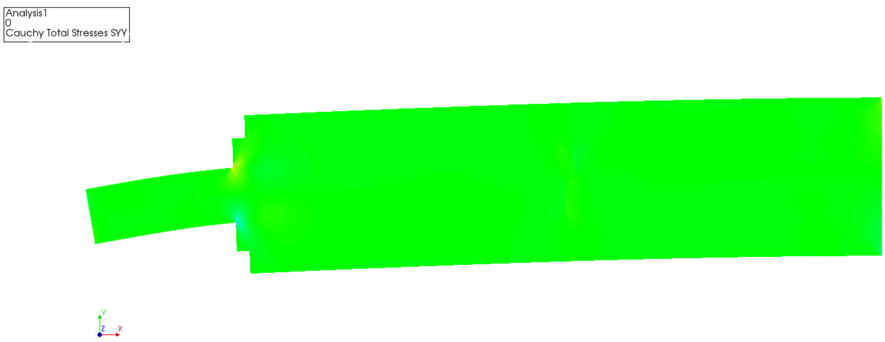
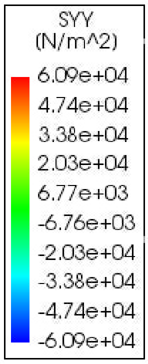


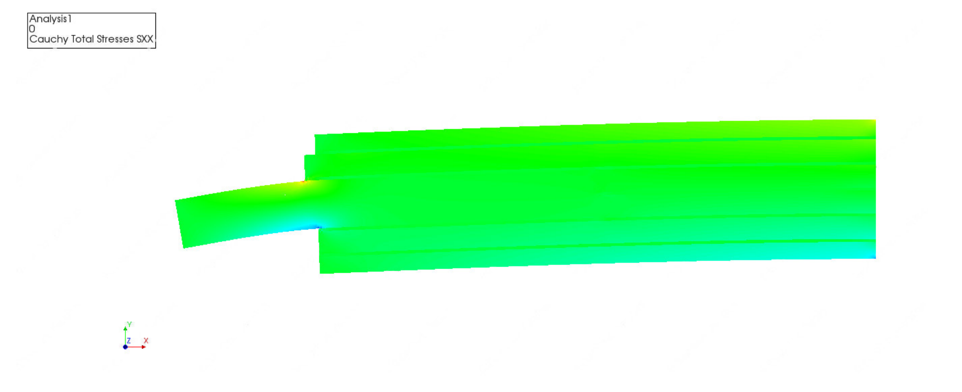
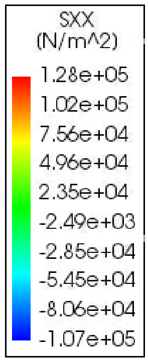
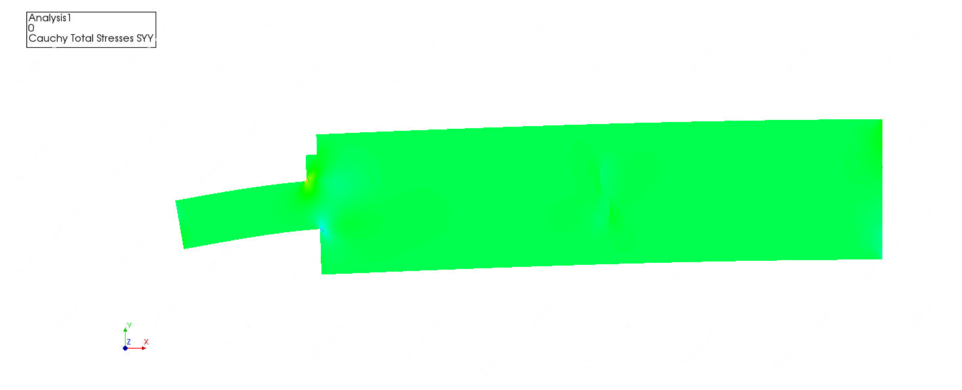
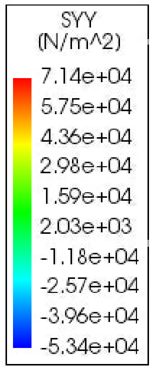
9.5.2.5 - Meshing

The mesh of all parts of the model will be quadrangular (QUAD/HEXA) with an element size of 0,001 m (1 mm).

9.5.2.6 - Boundary conditions

The analysed part is clamped on one side, while a transversal shear force works on the other end of the connection. This approximates the reality, where the plate is restrained by adjacent plates.

<table>
<tr><td></td><td>Stress Sxx & Syy</td><td>Legend</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Normal situation</td><td></td><td></td></tr>
<tr><td></td><td></td></tr>
<tr><td></td><td>Stress Sxx & Syy</td><td>Legend</td></tr>
<tr><td rowspan="2">Alignment 1</td><td></td><td></td></tr>
<tr><td></td><td></td></tr>
</table>

	Stress Sxx & Syy	Legend
Alignment 2		
		

9.5.3 - Results

Considering the stress in the connection, there are 2 points of attention: at the transition of glass to FRP or where the FRP embedded sheet protrudes from the glass. This experiment shows that the stress levels at these points are highest when the glass layers are aligned symmetrically (mirrored by the embedded FRP sheet).

When the glass is aligned unsymetrically, this results in a higher stress concentration at the point where the glass protrudes the most. The point where the glass is located inwards has a lower stress value.

Other areas of the detail are less affected by deviating alignments of the glass plates. A deviating alignment of the points R1, R2 and R3 have no visible effect on stress concentrations in the glass. This is a result of the higher stiffness of the glass plates.

In earlier research stress concentrations at the transition of glass to FRP have been shown. This area of stress concentration remains in the same place, but is not negatively affected by deviating alignments of glass plates due to fabrication tolerances.
Furthermore, when the deviating alignment is asymmetrical it will result in lower stress at either the upper or lower side of the embedded FRP sheet (point P2 or P3).

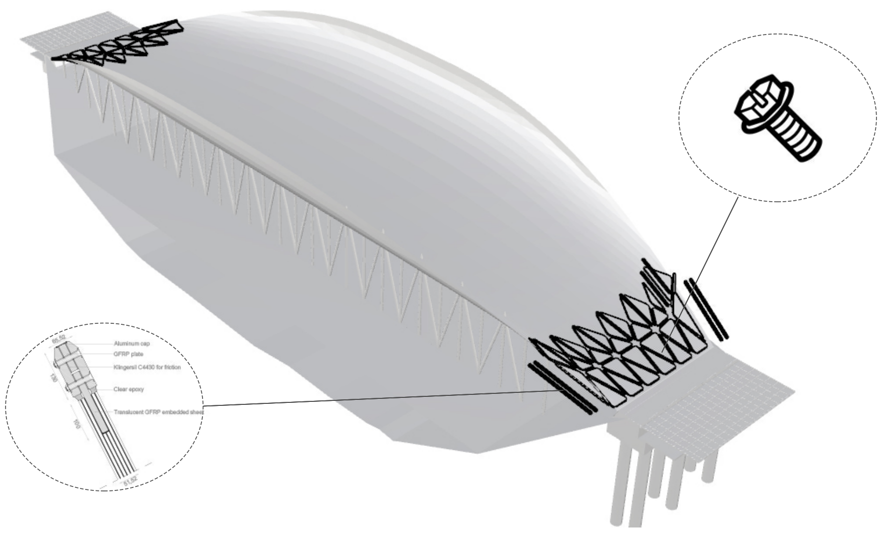
9.6 - Assembly

The plates will be assembled starting from the supports of the bridge. A temporary substructure will be necessary to support the bridge during assembly. The first row of plates can be placed on this substructure (using setting blocks to not damage the fragile glass) and subsequently the joint is loosely fastened. Plates are placed from left to right or right to left (per row). The joint is fastened completely when the next row is also placed, resulting in the right angle between plates. Depending on the size of the plates placement can be done with a crane or with glass suction cups. This process repeated for every row until the bridges' span is created. Then the substructure can be removed, leaving the bridge in its final state.

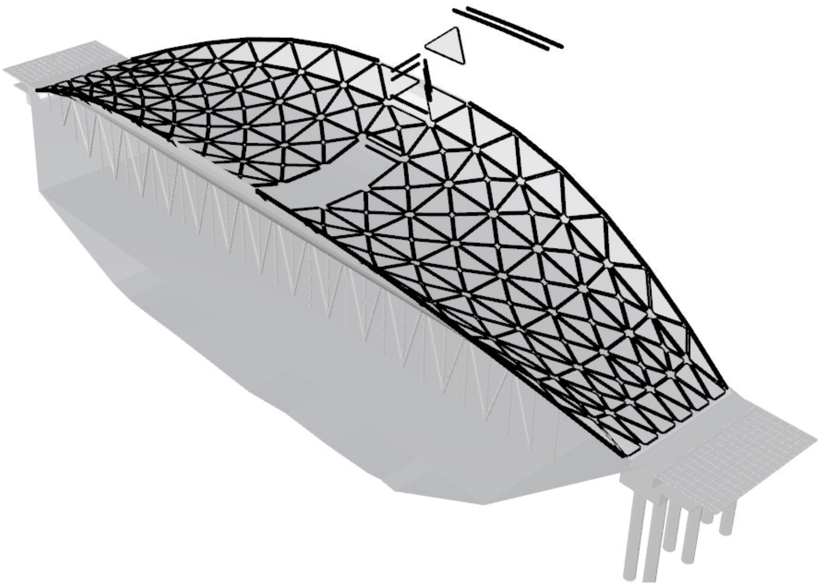
The substructure will consist of a spaceframe supported on several pillars.

1.

2.



3.



4.

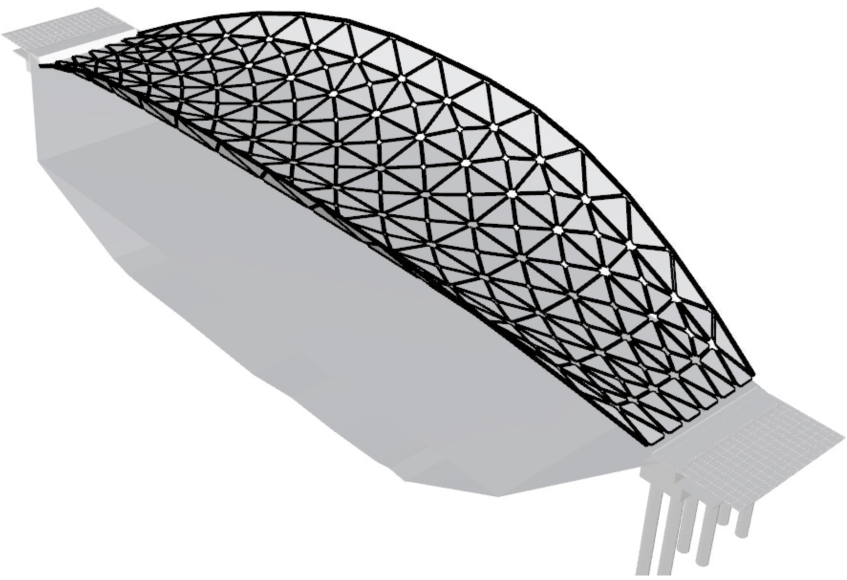
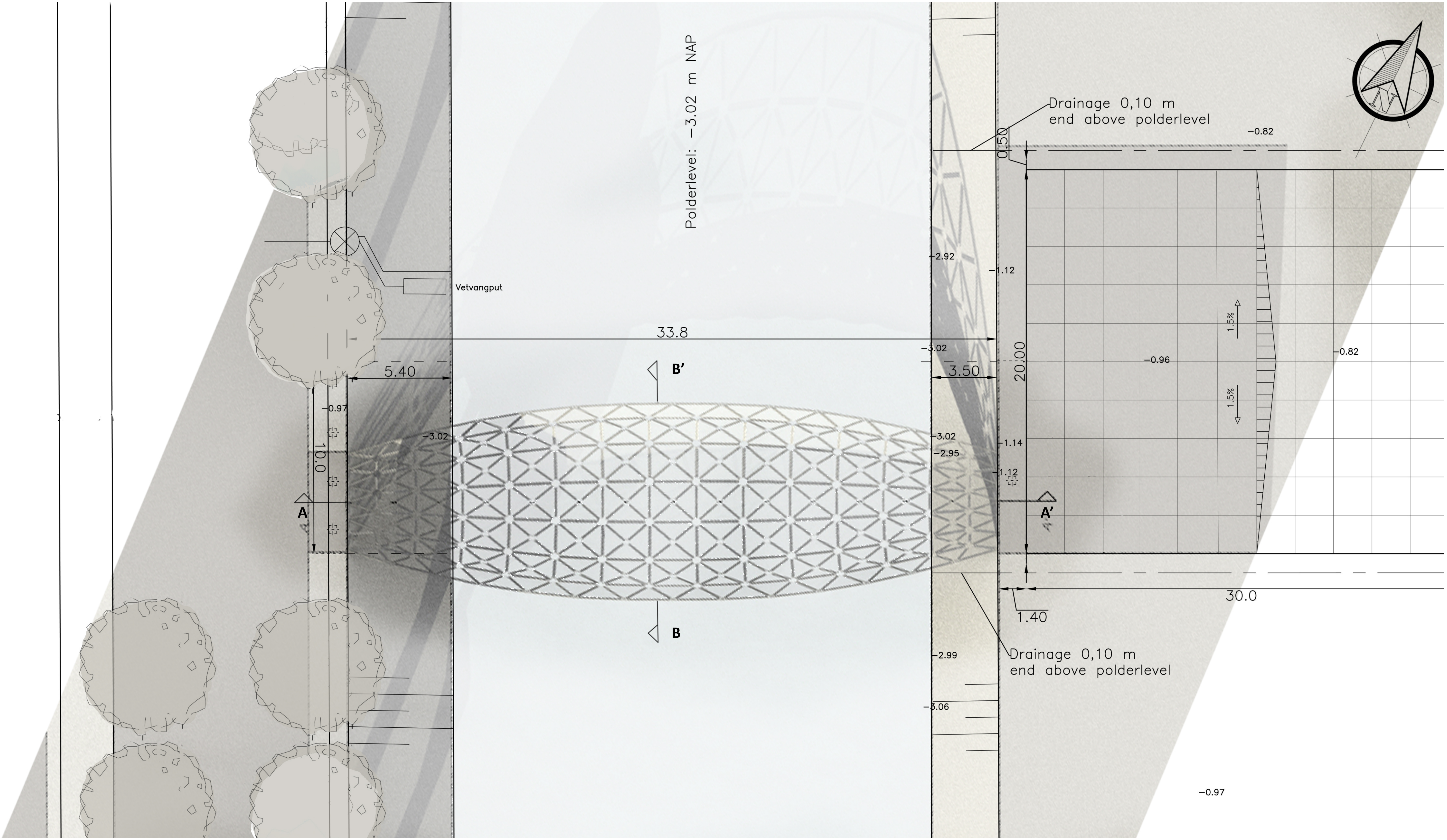


Fig. 9.20 - Assembly order in 4 steps.

10 Final design & reflection

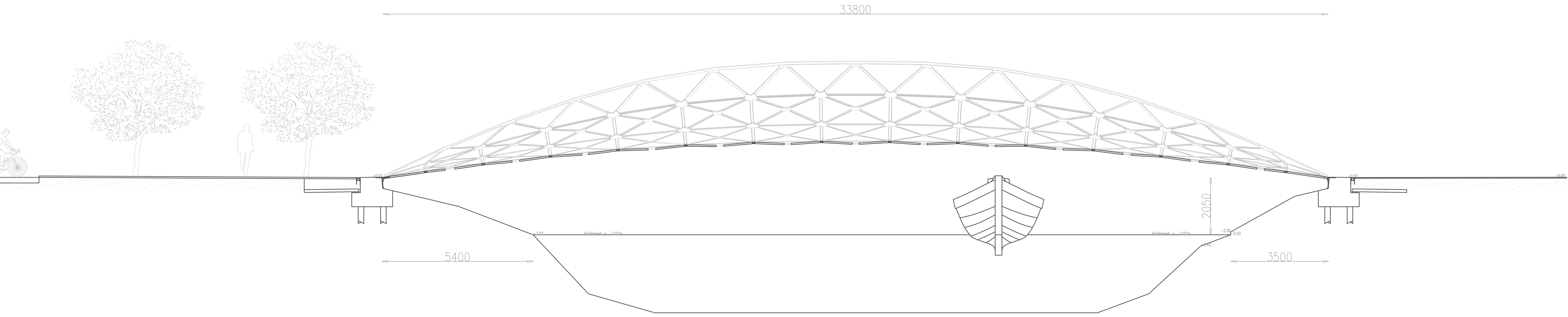
10.1 - Technical drawings

10.1.1 - Plan



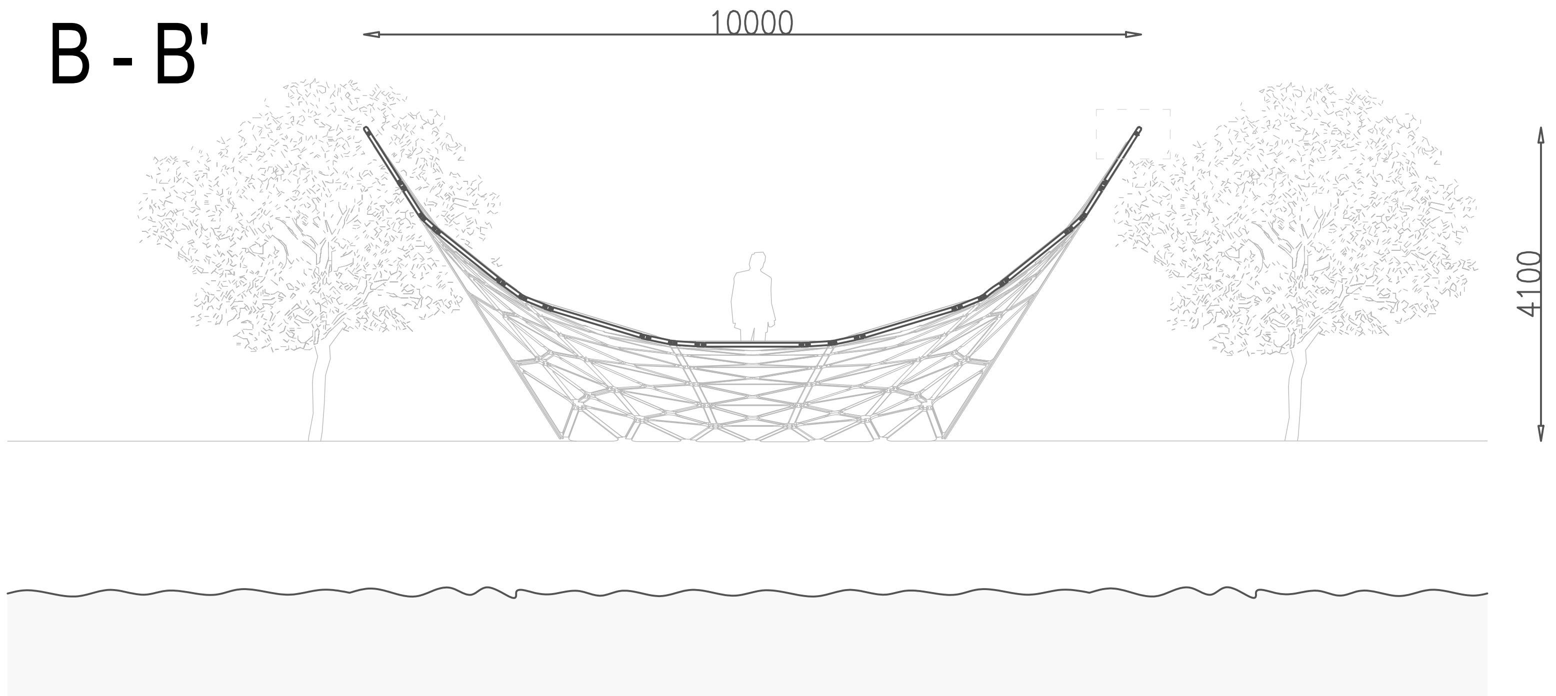
10.1.2 - Section AA’

A - A'



10.1.3 - Section BB’

B - B'



10.2 - Impressions

10.3 - Reflection

10.3.1 - Reflection process & method

The idea to create a hybrid fiber-reinforced polymer and structural glass bridge was driven by earlier research at the TU Delft. This previous research focuses on creating FRP reinforced glass beams and shows the potential of combining these two materials in a structural element. The aim of this thesis was to expand the potential of the combination of materials to a larger structural element: the bridge. To do so I wanted to research both materials, find the optimal properties and then combine these properties in a material adapted design of a hybrid bridge.

By choosing to create a hybrid bridge, two graduation labs and two distinct graduation subjects were combined: bridge design and structural glass design. The combination of two distinct graduation labs resulted in a broader subject than was initially taken into account. As the exact subject of the thesis remained quite vague at the start of the process – only the condition of an optimal hybrid bridge of these two materials was defined – a lot of extra steps were necessary to define the exact research topic. The bridge type was undefined, as were the location of the bridge, the way of combining the materials into a hybrid and the structural concept.
This uncertainty over the exact course of research resulted in a rush through the preliminary research – the theoretical framework – and therefore not an in-depth study at the P2 presentation. The first verdict was therefore a retake. In the second try the methodical line of approach (extensive literature research and conclusions) was followed to full extent, resulting in a go.

After extending the methodology and literature research of the thesis considerably, a choice for a structural concept could be made. This choice resulted in the need for a second literature research to conclude in a new theoretical framework regarding the plate shell. This second theoretical framework was very time consuming, particularly when considering that the first theoretical framework was already quite extensive.

The shift of the project towards plate shells brought another consequence. The guidance of a third teacher was necessary for purposes of form-finding and FEM analysis.
While executing the plate shell research and designing the hybrid bridge it became clear that this project was quite ambitious. The thesis strives for a free-form plate shell that is concave and at the same time functions as a bridge while only plate shells that are convex based on part of domes that function as roofs have been built in structural glass.
This research should therefore be seen as a first set-up to show the problems and opportunities affiliated with a free-form plate shell. The final design is probably not yet ideal or most efficient.

A problem that was encountered during research was the limitation of the applied software and the associated waste of time. First of all, it was impossible to use Karamba to perform a FEM-analysis on plate shells. Secondly, it was impossible to perform a hexagonal tessellation on a free form concave shell using Kangaroo. This resulted in several wasted attempts to script these actions, which cost a lot of time.

10.4.2 - Reflection project

The project is an interesting addition to the on-going research into plate shells from structural glass. It gives an overview of the problems that are encountered when designing a free-form (and concave) plate shell and gives possible solutions for these problems in the form of several variants. Additional research can pick up on several unexplored solutions for encountered problems. An example is the use of a part of a torus to create a regular shaped hexagonal tessellation on a concave shell. This solution was dismissed during research as it does no longer include a free-form and form-found shell. It could, however, be a better solution to create a plate shell with free edges than the method proposed in this thesis.

The project also proposes a new way of using glass in footbridges. Several pedestrian and cyclist bridges are increasingly built in the Netherlands. This new bridge can add to the development of sustainable and durable bridges. It shows the potential of the combination of FRP and structural glass to create longer spans in glass structures and an aesthetically interesting design.

However, the final design also shows the presence of flaws. The bridge did not achieve the level of transparency it was supposed to reach. The glass panels had to be smaller and thicker to minimize stress in the FRP connections due to the various loads working on a bridge. These measures affected the transparency of the overall design.

10.3.3 - Conclusion

The overall process took more time than expected due to the extra literature research that was needed and the drawbacks regarding the software and geometry limitations. However, in the end all predefined steps in the process have been followed.

The final product gives a good overview of the problems and possible solutions during the design of a free-form, concave plate shell. Additional research in this field remains necessary to find the most efficient design process for this type of plate shell. Also the final product does not meet the exact aesthetical expectations of the author.

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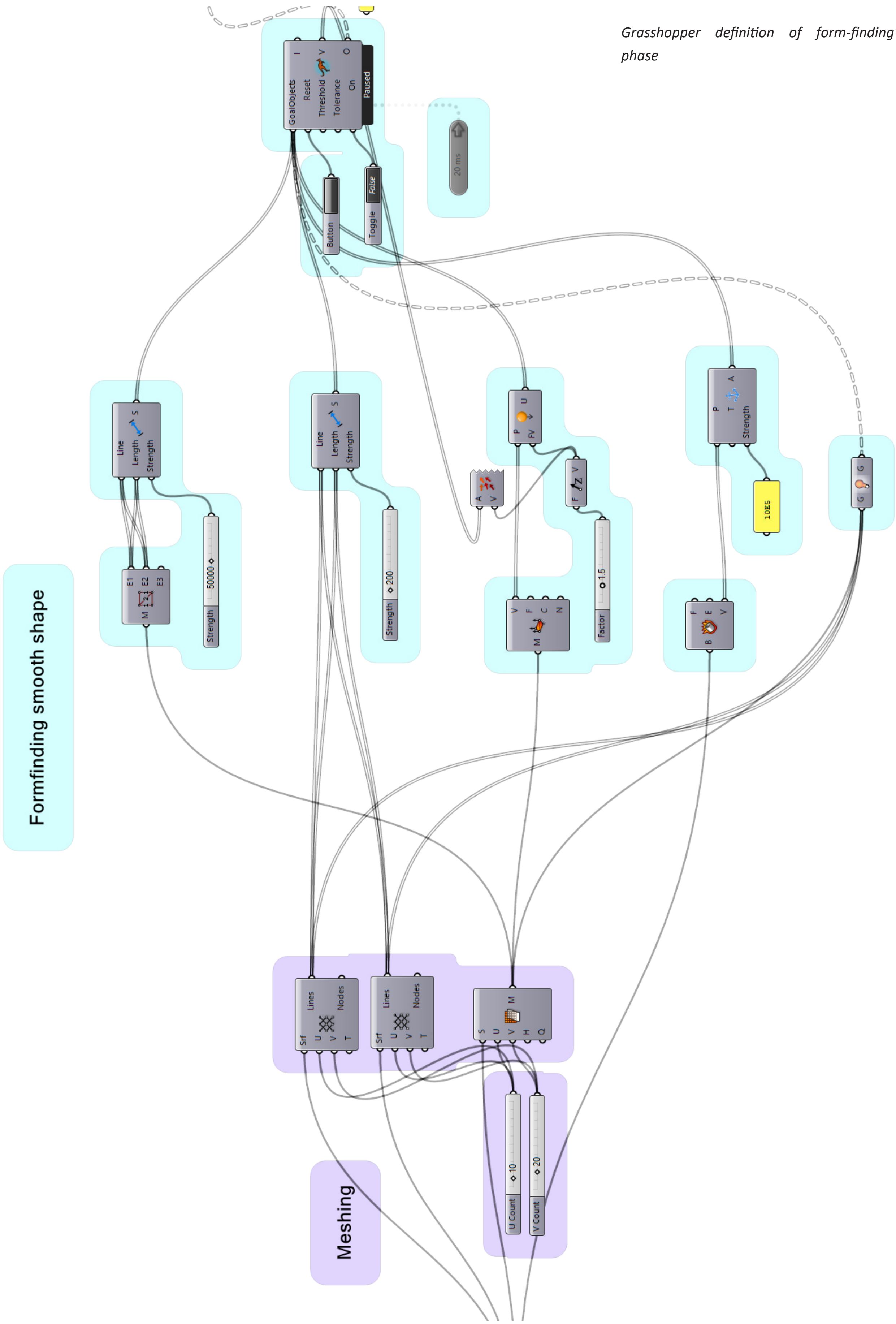
Software

Rhinoceros 3D by McNeel

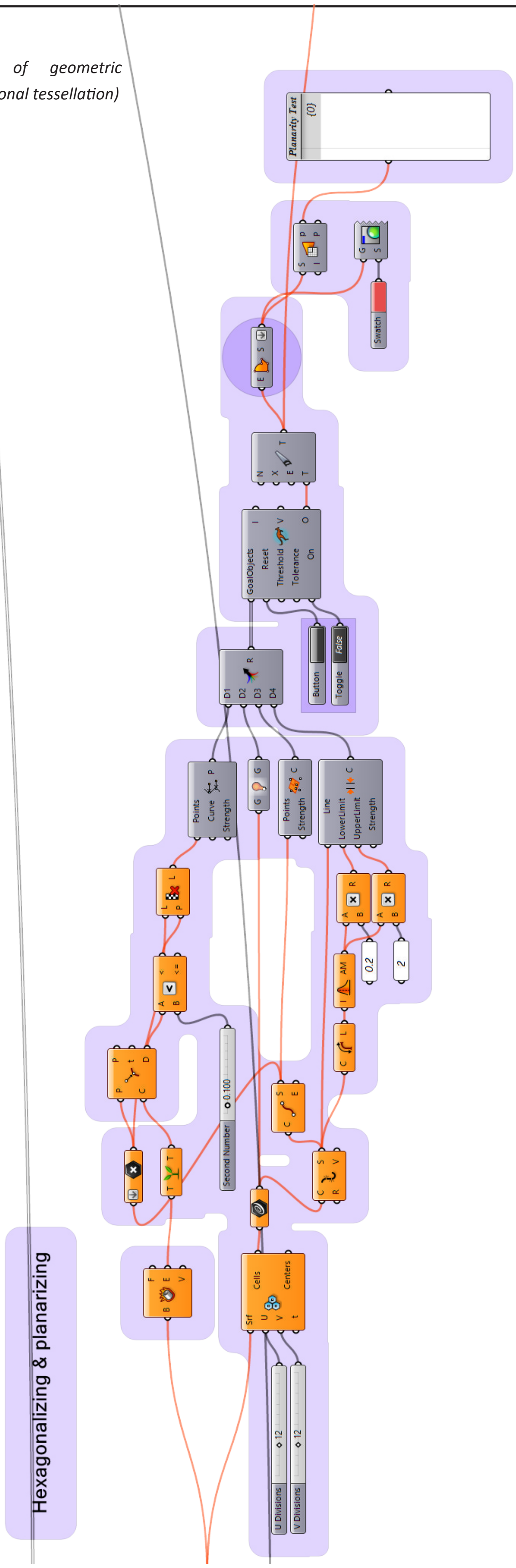
Grasshopper with its plugins:
- Kangaroo
- Karamba
- Lunchbox
- Weaverbird

DIANA by TNO

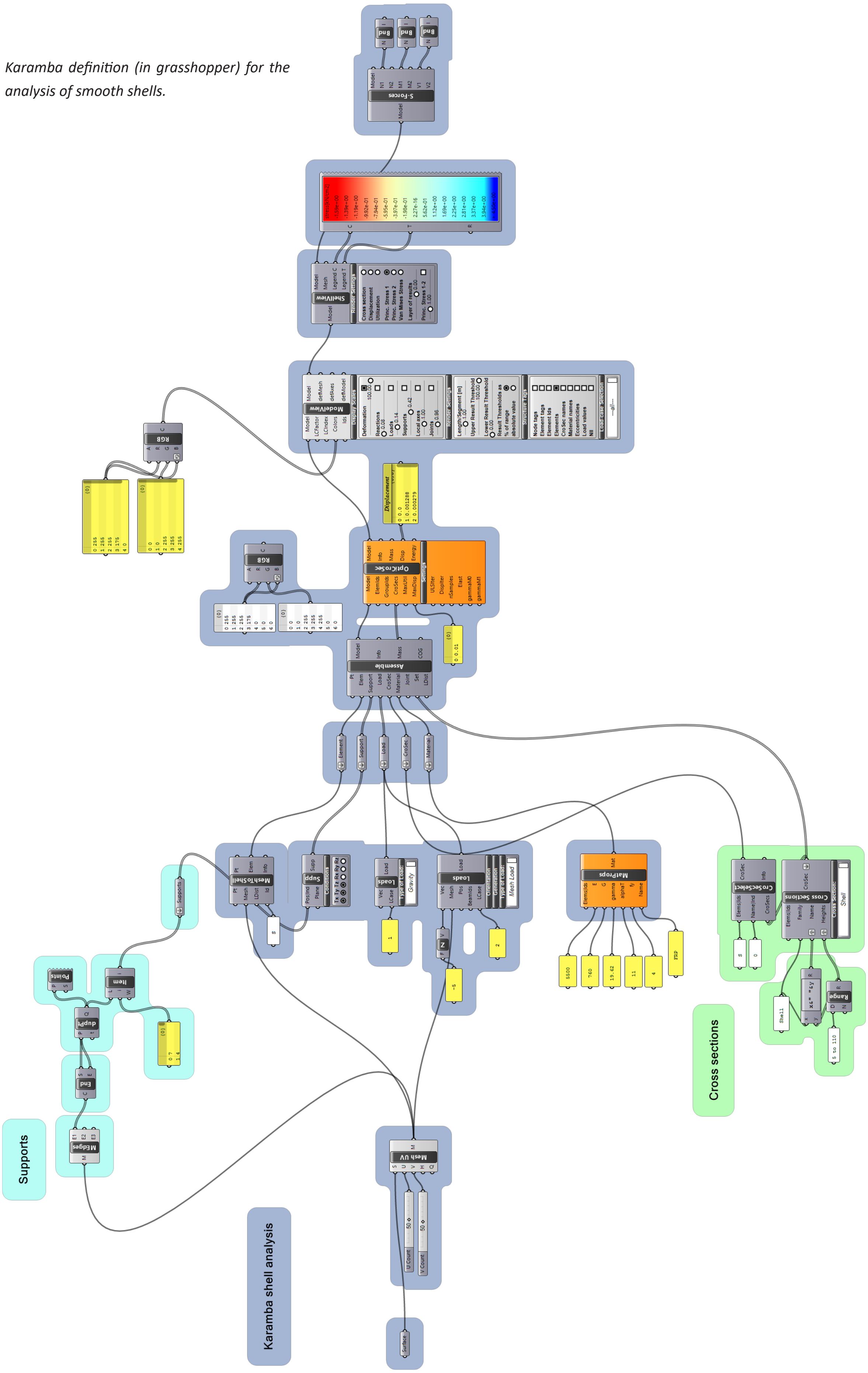
Grasshopper definition of form-finding phase



Grasshopper definition of geometric optimization phase (hexagonal tessellation)

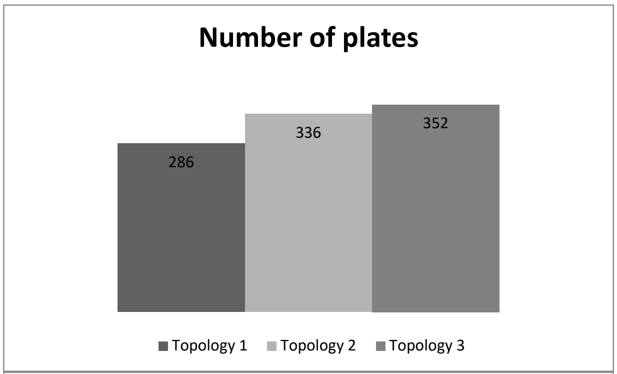


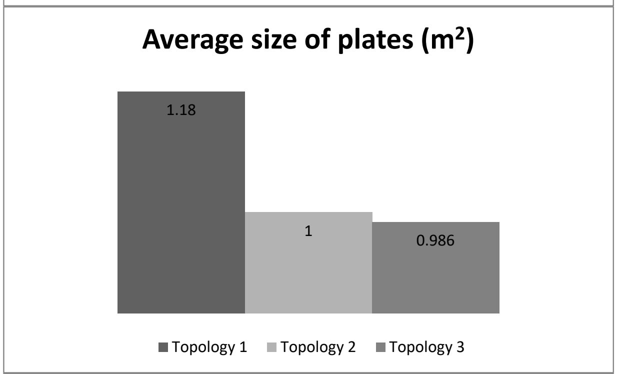
Karamba definition (in grasshopper) for the analysis of smooth shells.

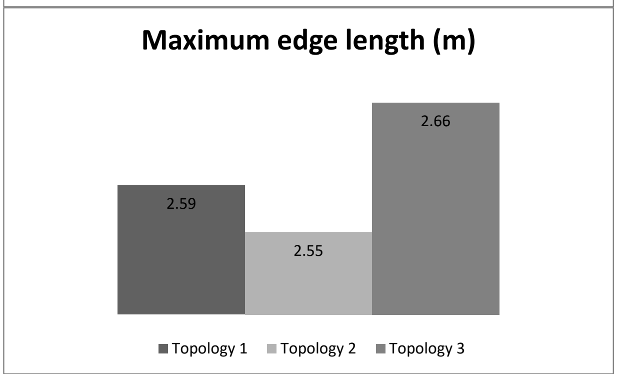


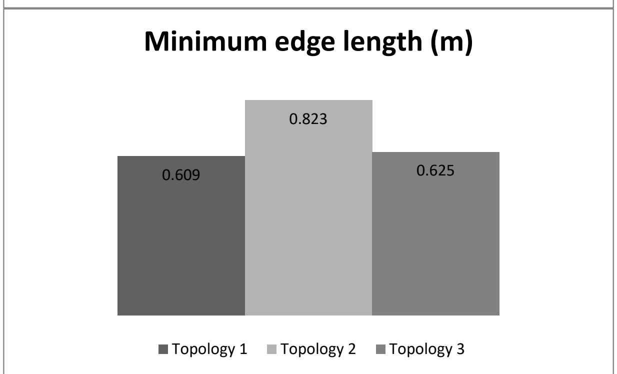
Comparison of numbers regarding the different topology variants researched in chapter 8.

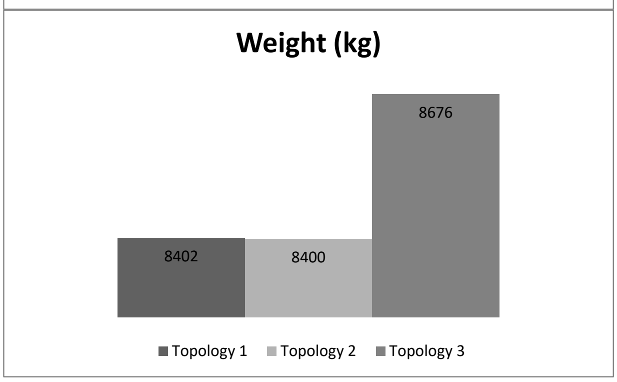
Variant 2 shows the most average plate sizes as well as the most average number of plates. It results, however in the variant with the lowest weight.



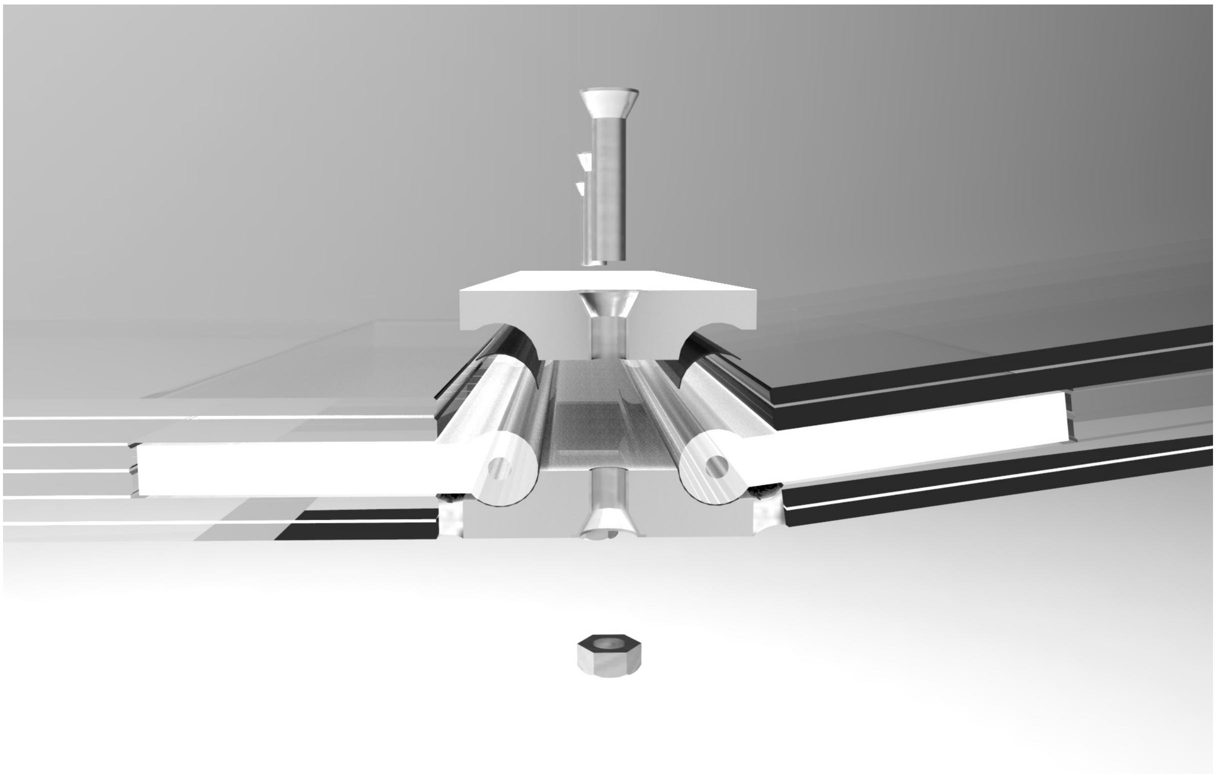




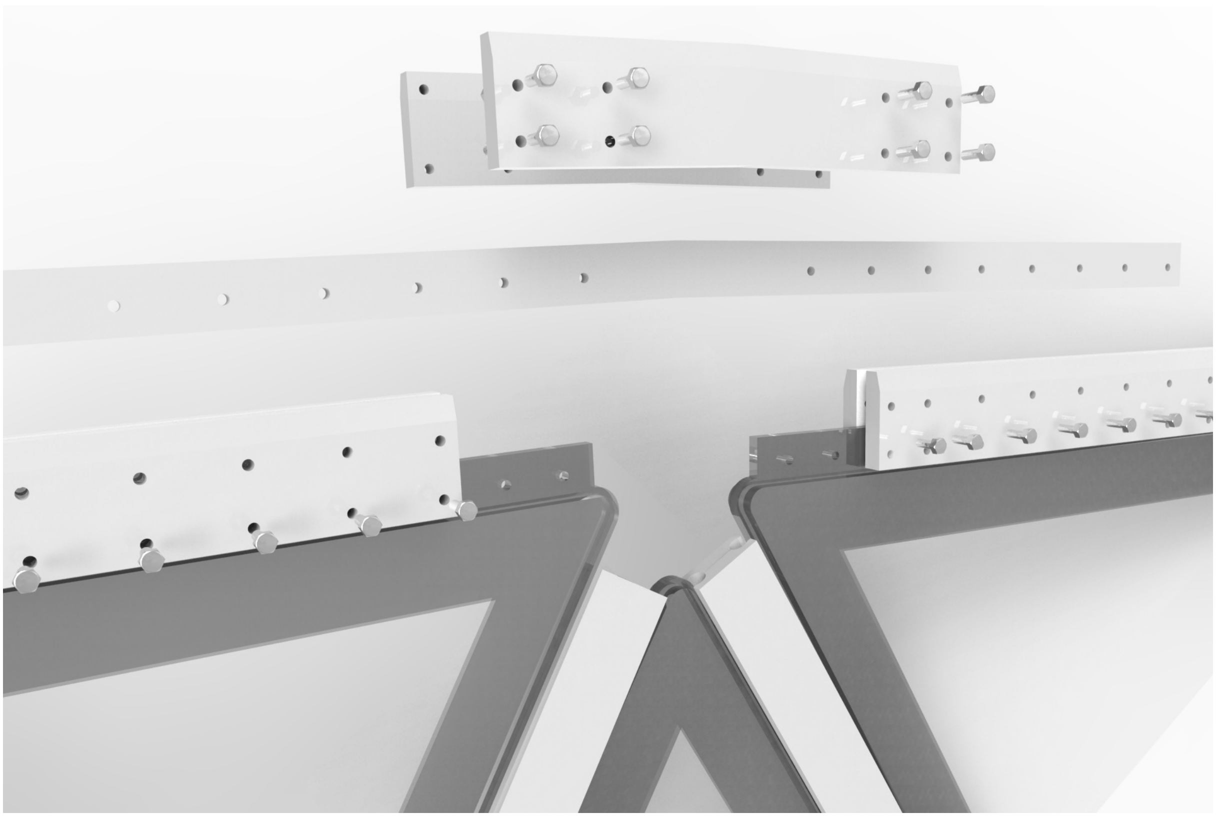




3D detail of the joint (see paragraph 9.3.2) showing the joining of the profiles using bolts. These bolts are placed in steel inserts to better distribute stresses around the bolt. Klingersil fibre sheeting causes high friction leading to a higher axial load of the detail.



3D detail of the free edge beam (see paragraph 9.3.3) showing the joining of the profiles using bolts. A second FRP plate is clamped between the profiles to approximate the behaviour of a continuous beam.



3D detail showing the "gapcap": a cap to cover the holes between the rounded triangular plates. Although these holes are small, it can still be possible for a little child to get stuck. Therefore these plastic covers are placed on the protruding part of the embedded FRP sheet around the holes or gaps.