TU Delft
Faculty of Architecture & Built Environment
MSc Building Technology

Master Graduation Thesis
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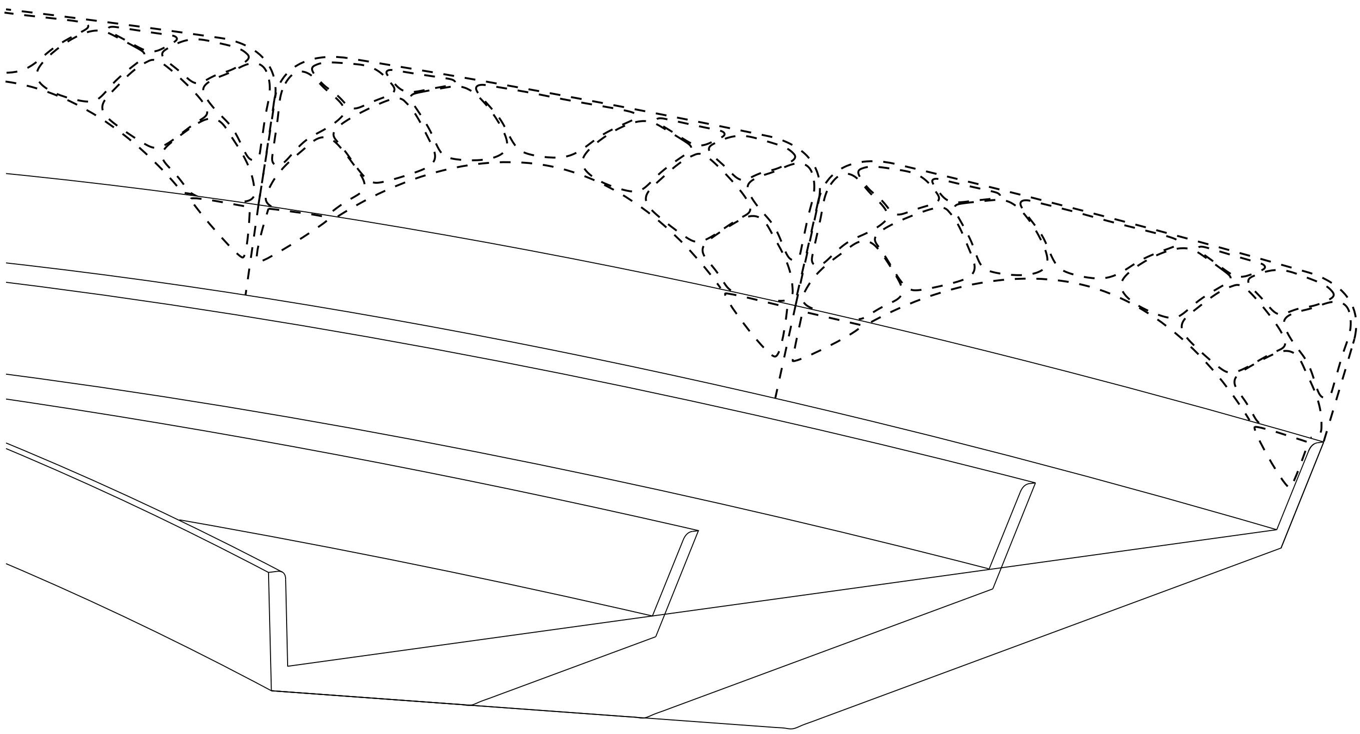
Modular series of FRP pedestrian bridges

The example of Tanthof Delft



Tutors: Joris Smits (main mentor)|Fred Veer (second mentor)|
Rafail Gkaidatzis (consultant)

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Structural Design and Innovative Materials

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Foremost, I would like to thank my main mentor Joris Smits for the productive discussions, through which he shown me how combine Infrastructure design with "typical" Architecture. Also my tutor Fred Veer for managing to set an order on my chaotic thoughts and teaching me how to work in a scientific manner. And of course my consultant Rafail Gkaitatzis for offering his knowledge and time whenever I would ask.

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Modular series of FRP pedestrian bridges

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Abstract

Bridges are of one of the most important infrastructures in the Netherlands. Due to Dutch landscape bridges of every size and types are needed in the rural as well as in the urban environment and often more than one piece is needed for a specific location. Due to the significant cost of bridge maintenance engineer's attention was drawn on Fibre Reinforced Polymers (FRP). This material is being used as structural material in steel cross-sections and as architectural material in double curve plates, produced via a modular production. The primary purpose of this research is to determine a series of FRP footbridges for the area of Tanthof Delft in the Netherlands that are manufactured via one modular mould. In that way, different bridge variations are produced based on different module combination. Also, the bridges are constructed all in FRP in order to create a new visual vocabulary of this material for bridge design by combining the free-form and structural potentials of this material. Initially the bridge structure starts as a U-shape bridge with non-structural railing. Through the use of parametric design the influence of the different geometrical variables of a bridge are investigated and the shape involves into a shell-like structure. Furthermore, municipality data of the demanded bridge's dimensions are analysed in order to identify the appropriate module matrix. Then, based this the modular mould of the Light Resign Transfer Moulding manufacturing technique is designed. The project managed to combine the research scopes and full-fill the setted aim, but this combination also limited the potential of each scope separately. Due to the small dimensions of the bridges and the need for repetitions the final product is double curved but not as "fluid" as other examples of roof or column examples. Also, the different width and lengths of the bridges provide a complex module matrix and at the same time a manufacturing mould of many pieces. Finally, by using the modularity exclusively for the mould design, its potentials to give solutions on connectivity limits the projects principle on monocoque structures.

Papangelopoulou K. (06/07/2017)

Content

Introduction

A.1 Background

In the Dutch rural and urban landscape the element of water is dominant resulting in extensive discontinuity of the land, which interrupts the productive transportation routes. The disjunction of neighbour towns or the inner city -mainly caused by canals or rivers- is resolved through the construction of bridges as the main infrastructure. Therefore, numerous and diverse examples of bridges in dimensions and load-bearing capacity can be encountered in the Dutch urban and also rural scenery. Usually large span bridges are constructed as unique structures, but often less structural demanding bridges, as footbridges are demanded in batches, in order to coven the municipal demand for such infrastructures. Characteristic is the example of the municipality of Rotterdam that requested 34 footbridges in one order in 2013. [W.07]

Moreover, the usage of bridges triggers a series of supplementary procedures, since such infrastructure also requires regular maintenance along with its installation. In fact, the Dutch bridges are ageing and the need of replacing existing components consists no longer just of a theoretical consideration within the scope of design, but a reality for the immediate future. Furthermore, bridge maintenance is a high-priced procedure as shown in (Figure A.4). Characteristically Klatter and van Noortwijk (2003) report that "The required annual budget for maintaining the Dutch stock of concrete structures of the road infrastructure is now (2003) 68 million Euro per year", meaning 0.66% of the construction cost. Such economic considerations result to be of increasing importance for the Netherlands Directorate-General for Public Works and Water Management. [A.01]

Furthermore, as the maintenance requirement is concerned, traditionally wood, concrete and steel are being used as construction materials for bridges, due to their adequate structural properties. The economic demand for low


A.1


A.2


A.3

A.1 Aerial photo of Amsterdam
A.2 Typical rural Dutch landscape
A.3 Typical urban Dutch landscape
A4 Maintenance costs versus age for bridges (less and larger than 300m2) in the Province of Overijssel (The Netherlands).
A5 Comparative table for different bridge materials made from CES material properties
A6 Comparison of energy consumption of a road bridge composed of various material options
A7 Comparison of carbon emissions for four bridges composed of different materials

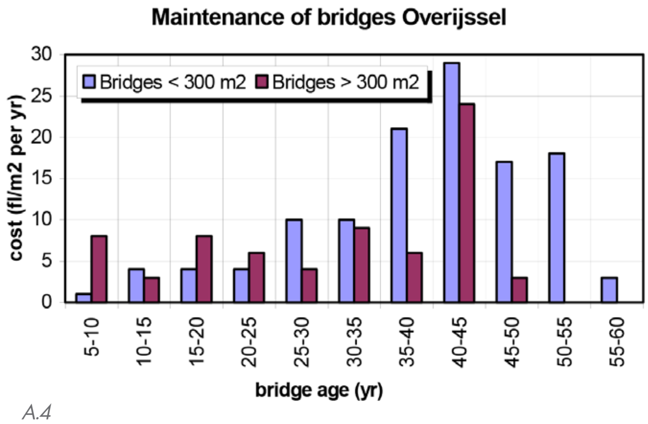
maintenance need and long-lasting life-cycle materials steered engineering interest towards fibre reinforced polymer (FRP) (Figure A.5). Additionally, FRP is a reasonable sustainable alternative, due its positive performance on life-cycle cost, its low maintenance needs, broader lifespan and easiness to repair and replace FRP components. [A.02] As shown on Figure A.6 and Figure A.7 FRP bridges in some sectors perform better than steel or concrete ones.

Even if composites are suitable as construction materials, architectural elements made from synthetic materials almost disappeared in the mid-1970s. The further developments of polymers have since then be taken on by other technologies such as aerospace and maritime industry. By the time the first public footbridges made from glass-reinforced polymers appeared in the late 1990s, viewed with great interest in the construction cycles, showing that FRP has more to give than already given. [B.01]

Especially from the '90s FRP has been used for the bridge industry as a main material for a new design, or as a reinforcement material on an existing one. For bridge structural applications, the focus has been given to the bridge deck. Fibre reinforced polymer (FRP) bridge decks have become an interesting alternative. Also, they have attracted increasing attention for applications in the refurbishment of existing bridges and the construction of new ones. [A.03]

A.2 Problem statement

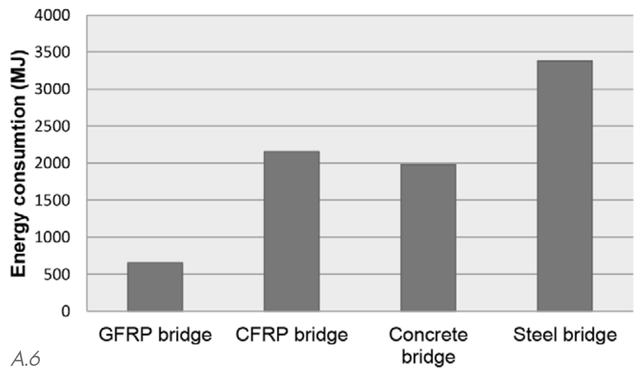
As already mentioned, the infrastructure industry desires to decrease the maintenance cost of a bridge. Apart from structural inefficiency, also aesthetic criteria suggest bridge replacement, as is shown on the Figure A.8 In many instances, bridges are structurally designed to withstand a lifetime of 50 to 100 years, but are substituted with aesthetically upgraded ones. Such cases occur even when the initial functionality of the bridge did not



A.4

	Steel	Concrete	Wood	FRP
Density (kg/m^3)	7.850	2390	936	1860
Maintenance need	yes	yes	yes	no
Corrosion/moisture resistance	weak	weak	weak	yes
Tensile strength (MPa)	365	1.2	147	250
Compression strength (MPa)	283	20	75.4	230
Geometrical properties (free form shape)	no/casting	yes	no	yes

A.5



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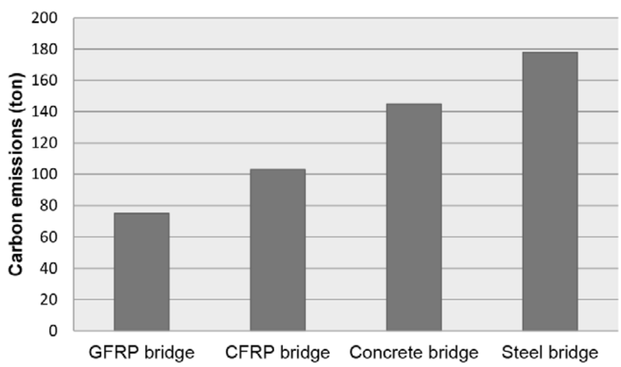

A.7

alter. Still bridges become obsolete, due to their antiquated look. Thus, a careful choice of both technical and architectural bridge requirements is crucial in accomplishing a long-lasting infrastructure. [A.04]

Moreover, the application of FRP in civil infrastructure projects is limited comparing to other aforementioned structural materials. Broad implementation of an industrialized approach to design, manufacture, construction of FRP based civil infrastructure depends on the availability of an innovative business model that is able to assure the demand and supply chain integration throughout the life cycle of the product.[A.02] For that reason, as can be seen from Figures A.9 and A.10 the existing example of FRP bridges imitate the steel bridges constructed with pultruded profiles. Thus the structural stiffness in based on the steel cross-section options.

On the other hand, in the sector of Architecture, the interest in designing with plastics is reborn, due to their ability to form random geometries. Through the moulding manufacturing technique free form, double curved elements can be produced, usually as cladding elements. Unfortunately, such components rarely serve structural purposes as well. Moreover, for the production of such components a modular principle is used. Meaning, the geometry is divided in smaller repetitive parts that are produced by specific number of moulds, thus the production is simplified by reusing the same moulds. [A.05]

Concluding, fibre reinforced polymer (FRP) is a light-weight, high-strength material, with low maintenance demand. When its used in civil applications it imitates the structural properties of steel cross-sections and when it is used in architectural applications is double-curved and modularly produced, but its not used in a structurally manner. As a result, FRP's material architectural and structural potentials are not thoroughly exploited. Thus further research

RIJKSWATERSTAAT MAINTENANCE CRITERIA

- **MOBILITY**
- **TRAFFIC SAFETY**
- **LIFE QUALITY**
- **USER COMFORT**
- **AESTHETICS**

A.8

A.9

A.10

A.8 Rijkswaterstaat maintenance criteria
A.9 FRP Fiberline bridge Kolding, Denmark, 1997
A.10 FRP footbridge Scotland 2013

has to be conducted combining both FRP's structural and architectural application .

A.3 Objectives

The main objective of the M.Sc. thesis is to research on the FRP composite material and moulding technology in order to prove that is possible to design an **all FRP footbridge series** and manufacture them via a **modular moulding manufacturing process**.

Regarding this objective 6 number of sub-objectives need to be set:

- Determine the suitable **raw materials** (resin, fibre, core) type for the project with sufficient mechanical strength, good weather conditions response and good cost-efficient rate.
- Determine the suitable **moulding manufacturing techniques** for sandwich FRP production with low tolerances, low surface roughness and high product rates.
- Determine the suitable **design principles** for the project that allow easy refurbishment and maintenance, creates double curved shapes, respects the technical requirements of footbridge design and can be replicated in different dimensions .
- Determine the suitable **module matrix** for the project that allows for possible length extension, respects the width and length pattern of the project and uses the minimum possible number of modules.
- Determine the suitable **bridge design** that has organic shape, minimum deformation and can be manufactured with moulding techniques.
- Determine the suitable **mould design** in respect of the most suitable manufacturing technique, bridge design, modules matrix, connectivity and re-use of modules.

A.11

A.12

A.11 Zaha Hadid's Chanel contemporary art container, New York's central park, 2008
A.12 FRP panels of free-form Zaha Hadid's free-form facade

A.4 Research question

The main research question of the MSc thesis is: **How can an all FRP footbridge series be designed and manufactured via modular moulding technique?**
In order for the main question to be answered the following sub-questions need to be answered:

- Which is the suitable **raw materials** (resin, fibre, core) type for the project with sufficient mechanical strength, good weather conditions response and good cost-efficient rate?

- Which is the suitable **mould manufacturing techniques** for sandwich FRP production with low tolerances, low surface roughness and high product rates?

- Which is the suitable **design principles** for the project that allow easy refurbishment and maintenance, creates double curved shapes, respects the technical requirements of footbridge design and can be replicated in different dimensions?

- Which is the suitable **module matrix** for the project that allows for possible length extension, respects the width and length pattern of the project and uses the minimum possible number of modules?

- Which is the suitable **bridge design** that has organic shape, minimum deformation and can be manufactured with moulding techniques?

- Which is the suitable **mould design** in respect of the most suitable manufacturing technique, bridge design, modules matrix, connectivity and re-use of modules?

A.5 Constrains of the research project

In order to research the wide range of the FRP's geometrical and structural potentials, all the parts of the pedestrian bridge will be designed as FRP components. Design solutions that include alternate materials should be avoided. Embedded steel connections consist an exception, when judged as the only suitable connection solution.

Furthermore, as the resign, core and fibre selection concern, only options that have proven their mechanical strength in fatigue tests and permanent load tests will be considered. As a result, the investigation of possible alternative materials will not expand to bio-based FRP. Additionally, material selection will be restricted on the footbridge engineering level, so specialized raw materials used for aerospace applications will be eliminated from the material selection.

Moreover, the mould manufacturing research will be restricted on existing mould manufacturing techniques for FRP and focused on Dutch footbridge manufacturers, in order to give an applicable proposal for the Netherlands.

Additionally, the data for the modular solution will be retrieved from the structural and aesthetic requirements of an existing neighbourhood (Tanthof Delft) that will be used as case study. Those data that will function as indicator for the further expansion of the proposal to more neighbourhoods. Also, the municipality data with the informations of the locations and the dimensions of the bridges will be used, without further actions in order to verify the information.

Finally, the structural assessment of the structural research will be done through simulation models and FEM analysis.

A.6 Research design steps

The research takes place in five (5) different steps: analysis, preliminary design, footbridge design, optimisation process, in respect to the research question.

Analysis step
During analysis step, the research is aiming to a better understanding of the material itself. Via literature review a general overview of FRP's mechanical properties, manufacturing techniques and connection types is investigated. Resin, fibre and core options and mould manufacturing methods are thoroughly investigated, in order to decide on most appropriate raw material choice and manufacturing technique. For that purpose, further literature and material data program (CES) is used.

Preliminary design step
During preliminary design step the manufacturing techniques and the existing moulding technologies of footbridges manufacturing in the Netherlands is examined. For the first step literature review is used as main research tool, while for this step in suit visits on FRP mould manufactures facilities take place. Based on their experience and importance on the pedestrian FRP bridge history, PolyProducts and FiberCore were selected as representative Dutch manufacturers. Apropos, PolyProduct built the first all FRP footbridges in the Netherlands and FiberCore is still active in footbridges manufacturing and works close with the municipality of Rotterdam for the replacement of a series of footbridges in the area. The research is also be based on relevant case studies where the use of mould manufacturing technique and the final architectural result will be evaluated. As a conclusion of this step the design principles for the project's layout is formulated.

Footbridge design step
During footbridge design step the concept of the modularity in the manufacturing process is explored. In order to do so, the existing bridge data of the municipality of Delft are analysed as to decide on area of intervention. Also, through the bridge population that needs to be replaced and their respective dimensions by the series of FRP footbridges the manufacturing modules matrix of the proposal is decided. Simultaneously the bridge design is researched as bridge structure with non-structural railing. The bridge design is decided in respect to the modularity manufacturing principle. As final result of this research step the general design on the footbridge series is shown.

Optimization process step
During optimisation process step further structural calculations determine the exact dimensions of the structure and its railing. Also the detailing of the mould layout and the bridge design is designed. Moreover the manufacturing, transportation and installation of the bridges is illustrated.

A.7 Research tools

The analysis and preliminary design phase of the research is based on literature review and site visits in order for the necessary information on the material properties, connectivity and manufacturing to be collected.

Furthermore, the raw material's and manufacturing technique's technical information is retrieved from CES Edupack. CES EduPack is a material database developed by Granta Design.

Additionally, through meetings with the municipality, site visits and official municipality data, a better understanding of the urban context of the area and replacement demands of the existing bridges is achieved.

Also, physical models are used to decide on the bridge design. The technical drawings of the design and the visualisation will be produced mainly by Rhinoceros (Rhino). Moreover, Autocad (CAD), Photoshop and 3ds Max will be used as well. Rhinoceros is a commercial 3D computer graphics and computer-aided design (CAD) application software developed by Robert McNeel & Associates. AutoCAD is a commercial computer-aided design (CAD) and drafting software application. Developed and marketed by Autodesk. Adobe Photoshop is a raster graphics editor developed and published by Adobe Systems. Autodesk 3ds Max is a professional 3D computer graphics program for making 3D animations, models, games and images

Finally, for the structural analysis of the project Karamba is used. Karamba is a plug-in for parametric engineering & structural modelling for Grasshopper & Rhino. Grasshopper is a visual programming language and environment developed by David Rutten at Robert McNeel & Associates, that runs within Rhinoceros.

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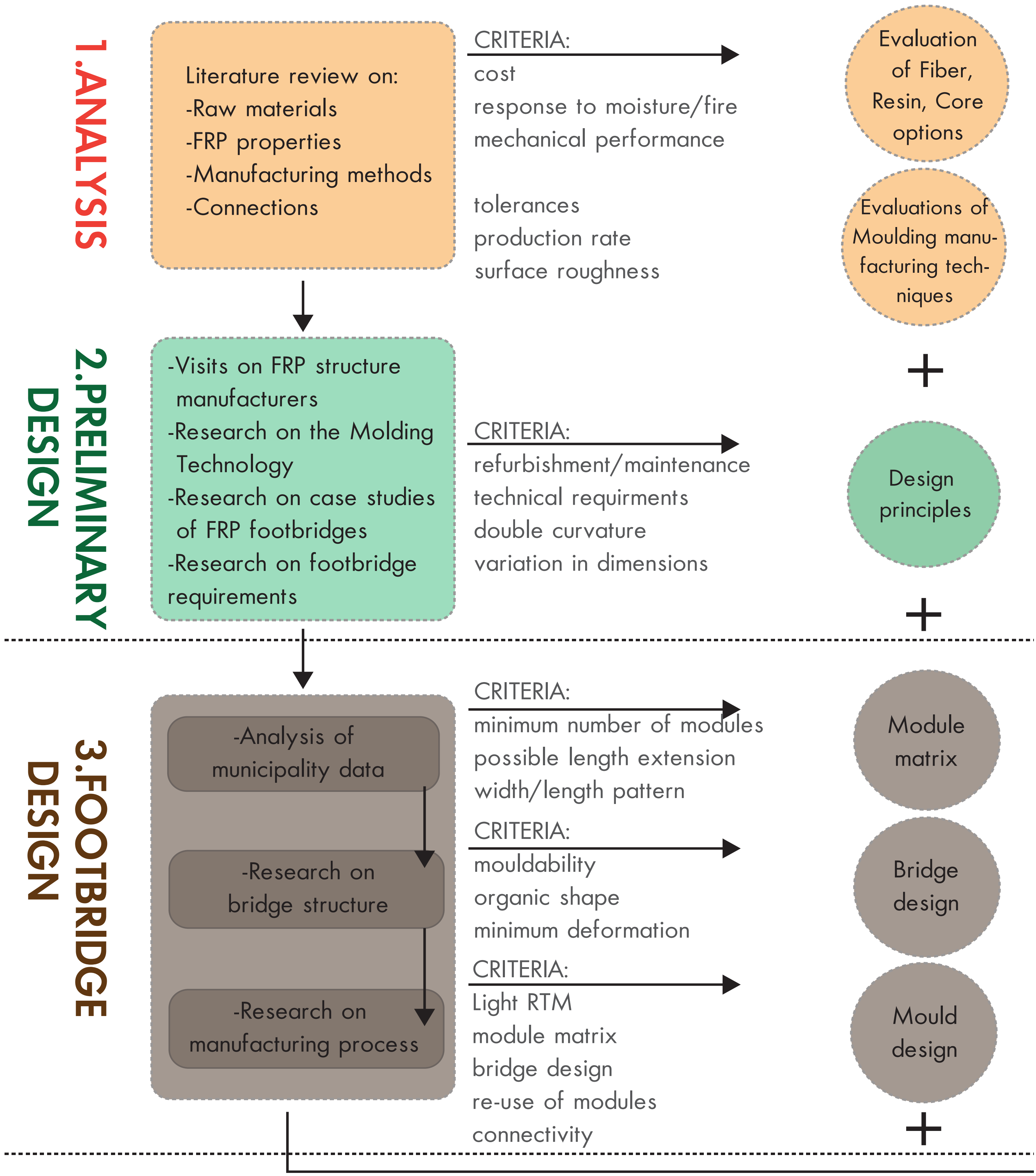
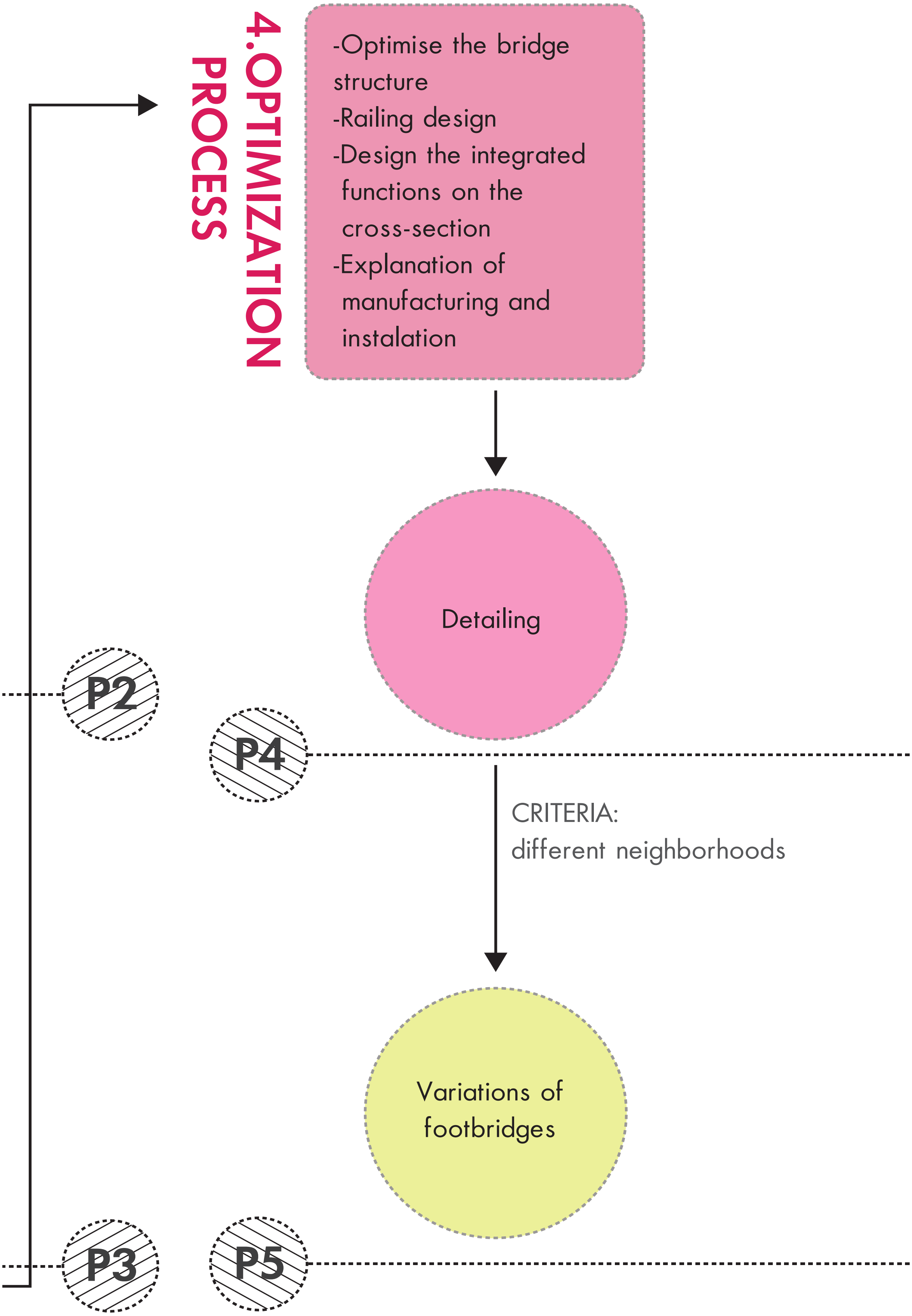
A.8 Research methodology(research by design)




4.OPTIMIZATION PROCESS
-Optimise the bridge structure
-Railing design
-Design the integrated functions on the cross-section
-Explanation of manufacturing and instalation
Detailing
P2
P4
CRITERIA:
different neighborhoods
Variations of footbridges
P3
P5

A.9 Time planning

Research Topics	September				October					November				December			Christmas vacation		
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SWAT Studio																			
SWAT Dubrovnic Workshop																			
SWAT Elaboration																			
Selection of Graduation Subject																			
Graduation Research																			
FRP Structural Material																			
Pedestrian Bridges																			
Material Properties																			
FRP Fibres																			
FRP Resins																			
FRP Cores																			
Manufacturing and Assembly																			
Types of Joints																			
Post-processing Operations																			
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Production Techniques																			
Types of Molding																			
Demolding Technique																			
Product Limitations																			
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Tanthof Delft Bridge Footbridge																			
Form Research Process of Design																			
Structural Comparison of Design																			
Railing Design																			
Mold Desing																			
Final Design																			
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Manufacturing and Installation																			
Conclusion and Recommendations																			
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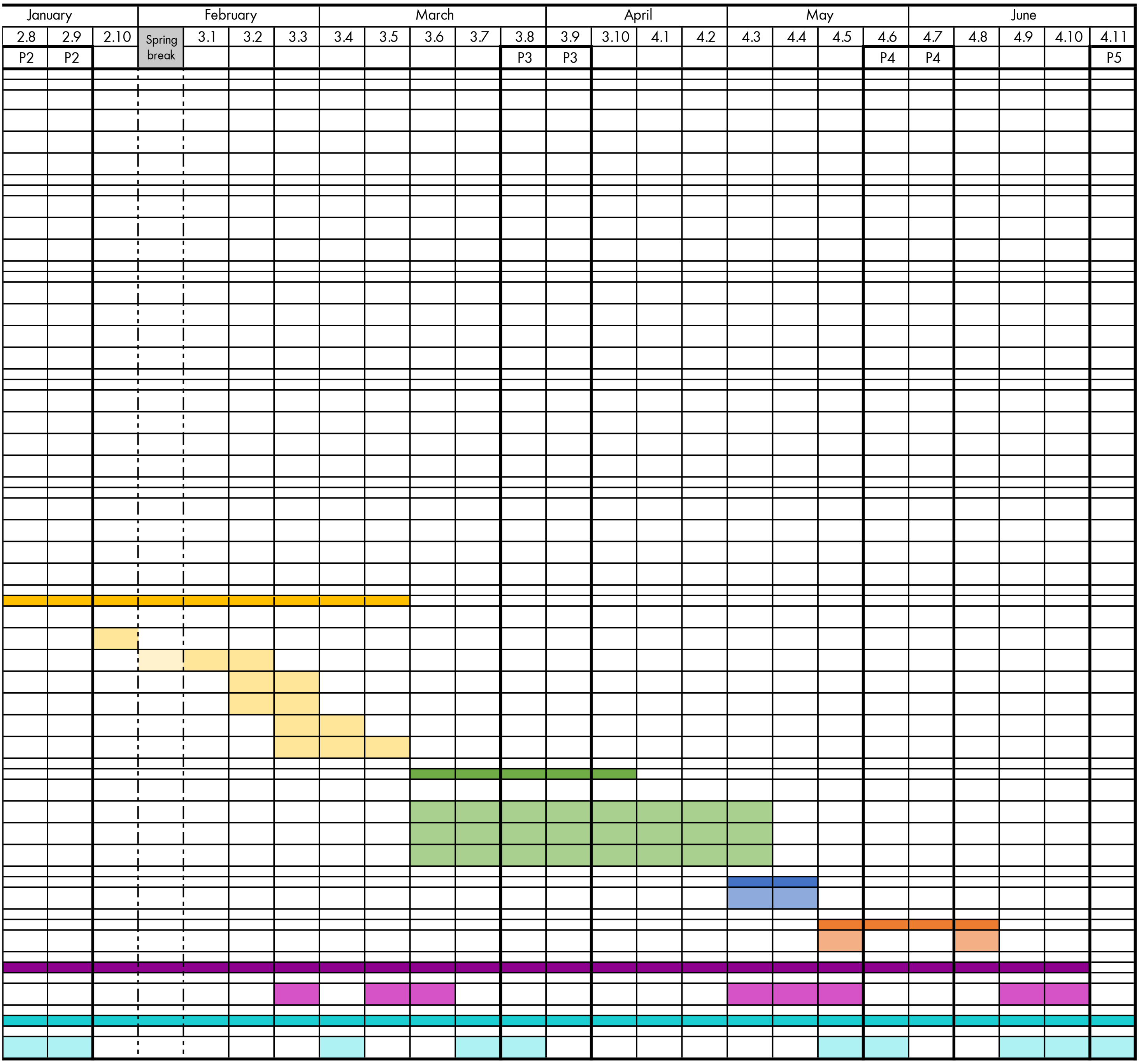
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P5

Raw materials for FRP

B.1 Polymer

Polymers are synthetic materials made from organic molecules, which form macromolecules. The different variations of molecules, aka monomers, determines also the different properties of the final polymer. The vast number of monomers available and the various combination options result in more than 200 different polymers, whose properties can be further adapted with additives. Whereas in traditional materials like steel, wood, concrete is the material that determines the construction, in the case of polymers (plastics) the material properties can be adjusted during manufacturing.

Also, despite all the possible variations, polymers have some properties common for all. For instance, they have low self-weight, distinct time-related behaviour, can be moulded and due to the carbon compounds they are combusted. [B.01]

Classification of polymers

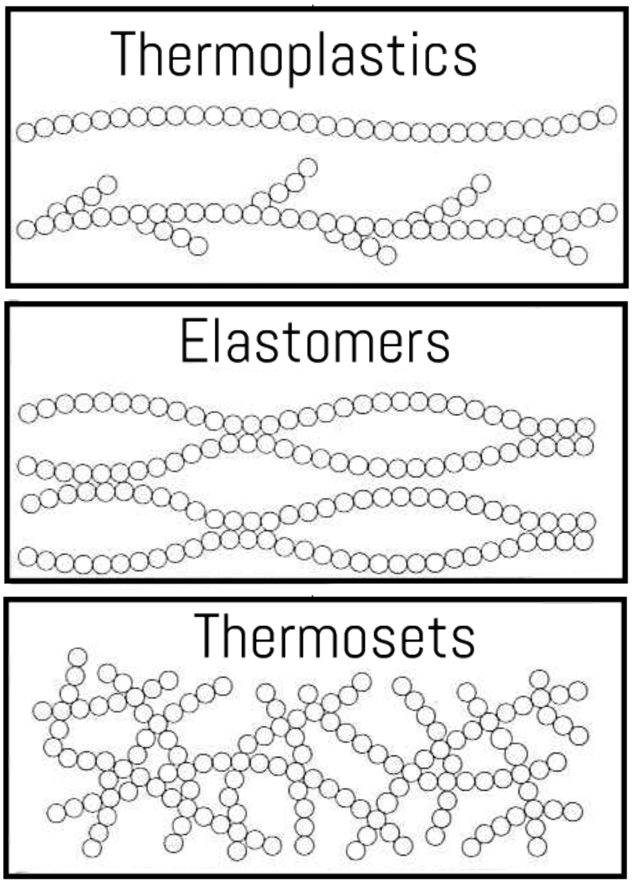
Polymers have three different degrees of molecules cross-linking which answer to the following type of polymers.

- Thermoplastics
- Elastomers
- Thermosets

As mentioned before polymer's properties are widely scattered, but their common molecular architecture is a characteristic indicator of common properties. In principle, the degree of cross-linking determines their strength and melting characteristics. [B.01]

More analytically, the majority of the plastic object in our house and everyday life, as well as packaging are made out of thermoplastics (or thermosoftening plastics). Thermoplastics consist of linear or branched molecular chains that are held together by weak physical forces and there is thus no chemical cross-link. When the material is heated, these so-called

B.1.1



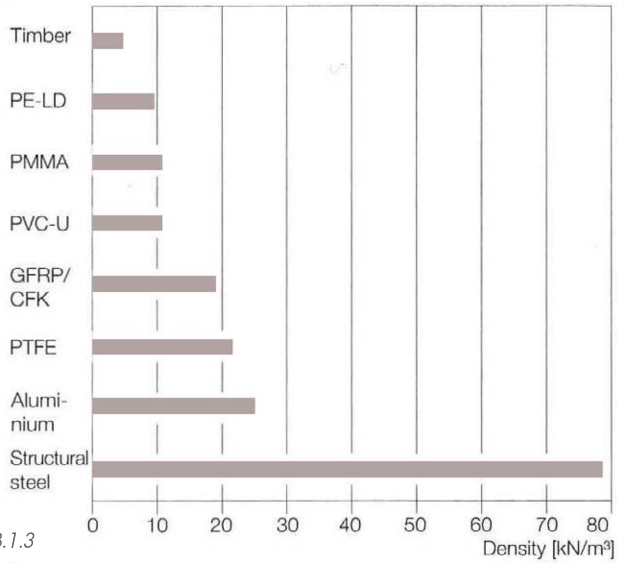
B.1.2

B.1.1 Polymer as raw material
B.1.2 Molecular structure of different types of polymers
B.1.3 Density chart of different structural materials
B.1.4 Thermal conductivity of different structural materials
B.1.5 Stress to stain graph of different structural materials

secondary valency forces are broken down allowing the molecular chain to move. As a result, the polymer softens up and becomes mouldable. Moreover, thermoplastics exhibit the viscoelastic material behaviour and can be welded and recycled. Due to their high viscosity this type of material is less suitable for fibre-reinforced polymers than thermosets. [B.01]

Vehicle tires are the most common application of elastomers (or rubber) on everyday life. Elastomers have an intermediate cross-link degree between the non-existing and the densely molecular cross-linkage. Unlike thermoplastics, elastomers cannot be softened after the molecular linking is complete and the mechanical properties of the materials stay constant as the temperature rises. Moreover, after severe elongation, elastomers can return to their prior form. Due to characteristics as such, elastomers are not appropriate as construction materials, but frequently used as load-bearing jointing materials or for waterproofing and sealing material. [B.01]

Light switches and plugs are frequently made from thermosets. Thermosets or thermosetting plastics form a dense, closely woven, three-



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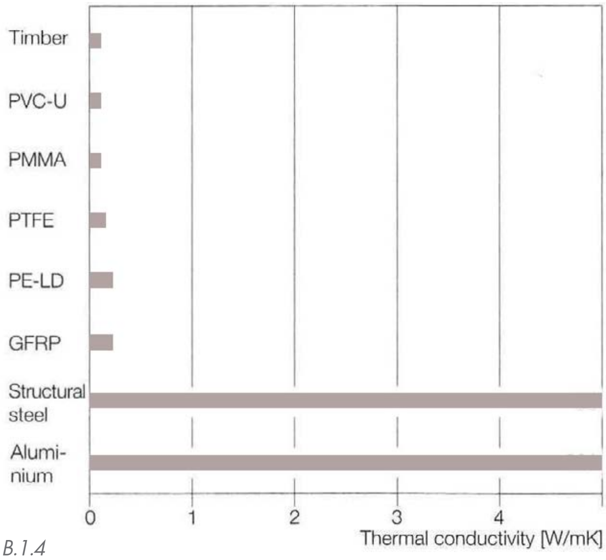

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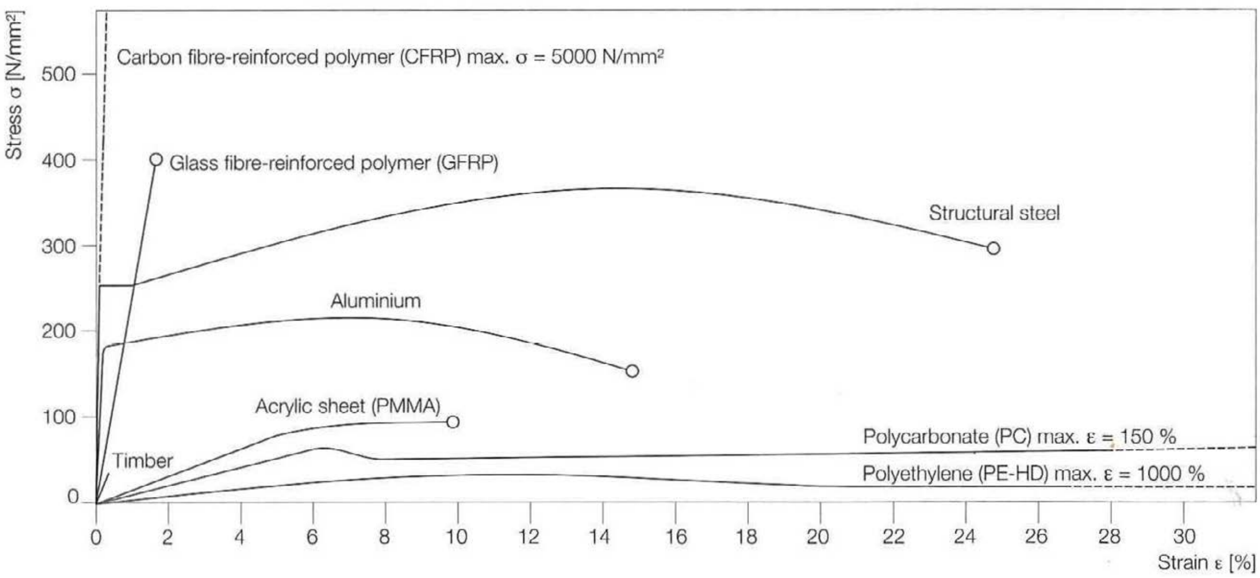


dimensional molecular cross-link. This results to a hard, brittle micro-structure, which prevents the infiltration of solvents and provides the material with high resistance to chemicals. This molecular structure is also not affected by heat providing high heat resistance to the material. Although their high heat resistance their strength and elastic module is severely decreased after the temperature of 100°C. Finally, thermosets cannot be melted and this is a severe disadvantage of the material in terms of recycling. [B.01]

B.1.1 Fillers and additives

Fillers and additives are mixed with the polymer to essentially influence its properties. Fillers are substances, which extend the polymer's properties, while additives add more properties on the polymer or are used as reactants. Since the additives influence the workability of the polymer, its effects need to be taken into account from the beginning of the component design and operation planning. [B.01]

The following aspects are critical when designing with a polymer and could be influenced by a filler of an additive:

- Desired service life
- Exposure to weather and UV light
- Chemical resistance
- Final processing intended
- Desired colour and transparency
- Fire protection requirements
- Mechanical properties specification [B.01]

Furthermore, fillers and additives could also reduce the cost of a polymer by adding kaolitine, chalk -or oil for elastomers-, or colour the polymer via the use of dies or pigments. Specifically, for the colour property of the polymer, special colour characteristics can be given to the polymer, through the use of special colourants, like fluorescent and brightening paint. Additionally, special fillers can control the chemical reaction of the

B.1.6

		Tensile strength	Compressive strength	Elastic modulus	Impact strength	Reduced shrinkage	Better heat resistance	Chemicals resistance	Economy
Spherical fillers	Sawdust	+			+	+			+
	Carbon black			+	+	+			
	Metal oxides			+	-	+	+		
	Calcium carbonate		+	+	-+	+	+		++
	Kaolinite				-	+	+	+	+
	Silica			+	-	+			+
	Sand/quartz powder		+	+	-	+			++
Flake-like fillers	Graphite					+		+	+
	Talcum		+	+	-	+	+		+
	Mica	+		++	-+	+	+	+	+
Fibrous fillers and reinforcing materials	Polymer fibres		+	+	+	+	+	+	+
	Carbon fibres	+++	+	+++	-	+	++		-
	Glass fibres	++	+	++	-+	+	++		+

B.1.7

B.1.6 Polymer with special effect pigments
B.1.7 Fillers characteristics table

polymer, enrich its UV light resistance and improve its fire resistance, through the use of halogens, aluminium trihydrite or hydroxide. Finally, prevent the brittleness and improve the coating properties. [B.01]

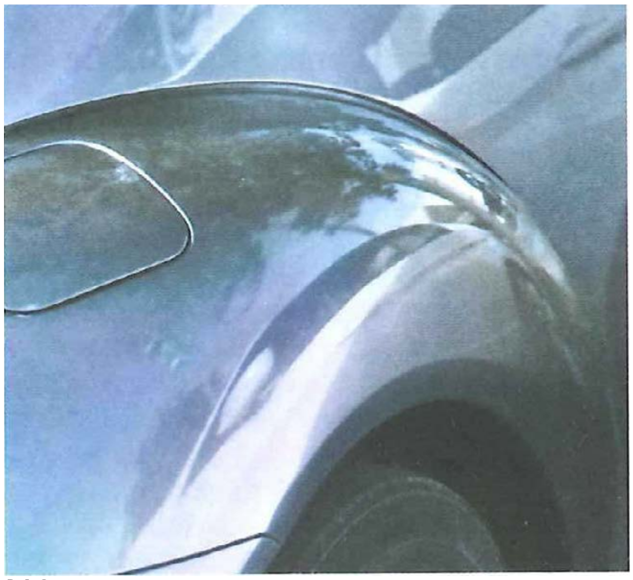
B.1.2 Coatings

Polymers themselves do not require any protective coating on their surface. The material in combination with fillers is able to fulfil the technical and visual demands, without the need of coatings. Nonetheless, coatings are still used in fibre-reinforced applications for different reasons, as will be explained further. For example, during production gel-coat, which is a pure polymer, is applied to the mould in order to facilitate the demoulding process. [B.01]

The majority of coatings used in the industry are based on synthetic materials, due to their easy workability and good resistance to environmental influences. In coatings three components can be found:

- Pigments of dues
- Binders as surface protection and bonding agent
- Solvents, which volatilise after application[B.01]

B.1.8



B.1.9

B.1.10

	Wet abrasion	Cleanability	Resistance to solvents	Resistance to alkalis	Resistance to acids	Resistance to petrol	Resistance to spirit
Paint, low binder content (dispersion paint)	-	--	--	--	--	--	--
Paint, high binder content (latex paint)	+	o	--	--	--	--	--
Acrylic lacquer, aqueous	++	o	--	--	--	--	--
Alkyd lacquer	++	+	+	--	o	+	++
Epoxy lacquer	++	++	++	++	++	++	++
Polyurethane lacquer	++	++	++	++	++	++	++

B.1.8 FRP water resistance coating
B.1.9 FRP sun resistance coating
B.1.10 List of coatings properties

The coating materials are classified according to the binder they contain, but since these products contain several additional components, a complex overlapping coating system is created. For that reason, they can also be classified according function. [B.01]

B.1.2.1 Coating of floor finishes and road surfacing

These type of coatings protect the surface of materials susceptible to corrosion, such as steel, concrete, fibres. Such corrosion is caused due to water, UV radiation, carbon dioxide, dissolved de-icing salts or petrol. Such coatings are especially used for floor finishes and road surfacing, where industrial floors, parking decks and bridges have to satisfy special requirements. Apart from protecting the substrate of concrete, steel of fibre-reinforced polymer the finish should provide a permanently coarse surface and be able to withstand high loads, as vehicles. [B.01]

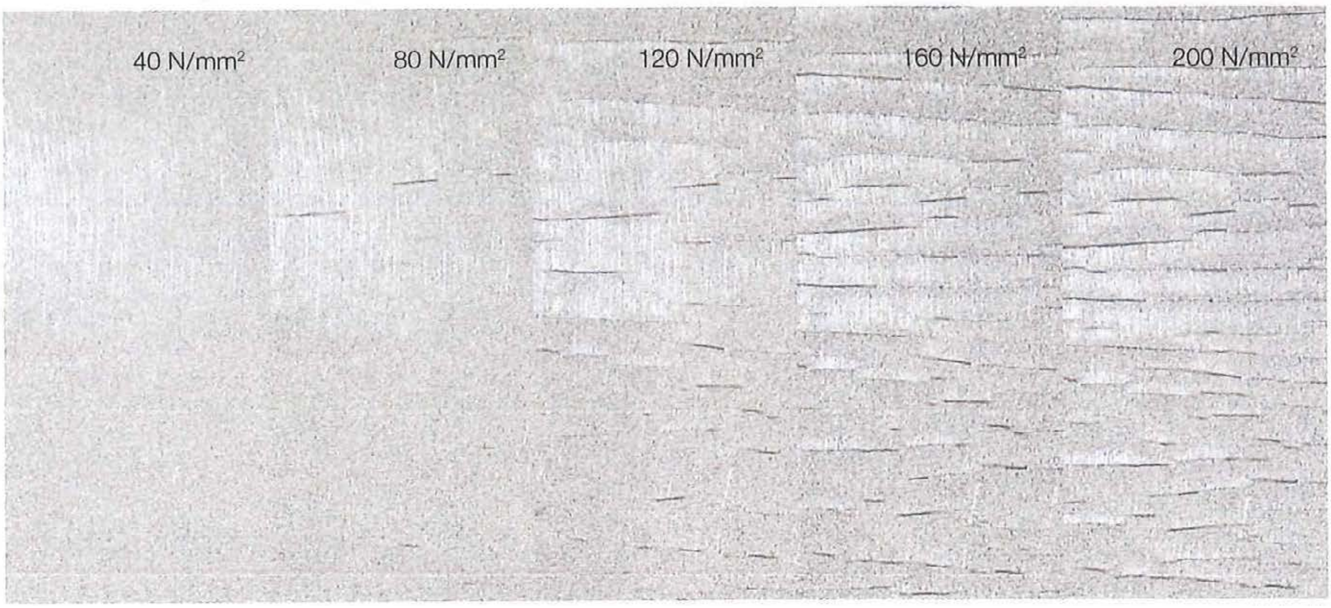
Polymer coatings in opposition to asphalt can be applied cold, cures in shorter time and usually exhibit higher load-carrying capacity. Based on the desired roughness of the finishing surface, the coating surface can extend from very smooth to coarse. [B.01]

More specifically, in order to increase the stiffness of the surface, epoxy resin or polyurethane are mixed with quartz sand. Alternatively polymer concrete could be used. This product is not a waterproof finishing, due to the low resin content, only 10% by weight (wt%), but can be applied in thickness of several centimetres. Via the use of a an additional resin of just a few millimetres, the surface can be sealed. Such applications can be found in steel bridges. [B.01]

Since both polymer concrete and reactive resin finishes exhibit poor surface adhesion, a coat of primer(epoxy resin without fillers) is necessary between the substrate and the coating. [B.01]

B.1.2.2 Coating for fire protection

Fire protection coatings are based on dispersion paints or acrylic resins to which a blowing agent has been added. When the temperature rises above 200°C, the blowing agent swells to up to 120 times its original thickness functioning as a layer of thermal insulation. In such way the coating functions as



B.1.11 Tensile stress test of FRP coatings a layer of thermal insulation between the fire and the component requiring protection. [B.01]

Usually, intumescent coatings are used successfully on steel beams in order to increase their fire resistance. On the contrary, fire protecting coatings are not so effective when applied on fibre-reinforced polymers. Tests with beam sections made from glass fibre-reinforced polymer (GFRP) concluded that their fire resistance showed no significant improvement, since the polymer weakens considerably before the reaction temperature of the coating is reached and so the protective function is triggered too late in fire incident. [B.01]

B.1.2.3 Coating as decorative surface function

Polymer components can achieve different colours and smooth surfaces from primary shaping procedures and thus they use coatings for decoration in exceptional circumstances. Nonetheless, since polymers and composites have a low elastic modulus the extensibility of the coating must be checked first. [B.01]

Paints

Most paint finishes are dispersions, which include latex, the silicate or silicone resin paints and dispersion paints. These mixtures of two or more substances, which are not dissolved in each other, generally consist of pigments, binders and solvents, usually water or another organic solvent. The binders used are synthetic materials such as silicone resin or acrylate, but also slacked lime or potassium water glass. After applying the paint to the substrate, the solvent volatilises and the pigments and binders are deposited on the surface. In contrast to lacquers, dispersion paints are permeable to water vapour. Latex paints contain a relatively high proportion of binder and are therefore less permeable to water vapour. Dispersions can be applied with simple tools and are relatively inexpensive. [B.01]

Synthetic resin finishes

Synthetic resin finishes are based on dispersion paints. A siliceous aggregate (quartz sand) has been added to improve the capacity for forming into various shapes and mouldable consistency. Despite their unfamiliar feel, such synthetic resin finishes are more elastic and more waterproof than mineral renders, and thus preferred in combination with external thermal insulation composite systems. [B.01]

Lacquer systems

Lacquer systems consist of several components or coats that must be applied in different order. The top coat that is responsible for the properties of the final surface, but the combination of the individual components also influences appearance and the characteristics of the coating. [B.01]

In order to achieve a flat final surface, it may be necessary to apply a levelling layer first in the form of a filling compound, e.g. of saturated polyester resin(UP). Afterwards, a primer is applied to ensure a good bond between the substrate and the subsequent coats of lacquer. On polymers only a physical bond develops between the substrate and the primer, which is normally a two-part polyurethane product. In the next step minor unevenness is compensated for with a filling compound, which also fills any pores. Systems based on unsaturated resin with a filling compound, which also fills in any pores. Systems based on saturated polyester resin, alkyd resin, acrylate or epoxy resin are used for this and can be sprayed on to the surface to achieve thickness of up to 0.1mm. Alternatively, an undercoat can be used, applied with a brush or roller. Once it has dried, the layer of filling compound is rubbed down, baked or immediately given a final coat which determines both the appearance and the protective function. [B.01]

The transparent top coat protects the lacquer system against mechanical and chemical effects and consists of acrylic, epoxy, polyurethane or alkyd lacquers. The top coat is crucial for the technical properties of the final surface. Acrylic lacquers are more elastic, more diffusion-permeable and more resistant to UV light, but alkyd lacquers are easier to clean and more scratch-resistant, and epoxy and polyurethane lacquers have excellent resistance to chemicals. [B.01]

B.1.2.4 Coating application methods

There is a broad variety of coating application. For instance, paints are usually applied with brushes or rollers, while lacquers are sprayed on. For large batches or large area, coil coatings are more suitable. Finally, powder coating is also possible on electrically conductive substrates and results in even coating thickness. [B.01]

B.1.3 Preparing the polymer

Polymers are treated in reaction vessels out of which the polymer mixture, aka compound, is composed. Due to their distinct characteristics, elastomers, thermoplastics and thermosets have different process steps. Thermoplastics can be melted and remelted for infinite cycles, but elastomers and thermosets cannot be reshaped after the cross-linking is done. The primary product is crushed or blended and then mixed with additives and fillers. Blending in the dry state is called mixing, in the plastic state homogenizing. Those treatments of the basic material up to the stage of making the polymers processable are polymer supplier's responsibility [B.01]

B.1.4 Thermosets

Thermosets are created on the final processors in the form of liquid reaction resins and less often as premixed moulding compounds. This type of polymers, as the elastomers, cannot be reshaped or remelt after curing. The non-cross linked resins are supplied as reactive solvents that usually have a self-life time of 1 year. Fillers and additives are already mixed on the resin by the suppliers. During the gel time the polymer can be shaped and reinforced, but as the curing time approaches the workability becomes more and more difficult until the final rigid state is reached. Also, it has to be noted that this chemical reaction is exothermic and thus during curing heat is produced. In some occasions, like on Unsaturated polyester resin (UP) curing, also water is produced as by-product of the reaction, which must be removed from the main product. [B.01]

B.1.5 Resin

In order for fibre-reinforced polymer (FRP) to be manufactured, thermoset polymer is used as resin. This resin is the matrix of the composite material and determines the material properties and structural performance of the FRP. Matrix restrains the reinforcements in place, acts as a path for stress transfer to the fibres and at the same time protects the reinforcements from an adverse environment. Moreover, the matrix has an additional minor role in the longitudinal tensile properties of a unidirectional continuous fibre composite. However, the selection of the matrix influences the transverse tensile modulus and transverse tensile strength, both longitudinal and transverse compressive properties and shear modulus and shear strength. [B.02]

In the building industry five (5) polymers are mostly used: Unsaturated polyester resin (UP), vinyl ester resin (VE), epoxy resin (EP) and phenolic resin (PH). There are also more types of resins used in natural fibre-reinforced polymer and bio-based polymers. [B.01]

Unsaturated polyester resin (UP)

This type of polymer is used for glass fibre-reinforced polymer (GFRP) and sealing materials. UP resin is mostly used for producing GFRP due to its adhesion behaviour with glass fibres. UP also demonstrates excellent workability and relatively low cost. Additionally, it shows good tenacity even in low temperatures. It has a transparent to pale yellowish colour, depending on the UP thickness and mediocre mechanical properties comparing to the rest of the thermosets resins. UP's low moisture absorption capacity makes it ideal option for external FRP applications. On the other hand, its main disadvantage is its high rate of shrinkage during curing that cannot be compensated entirely by fillers use. Finally, polyester resin cure after adding a catalyst with an exothermic reaction. The ratio between the two parts can differ without its mechanical properties to be affected. This is a major advantage for the manual production techniques. The annealing temperature is approximately 70°C, but with the use of an accelerator UP can cure in room temperature. [B.01]


B.1.12

Epoxy resin (EP)

Epoxy resin is mainly used as surface protection and coating, adhesive and carbon fibre-reinforced polymer (GFRP). When used for adhesives and coatings with a silica addition the dimensional stability and the tendency to creep can be improved. When working with EP resin protective gloves need to be worn, but after the curing it causes no health problem. Also, in contrast to UP resin during the curing of EP resin there are no unpleasant odours. In general EP resin is used for high performance fibre reinforced polymer products, mostly for carbon fibre-reinforced polymer (GFRP). Furthermore, this type of resin has high strength and good chemical resistance, while its moisture absorption capacity and shrinkage rate are extremely low. Such material properties make EP an excellent material for heavy loaded component or hostile environmental conditions. EP also has good fire resistance properties. Even if it is not self-extinguishing material it is not really flammable. [B.01]


B.1.13


B.1.14

B.1.12 Polymer resin production
B.1.13 Epoxy resin
B.1.14 Unsaturated polyester resin

EP resin is usually transparent and is produced from non-cross linked EP and a hardener. The reaction is again exothermic as in UP resin, but for this material the mixing ratio need to be exact, which could increase the difficulty in a manual method of manufacturing. Usually cold curing takes 24h and then the components are let to cure further for a couple of hours at 100°C. When curing in higher temperatures the hardening could just last for some minutes. Then also EP's heating resistance performance is improved. [B.01]

Vinyl ester resin (VE)

Vinyl ester resin is mainly used for special applications in the chemical industry. It is obtained after a chemical reaction of EP and is processed the same way as UP. VE is stronger and have better wetting characteristics for an FRP than UP, but is more costly. The mechanical properties are superior of a UP resin, but lower than EP resin. Nonetheless, VE resin is selected when high chemical and impact resistance is required, as well as better fatigue performance. [B.01]

Phenol formaldehyde resin (PH)

This polymer has a wide range of applications, apart from fibre-reinforced polymer application. Power sockets, fanade cladding and door linings are also manufactured by PH resin. When first came out in 1905, it was called Bakelite and from then since now PH has an important role on the plastic industry, due to its very good mechanical properties and low production price comparing to other thermoset resins. PF polymers are naturally opaque with a yellowish brown colour and suitable for dark-coloured products. When exposed to light, PH polymer gets even darker. Moreover, during curing water is produced as a by-product that has to be drained away. Finally, this material is appropriate for applications when high service temperature and better reaction to

B.1.15

B.1.16

B.1.17

B.1.15 Vinyl ester resin
B.1.16 Phenol formaldehyde resin
B.1.17 Thermoset bio-resin
B.1.18 Resin comparative table

fire is required. During a fire incident, PH resin produces smoke and toxic fumes. [B.01]

Thermoset bioresins

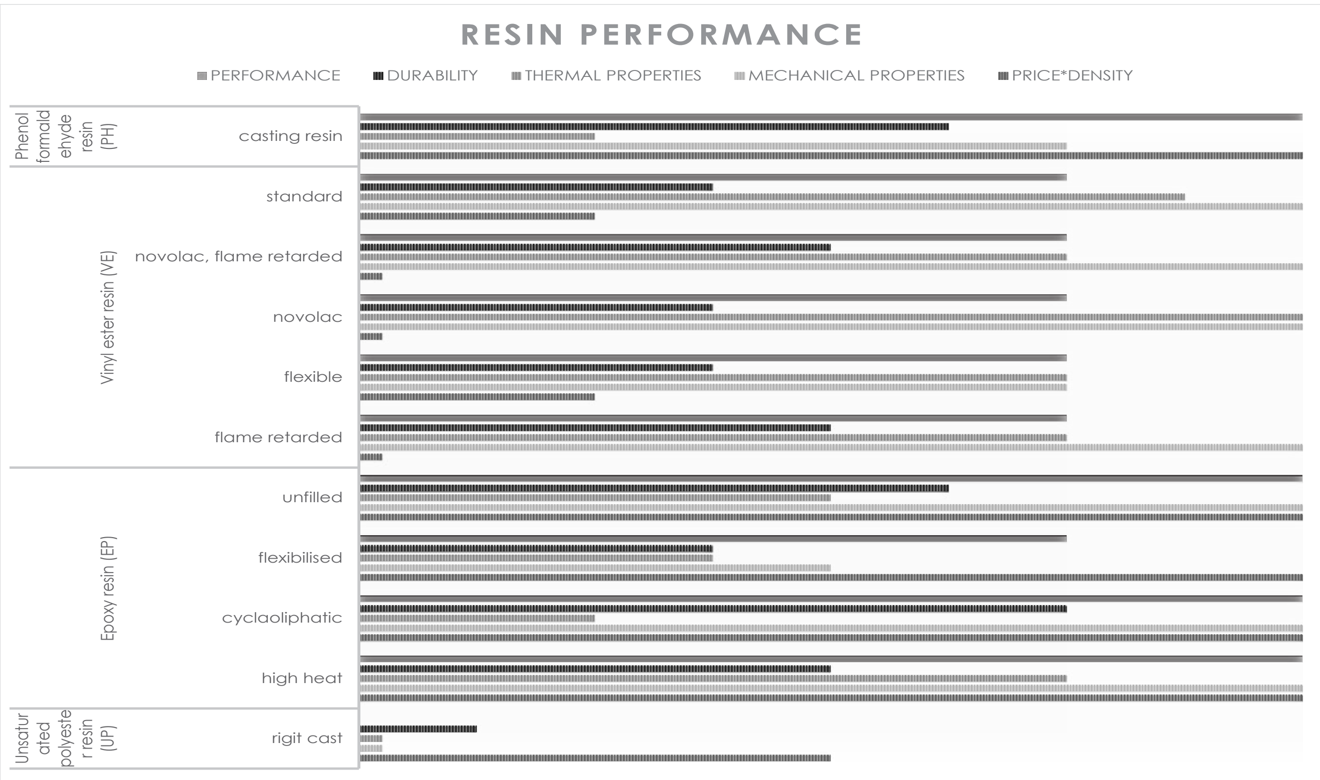
Compared to conventional thermosets, bioresins are less stiff and absorb less moisture. Fatty acids from vegetable oils can be converted into bioresins through a chemical reaction, but the substances used for curing are mostly non-bio-based. The maximum permissible temperature for these type of resigns are 180°C. [B.01] Since the bioresins are still undergoing development so it will not be considered further for the final thesis.

B.1.6 Resin Comparison

Up to this point of the research, general characteristics of resins that are frequently used for FRP applications were described. In this stage, the aforementioned resins will be compared further in order to comprehend the relative qualities of each type. Criteria for these comparison are formed based on the technical requirements of the project, hence cost-efficency, thermal properties, durability performance and mechanical properties consist the assessment criteria. It needs to be noted also that all the data was retrieved form CES EduPack 2016, a scientific material data based provided to us by TU Delft.

More specifically, cost-efficiency was based on the price*density value, since this is a more accurate indicator than only price value.

Furthermore, concerning resin's thermal performance, the maximum service temperature was taken into account as a first indicator of the material's structural performance in a case of fire incident. Also, the thermal expansion co-efficiency was taken into consideration for further joining detailing tolerances.



B.1.18

Moreover, the durability performance was based on the qualitative material performance as a material exposed to weather conditions, meaning resistance against alkalis and acids substances, as salt for the snow, is important, as well as UV radiation and flammability. Especially, in case of a fire incident, the structure not only need to withstand the high temperatures, thus the softening phase of the material should not set in jeopardy its structural integrity. Additionally to that, in case of fire, a safe use of those bridges must be guaranteed, as exit route, where no smoke and toxic fumes are emitted on the atmosphere, causing suffocation and possible death to the users. Also, water absorption at 24hrs is also taken into account, as an indicator of materials durability against degradation due to water ingress or osmosis.

For the resin's mechanical properties, the young modulus is an indicator of rigidity, the shear modulus and tensile strength is used as an indicator for their bond and coherent mechanical performance with the reinforcement fibres and last the compressive modulus and strength were used in order to evaluate the load bearing capacity of the resin in a composite element. Since the resin mainly functions as the material to withstand compressive stresses, the compression strength has a factor of two (2) on the evaluation procedure. Finally, the bioresins where eliminated from the assessment process as type of polymer not structurally credible for load bearing public structures, since their long-term structural capacity is not yet verified.

Focusing on the outcome of the comparison table (Appendix 1) it is seen that epoxy resin (EP) and phenol formaldehyde resin (PH) perform best in general terms followed by the vinyl ester resin (VE). Worst general performance demonstrates the unsaturated polyester resin (UP). All the resins illustrate an excellent performance on water -fresh or salty- resistance. More analytically, vinyl ester resin (VE) shows good mechanical performance, high service temperature and excellent alkalis and acids resistance. Also, its fair UV radiation performance is satisfactory for the Netherlands standards, but VE's high water absorption rate and high cost turn it as a inadequate choice as project's resin.

Concluding, more economic but satisfactory strong resins as the epoxy resin (EP) and the phenol formaldehyde resin (PF) would be more fitting options. It needs to be highlighted that even if those two types of resins are suitable options for the series of footbridges, their scattered properties on alkalis and acid resistance need to be taken into account for the final material selection and design.

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B.2 Fibre

Fibres is the main reinforcement of FRP applications and a highly anisotropic material, since its cross- section is a lot smaller than its length. [B.01] Fibres are more effective when used in long continuous lengths than in short discontinuous lengths[B.03] Also, elongation is more important mechanical property than elastic modulus when comes to design a fibre reinforced polymer. The tensile strength of soft fibres cannot be fully exploited because the resin will crack before this value is reached. [B.01] On the other hand elongation can be an indicator of homogeneous material expansion inside the material avoiding micro cracks inside the material. [W.01]

Moreover, fibres are the principal tensile-carrying component in a fibre-reinforced composite material. The effectiveness of a fibre-reinforcement depends on the type, length, volume fraction, and orientation of fibres in a matrix. In an uni-axial tensile loading, fibres are most effective when the fibre orientation angle is 0°, i.e. when they are oriented parallel to the loading direction. However, in pure shear loading, the fibres are most effective when they are oriented at ±45° angles with respect to loading axis. [B.03]

Proper selection of these fibres parameters is very important, since they influence one or more of the following characteristics of a fibre reinforced composite: its density and tensile/compression strength and modulus, its impact loads and fracture resistance as well as fatigue performance and finally its electrical/thermal properties and cost. Different type of fibres is also used according to the manufacturing process of the final FRP product. Continuous fibres are used in filament wound and pultruded laminated structure in which the fibre orientation can be precisely controlled. Discontinuous fibres are either directly mixed with the matrix, for example in injection-moulded structures, or combined with a binder to form a planar mat. In these

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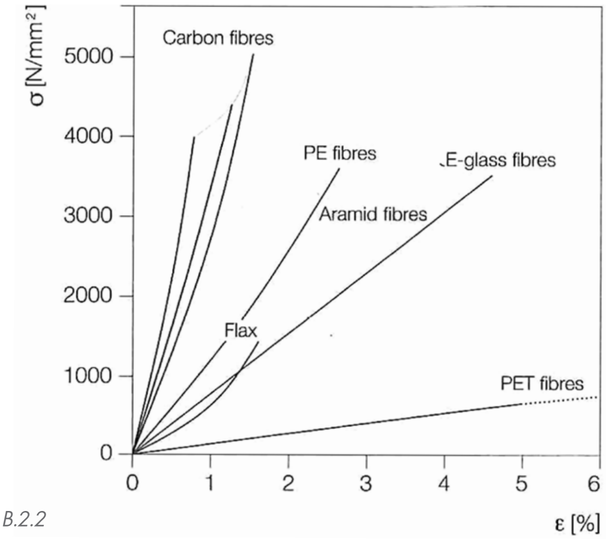

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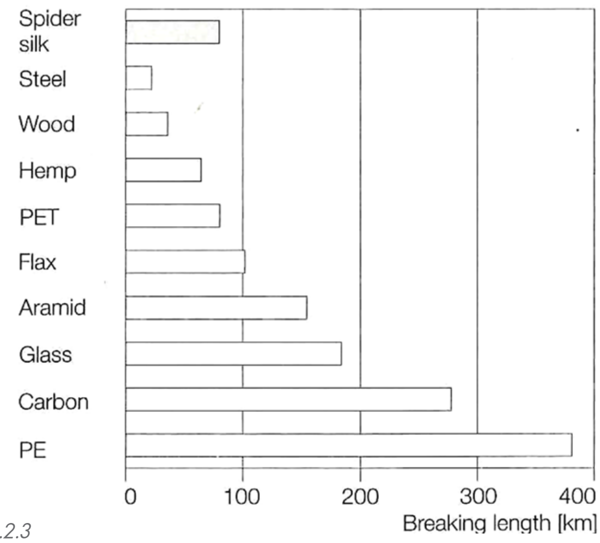


B.2.3

B.2.1 FRP fibres manufacturing
B.2.2 Stress to stain chart of different fibres
B.2.3 Breaking length of different materials

cases, there is very little control over the fibre orientation. [B.03]

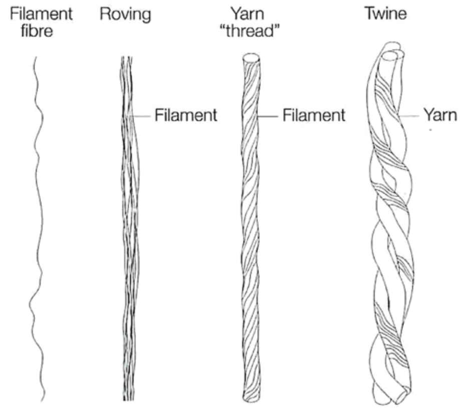
B.2.1 Weave types

The majority of fibres consist of bundles of tiny fibres only seen under the microscope. Their diameters vary between 5 to 500 μm with the polymer fibre having the smallest diameter (5-24μm) and the natural fibre the biggest. The individual fibres or otherwise filaments will be processed further and create the roving, meaning a bundle of parallel filaments or the yarn, a twisted bundle of fibres. Roving is used as direct reinforcement in FRP and yarn is used to create textiles used as reinforcement. [B.01] Textiles are commonly used as reinforcement for FRP. Textiles are preferred for their better workability in manual manufacturing processes of FRP. Their fibres have already the right orientation given by the weave. It is also possible to mix different types of fibres. The most commonly used textiles in FRP is woven, non-crimp, braids, chopped strands and fleeces as reinforcement and peel-ply and knitted for repairing and joining. The less strong the interwoven of the textile is the better bonding will be achieved with the resin and the better structural performance the composite will have. So, non-crimp fabrics and chopped perform better that the rest and that's why they are increasingly used as fibre-reinforcement. [B.01]

Woven fabrics

Woven fabrics are produced by a system of threads crossing in right angles. The warp threads run parallel to the longitudinal direction of the fabric while the weft threads are interwoven perpendicular to these. According to material loading, different strains appears in the wrap and weft directions, depending on the type of the weave sequence. [B.01]

The mechanical properties of the fabric depend on the weave. In plain weave the



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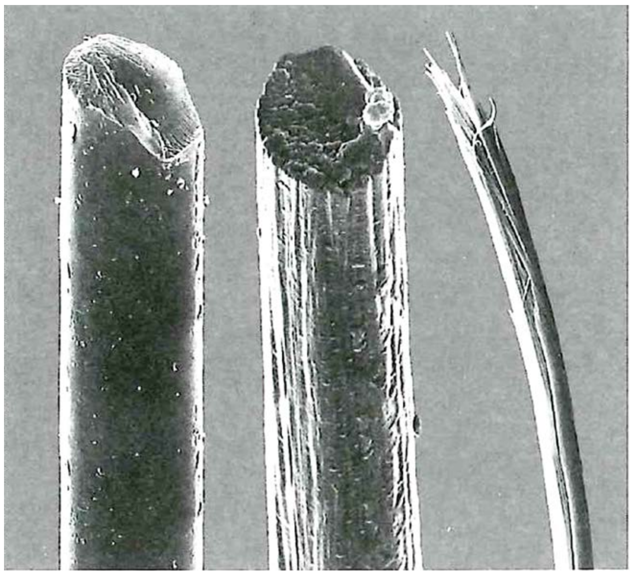

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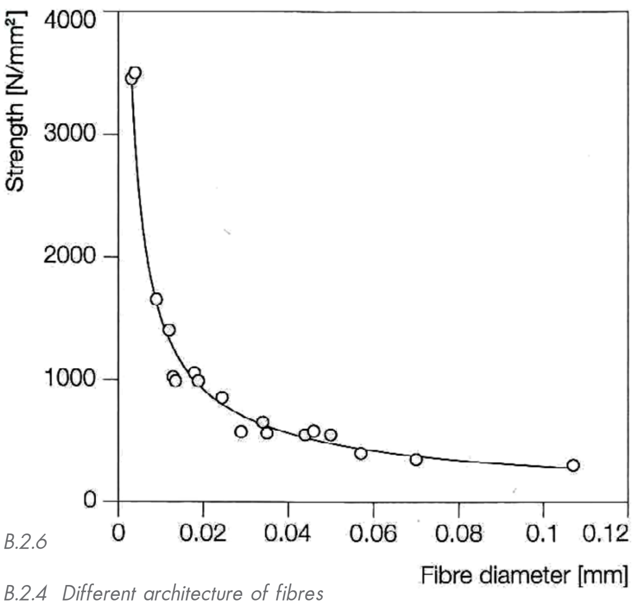


B.2.6

B.2.4 Different architecture of fibres
B.2.5 Different fibre sizes
B.2.6 Stength to fibre diameter graph

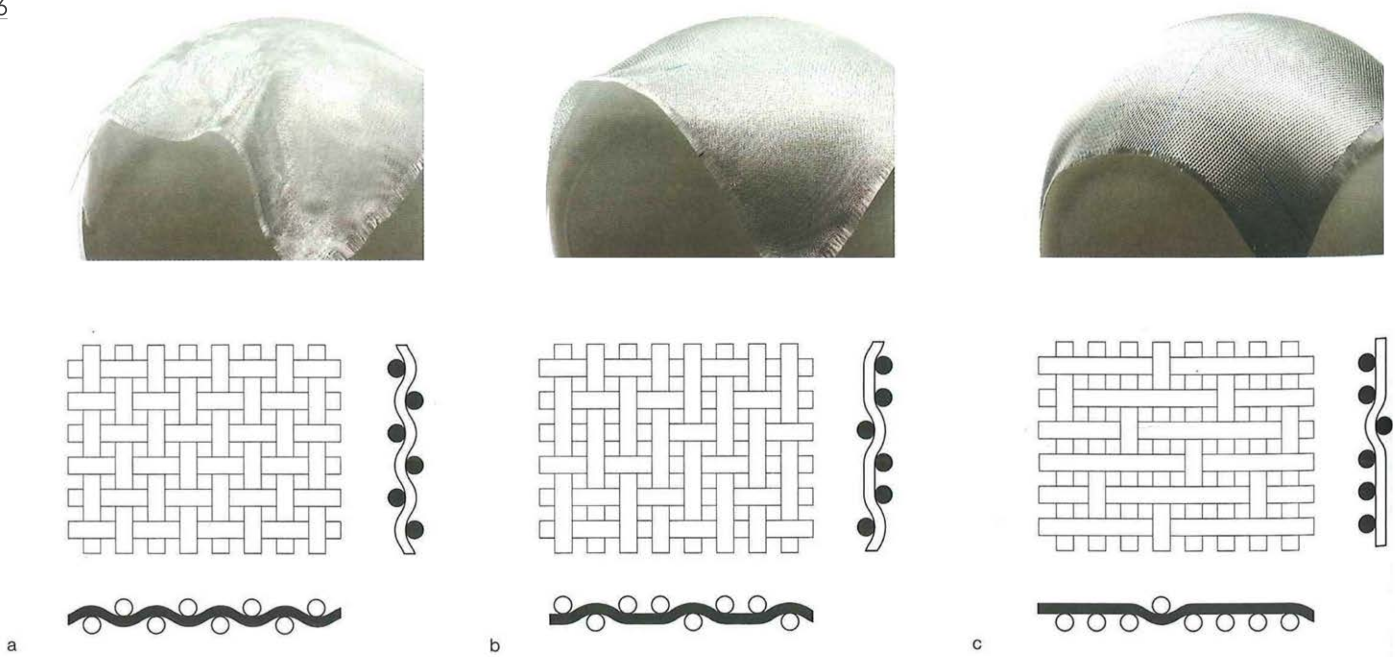
warp threads lie alternately above and below the weft threads, providing this type of textile with good dimensional stability even after cut in smaller pieces. This is the simplest and tightest type of fabric. Hopsack weave is a specific form of plain weave in which two of three parallel warp and weft threads are woven together. Also, till weave is the result of an unequal sequence in which the weft thread passes once above and then at least twice below the warp thread. By shifting the change by one step per course a diagonal rib is produced. Through this weave, a textile stronger and stiffer than the plain weave is created, since the strain in the warp direction is lower. Also, the drapability of the textile is better than in the previous weave. Finally, there is the satin weave, where the weft threads initially pass beneath a warp thread and subsequently above more than two warp threads, with a change shift of two steps after each course. This weave produces excellent drapability and is used as reinforcement in producing smooth surfaces in tight radii in FRP. [B.01]

Non-crimp fabrics

Non-crimp fabric is similar to the woven fabric but produces fibre composites with higher mechanical strength than the woven textiles. In this type of textile the layers of different threads are not interwoven to each other but laid on top of each other. In such a way the orientation of the fibres per layer is not limited to perpendicular, but can expand to whichever angle and amount of layers are necessary according to the load case. This type of reinforcement is widely used in textile-reinforced concrete. [B.01]

Braids

Braids are usually used for impact resistance requirements. Their criss-crossing result in



B.2.7 Drapeablllty of woven fabrics:
a Plain weave
b Twill weave
c Satin weave
Various textiles (undulations of threads in warp and weft directions omitted for clarity):
a Plain weave
b Twill weave
c Satin weave

a higher friction force upon fracture and in this way the product improves its impact resistance. The angle between the fibres can be adjusted according the impact load. This type of textile is commonly used for pipes. [B.01]

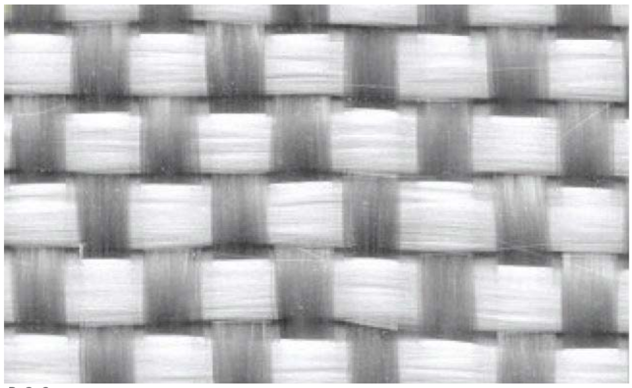
Chopped strand mats and fleeces
Chopper strand mats are made from random arrangement of pieces of fabric that are bonded together. Since there is no dominate fibre direction the reinforcement is considered to be the same through all the angles. Once the mat contacts the resin it becomes more flexible and can form better curves. The load-bearing capacity of these fabric is low. The fine mats are also called fleeces are used as the outer ply in a composite in order to produce a smooth finishing surface. Fleece can be used also as a core for sandwich composites. [B.01]

Knitted fabrics
Knitted fabrics are produced by forming loops and stitches from threads that has good drapability, like in hand knitting. Their use in FRP in limited but they are used as backing material for other reinforcing fibres or for repairing them. [B.01]

Peel-ply fabrics
Peel-ply fabrics are not used as reinforcement for polymers, but as intermediate stage for post laminating two different FRP components. Peel-ply fabrics are attached to the fibre reinforced polymer as the final ply but removed again before the polymer fully cures. As a result the surface is rough and thus better bond can be achieved between the new ply and the existing almost cured polymer. [B.01]

B.2.2 Types of fibres

Fibres have much higher strength than their raw material, which is gained due to their processing[B.01]. In order for the fibres to be used as polymer reinforcements they are wetted with a special coating, which is called size



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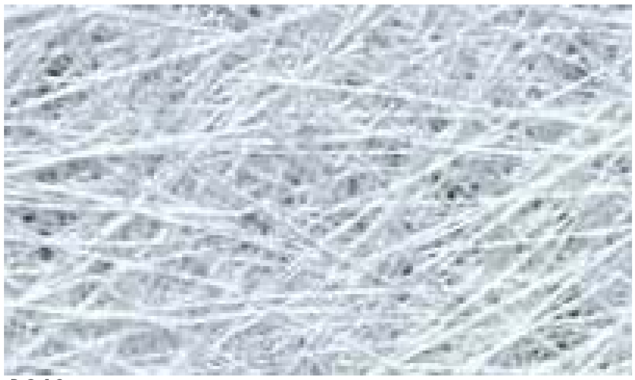


B.2.10

B.2.11

B.2.8 Plain woven fabric
B.2.9 Non-crimp fabric
B.2.10 Chopped strand fabric
B.2.11 Braid wave

or finish, immediately after production. These substances reduce the danger of buckling and improve the adhesion between the surface of the fibre and the polymer matrix. [B.01] Different types of fibres can be found on the market with different mechanical properties, size and durability. For structural applications mostly inorganic polymer and metal fibres are used with tested performances over time. There are also natural fibres that are mostly used for bio-based FRP and particularly vegetable fibres. Those fibres have promising mechanical and recycling properties but they are not yet credible as main load-bearing material in structural applications. [B.01]

B.2.2.1 Inorganic fibres

Inorganic fibres are all the synthetic fibres based on carbon and carbon compounds. Inorganic fibre are much stiffer and have higher service temperatures than organic ones and they are not subjected to creep. Metal fibres are also inorganic, but they are considered as a different fibre group. [B.01]

Glass-fibres

Glass fibres are made from glass of different types: E-glass (electric), AR-glass (alkaline resistant), C-glass (corrosion), R-glass (resistance) and S-glass (strength). In contrast to other common fibre, glass fibre have a uniform and almost circular cross section and their load-bearing behaviour is linear-elastic up to brittle failure. Even if they are fibres, their amorphous structure makes them isotropic, which means that the tensile and compression strength of the glass fibres is the same in longitudinal and transverse direction. They may tend to buckle easily but they are very flexible due to their small diameter. Since they are sensitive to notches they are given extra size by coatings during production. Glass fibres have also very good fire resistance with steady mechanical properties even in temperatures of 250°C. Glass fibres are generally transparent with a greenish tinge that is noticeable as the thickness rises and combined with a transparent resin a translucent result can be achieved. On the other hand, glass fibres can be subjected to little creep and even if they absorb a bit of moisture, they tend to corrode. Therefore an extra coating is needed to enhance the weather resistance of the glass fibres. [B.01]

Carbon fibres

Carbon fibres have much higher elastic modulus than the rest of the fibres and their mechanical properties are not the same per different form. There are three different forms: The standard modulus fibres with high tensile strength (HT), the high modulus fibres with high material stiffness (HM) and the intermediate modulus fibres with moderate tensile strength and material stiffness (IM). All of those types are anisotropic material with good dynamic properties low self-weight and creep and very high corrosion resistance. Products made out of carbon fibres are opaque due to the black colour of the carbon. The fibres are sensitive on buckling and their surface needs to be protected by epoxy resin coating. Also, their thermal expansion is negative along their length, which means that they get shorter as the heat rises. Finally, this material despite its advantages is used more often in the aerospace industry and rarely on the building industry due to its high price. [B.01]

Basalt fibres

Basalt fibre is a comparatively newcomer fibre for fibre-reinforced polymers. Its chemical composition is similar to glass fibres but its mechanical strength is higher than the glass fibres. It has better oxidation resistance, radiation resistance, compression and shear strength than carbon fibres and its price is in the range of the one of glass fibres. Also, basalt fibres have high resistance to alkaline acidic and salt attack, which makes them ideal for concrete and bridge structures. [W.03]

B.2.2.2 Polymer fibres

Polymer fibres are lighter and tougher than inorganic fibres with lower elastic modulus and high strength. Polymer fibres are made from synthetic materials and thus they are extensible and combustible, but tend to creep. Also, in order to make this type of fibres weather-resistant an extra protective coat is required. [B.01]

Aramid fibres

Aramid fibre has a diameter of 12 μm and is produced by aromatic polyamides. As a material it is very lightweight and extremely anisotropic, which makes it ideal for ropes. It tends to absorb moisture and has low heat and UV light resistance. Also, aramid fibre-reinforced polymers (AFRP) are difficult to machine because they are tough and cause high tool wear. On the other hand, they absorb impact energy on their failure behaviour as a cushion and thus are used mostly in products like safety helmets than in building industry. [B.01]

Polyethylene fibres (PE fibres)

Polyethylene fibres (PE) have a very load self-weight and can even float in the water. They are extremely anisotropic material with negative thermal expansion the longitudinal direction and thus ideal for tensile applications like ropes. Their impact capacity is similar to the ones of aramid fibres and they also have adhesion difficulties with the resin that can be solved with special coating. [B.01]

B.2.2.3 Metal fibres

Metal fibres are use in the build industry but as reinforcement to concrete. Because of their sensitivity to corrosion and their bad bond with the polymer resin due to its relatively large diameter and smooth surface, this type of fibre is not appropriate for FRP. Aluminium fibres are only used on aircrafts because of the electrical screening requirements. [B.01]

B.2.12

B.2.13

B.2.14

B.2.15

B.2.12 Glass fibres
B.2.13 Metal fibres
B.2.14 Natural fibres
B.2.15 Aramid fibres

B.2.2.4 Natural fibres

Natural fibres are categorized under mineral fibres (e.g. asbestos), animal fibres (e.g. silk) and vegetable fibres (e.g. flax). Only vegetable fibres are used in the building industry and asbestos that was used in the past is banned from EU on the ground of carcinogenic risks. Natural fibres can produce extremely lightweight components due to fibres low self-weight and weather resistance. This resistance is not a permanent property of the natural fibres and they can also decompose due to microbes. Also, they tend to function as winks during fire, so they must be protected with a suitable flame retardant. On the other hand they can be recycled and require less energy and less tool wear and protective equipment (mask, gloves, suit) comparing to similar products like fibre glass during production. As a result FRP products made out of natural fibres are more economical than others made out of ordinary fibres. Natural fibres have rough and uneven surface, which results in a good bond with the resin. Also, natural fibres have specific length, in contrast to synthetic and thus can be produced in fleece or matting. Finally, a loss in strength is evident when 180°C is reached and it disintegrates at 200-250°C. [B.01]

Since natural fibre tend to absorb moisture and their mechanical properties are scattered[B.01] they cannot be considered as load-bearing component materials for the present so they will not be considered further for the material selection of this project.

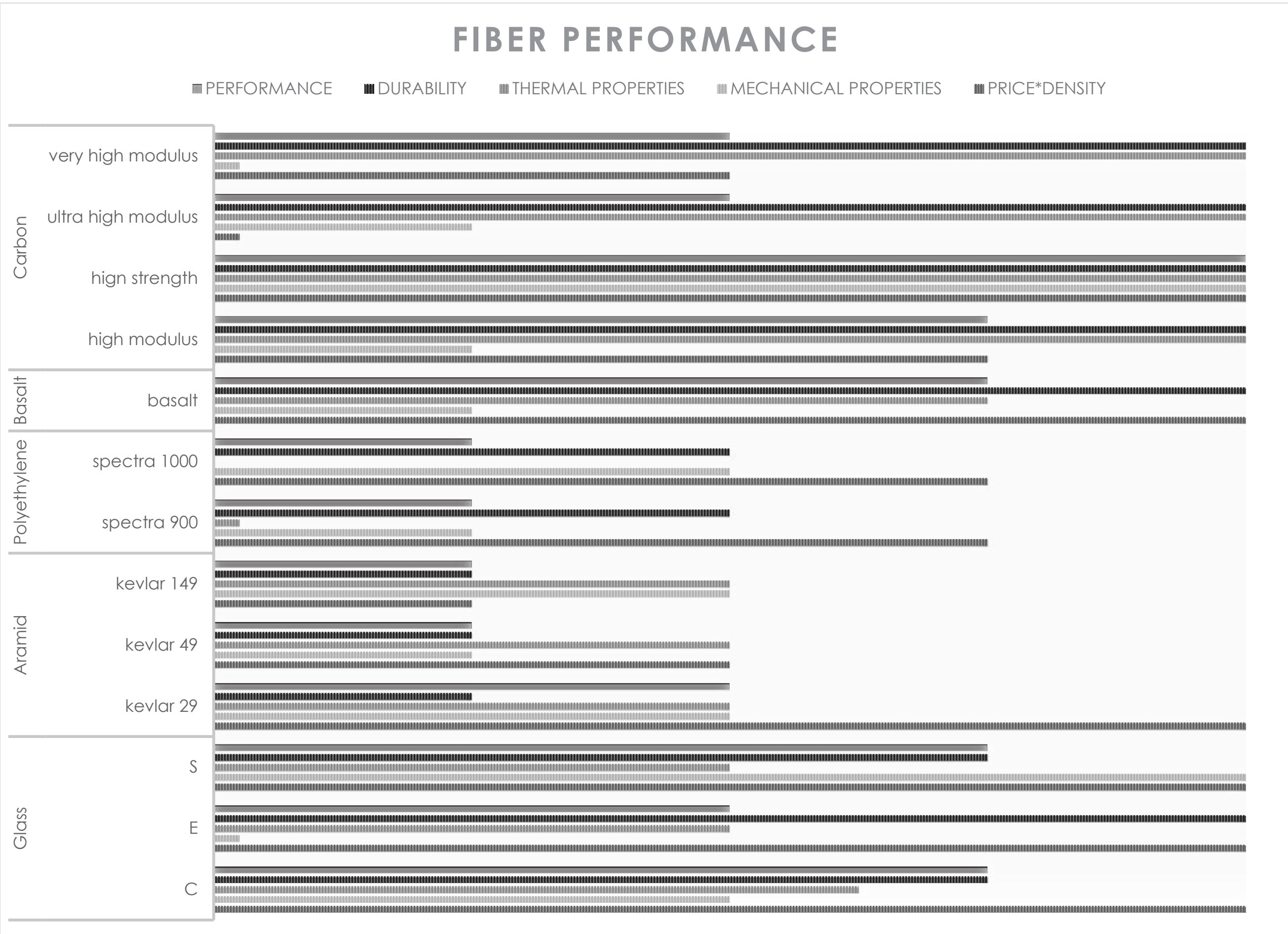
B.2.3 Fibre comparison

Fibre's performance in a composite material is influenced from the polymers performance as well. As mentioned before, the fibres are impregnated on the polymer matrix and thus their tensile strength is minimized by the tension capacity of the polymer, otherwise micro cracks appear. Also, the mechanical performance of the fibres and their chemical bond with the polymer is influenced be the weave architecture of the fibres as well. As seen in the previous chapter free fibres carry load in a different way than textiles. In that sense, comparison of the fibre types based on their production material shows only parts of their general performance as reinforcement in a FRP component. None the less, even this knowledge is useful for the designer, in order to have a more spherical opinion for the material selection for its design in specific areas. All the data were retrieved from CES EduPack 2016, a scientific material data base provided to us by TU Delft. Metal fibres and natural fibres were eliminated from the table, thus they were considered as not appropriate for a load bearing structure of FRP. Metal fibres are sensitive to corrosion and natural fibres are not yet credible enough as a load bearing material in an infrastructure.

The criteria for the fibres general performance were their mechanical properties meaning the tensile strength and elongation capability. Elongation is even more important for fibres, so a factor of 2 is added to the evaluation process. Also their thermal properties focusing on the maximum service temperature in order to understand their capability as material with fire resistance. Also, their durability is graded qualitatively from CES, but was turned into quantitative data in order to get the general performance ranking. In a composite material fibres don't come in direct exposure to the weather conditions, but is important for the designer to choose a material that can be used with the appropriate polymer and thus the durability properties of the fibres are taken into consideration as reflection of the polymers. Most of the failure patterns of a composite as will be explained in a later chapter is cause due to the different behaviour and insufficient bond of polymer matrix and fibre-reinforcement.

What can be seen from the comparison table is that the performances of the sub categories of the glass, polyethylene and carbon vary. In general glass and carbon fibres have the best general performances. Glass shows excellent price*density performances and high general resistance. Its resistance on alkalis and acids is almost excellent, as well as their water adsorption. Also, the material is non-flammable, a feature extremely useful for a public infrastructure as a footbridge. This can compensate the comparatively low service temperatures (310-444 °C). Aramid and polyethylene fibres have good mechanical and economic performance, but they are inappropriate materials for an outdoor application. More specifically, they show lower water resistance than the rest of the materials, their alkalis and acid performance is poor and most important they are high-flammable as materials, so in case of fire their mechanical strength will be reduced almost instantly. Finally, basalt performs well in all the criteria mentioned before, but there is insufficient data from its general durability performance. So, even if it appears as a promising option the material data for that fibre is insufficient.

Concluding, from the comparison table of fibres material the optimum option is glass and carbon fibres. Due to high price of carbon fibres though this selection will be eliminated from the selection and hence the glass fibres would be the optimum option.



B.2.16 Fibre comparison table

B.3 Core

Core materials are lightweight materials that are used as the middle part of a sandwich composite component. Their strength is lower than the one of the load-bearing plies, but they are responsible in keeping the upper and lower surfaced together and transfer the shear strength throughout the components. [B.01]

B.3.1 Types of Core

B.3.1.1 Polymer foam core

Sandwich elements made from polymer foams generally have the best mechanical properties compared to the other core options and are preferred very often by Architects for their design when the polymer does not need to be translucent. [B.01]

There are different types of polymer foam cores. The flexible, the tough and the brittle one. All of them can be used as insulating material, but only the tough foam can be considered as cores of load-bearing sandwich. [B.01]

Polystyrene foams (EPS, XPS)

Polystyrene foams may be in tough form, but have a comparatively low load-carrying capacity. Expanded polyester (EPS) has white colour and is used as an insulation material, where water must not contact it. Extruded polyester foam (XPS) on the other hand has a finer molecular structure and is thus heavier than EPS but can be used as a load bearing, waterproof material. The colour varies depending on the manufacturer (pink, blue, green). Both of those materials have considerable mechanical and geometrical benefits when used as core for sandwich FRP. Comparing their load bearing capacity to other options is low, but their low price make them and considerable core option. [B.01]

Polyurethane foams (PUR)

Polyurethane has a big variety of products of different rigidity. One of them is a tough rigid foam, used as core material, with excellent load bearing capacity and good adhesion properties between the facing plies, without the need of any other extra material. Also, PUR is appropriate for CNC milling processing, which turns PUR into a good option for free form shaped structural sandwich FRP elements. Due to the latter property and the economic price it is widely used as material for mould making. [B.01]

Polyvinyl chloride foams (PVC)

PVC foams comes in products of different rigidity. The tough version has better mechanical properties from the other polymer foam options. This material is ideal option for core material, since almost no resin is absorbed from the foams surface. Its high production cost makes it proper only for high load bearing structures. [B.01]

Polymethyl methacrylamide foams (PMI)

Polymethyl methacrylamide foams can be found in different strength and stiffness properties. Rohacell is a type of PMI ideal for structural use. Also, due to their good dimensional stability they are compatible with prepregs curing, but their high price makes them only proper for aerospace applications. [W.01]

B.3.1.2 Honeycomb cores

Hollow structures with honeycomb cores are usually more economic from the foam cores but they are harder to work with. [B.01] Its angle of folding its limited to gently curved sandwich panels. Aluminium, aramid paper impregnated with phenolic resin, thermoplastics like polyethylene (PP) or polypropylene (PET) or even fibre-reinforced polymers are the common material for creating a honeycomb core. Its thickness is usually 1.5 and 90mm. In a sandwich panel the facing plies are bonded or laminated to the core and sometimes to simplify this procedure and extra layer of fleece is used. [B.01]

Sandwich components made out of honeycomb core are particularly light weight and large strength can be achieved. This type of core combined with transparent plies can create a translucent component. [B.01]

Aramid honeycomb core

The aramid honeycombs are produced as sheets of 1.20x2.40m and with thickness 1.5mm. This type of honeycomb core is more flexible and thus very popular in boats and light aircraft manufacturing. The facing plies are directly placed on the hexagonal shaped surface of the core. The resin is bonding the plies with the core and so extra resin must be estimated for the manufacturing of sandwich components with aramid honeycomb core. [B.01]

Thermoplastic capillary honeycomb cores

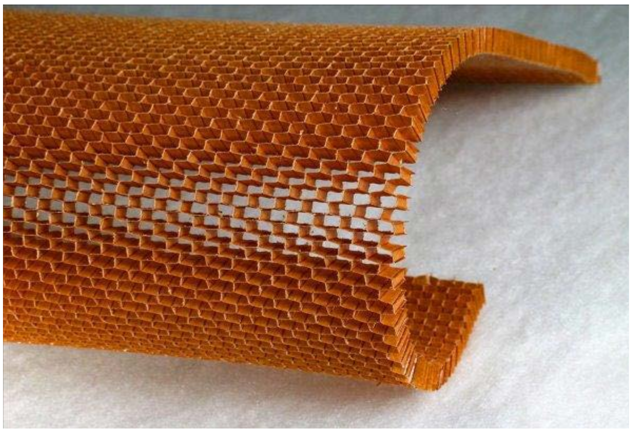
Honeycomb made out of thermoplastics like polyethylene (PP) or polypropylene (PET) have a circular cross-section and are suitable for impact-resistance and absorbing shocks or reducing vibrations. When bonding the core to the FRP plies a layer of fleece is first applied in order to improve the bond.[B.01]

B.3.1.3 Fleece and spacer fabrics core

Prefabricated cores and spacer fabrics can be used as core to thin sandwich panels. This type of sores bonds easily and very well to the plies and is also economic. There is a big variation though on the transparency and the mechanical properties of this type of sandwich panels. [B.01]


B.3.1


B.3.2


B.3.3


B.3.4

B.3.1 Balsa wood FRP core
B.3.2 Foam FRP core
B.3.3 Spacer fabric FRP core
B.3.4 Honeycomb FRP core

Spacer fabric

Spacer fabrics are made from two facing plies of fibre glass cloth linked by perpendicular threads. During lamination the spacer is pre-stressed and impregnated to resin. The result is a sandwich component of 3 to 23mm thickness improved of flexural stiffness. With this type of core there is no need for extra plies, since the outer surfaces of the core functions as a structural ply. In order to reduce the danger of styrene accumulation on the centre of the composite special resin formulation need to be used. Finally, due to the fact that this composite only used fibre glass and resin a good degree of transparency can be achieved. [B.01]

Fleece core

This type of core is produced from perforated fleece material made from polyester fibres and hollow micro spheres especially used for sandwich structures. The thickness of such components is about 6mm. This type of core delaminates less easily than a polymer foam core component. During the lamination phase the perforations are filled with the resin in order to create a steady and strong bond with the plies, but the existence of hollow micro-spheres reduces the overall weight of the component. [B.01]

Balsa wood

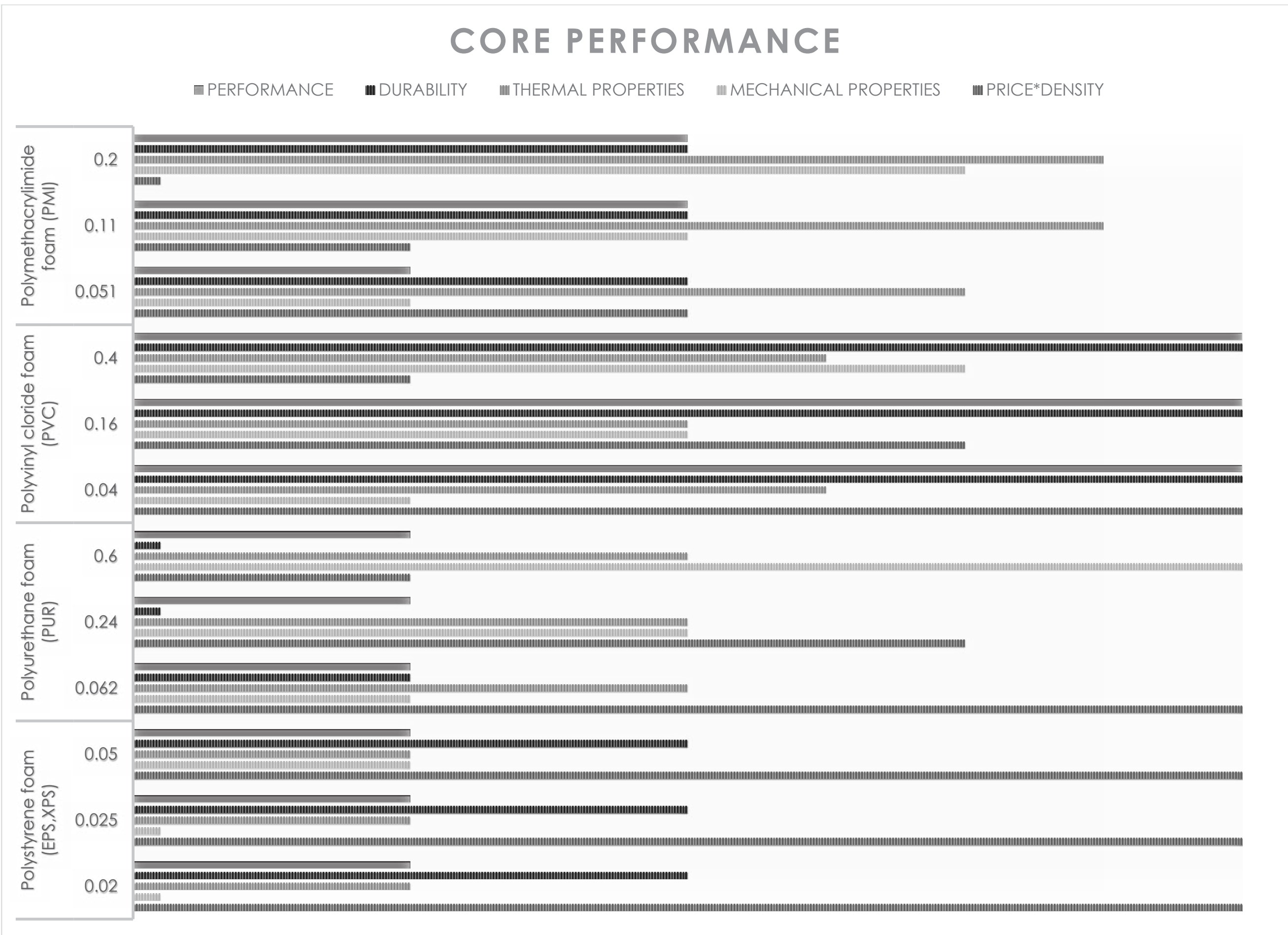
Due to its density (100-120 kg/m^3) balsa wood can be found in the middle of the rigid foam products, but its sensitivity to moisture influences the mechanical stability of the composite components. Its mechanical properties are lower than the ones of rigid foams, but still can be used for a certain load bearing structure. None the less balsa can still be used as sandwich core due to its low price. [B.01]

B.3.2 Core comparison

In the case of sandwich FRP the core is responsible for the increasing of the stiffness of the components by increasing the stress area (cross-section). It is also responsible for carrying the shear forces thought the composite element. There are different types of cores for creating a load bearing FRP component like polymer foam, honeycomb core or fleece and spacer cores. Balsa is eliminated already as a material option due to its low load-bearing capacity. Between the rest of the options only polymer foam core can be free shaped though a CNC machining and thus the further comparison between the core options will be done between different polymer foams variations. Again CES EduPack 2016 is used for the material data. Since there were a lot of options per different types of polymer foam, only three (3) types where indicated as representative properties for a bigger range of materials. The selection was based on the specific gravity of each option, which is based on the density of the material compared to water's density. So, the version with the lower, the maximum and the average specific gravity are used.

Important aspects for the comparison is again the price*density value, the mechanical performance with more focus on the shear strength, where a factor of 2 has given. Also, the thermal properties and the durability of the cores are important as in the fibre selection. It is not expected for the core to be subjected to weather conditions directly, but it should reflect the polymers durability. Also, by choosing a durable core material the whole structure is protected in case of failure. As an example the fire resistance is mentioned, because material failure also needs to be taken into account.

As can be seen on the comparison chart below, there is a big deviation on polymer's general performance. Polyvinyl chloride foam (PVC) shows the best general performance of all. It performs really well on water absorption, UV radiation, acid and alkali resistance and is self-extinguished. There is of course a variation in price due to different density, but in general it is affordable. On the other hand, polystyrene foams (EPX, XPS) is the most economic option, but its durability performance is not so good. Especially its high flammability is a big disadvantage. If this could be taken care with extra material or additives it could still be an option. Polyurethane foam (PUR) has the highest service temperatures from all, but it is as well high-flammable and so droughts are created for if it is proper for a pedestrian bridge design. Finally, polymethacrylimide foam (PMI) fails all the criteria, since it is one of the most expensive options.



B.3.5 Core comparison table

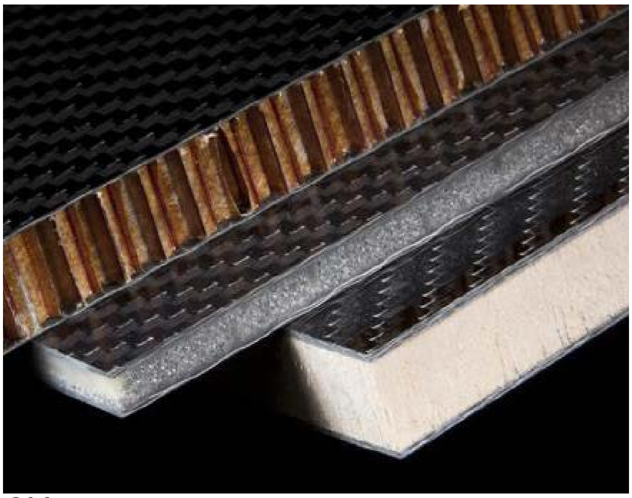
Fibre Reinforced Polymer

C.1 FRP material properties

Fibre-reinforced polymer (FRP) is an important type of composite for the Architecture and Building environment, since it has the benefits of plastics, meaning that is lightweight, strong, durable, but also can produce large-format components and cover bigger spans. The optical and mechanical properties of FRP are determined by the interaction of its constitutes. In principle, the polymer stabilizes and protects the fibre while the fibres are responsible for the load-bearing capacity and stiffness of the composite. The strength of the composites components depends on the interaction of the fibres with the polymer matrix. The adhesion between the fibres and the polymer is crucial for FRP's load-bearing capacity. A matrix crack could lead to lamination fracture. Also, delamination could happen due to shear or lateral tension. [B.01]

The polymer matrix defines the shape of the final product and protects the fibres against impact, UV radiation and moisture. As mentioned before, special fillers and additives can be added and change the appearance and the mechanical properties of the polymer. Normally semi-finished products are not coated again after production, so the polymer determines the transparency, surface feeling and final appearance. Typically, thermosets are used as FRP polymers that have low viscosity prior to curing reaction and thus provide well wetted surfaces. Also, thermosets have better resistance to environmental influences than thermoplastics. [B.01]

Different types of fibres can be used according to the production technique of the final product and its mechanical demands. Generally, fibre can be categorized as long fibres, short fibres and then textiles. Long fibres can provide linear reinforcement with a high content of fibres and provide good mechanical properties, but for manual methods are hard



C.1.1

C.1.2

C.1.3

C.1.1 Sandwich FRP examples
C.1.2 Sheat FRP example
C.1.3 Sandwich FRP example

to be used. Short fibres are spread across the polymer in random directions. To improve handling the short fibres are usually formed as chopped strand mats. It is also possible to mix short fibre into the polymer matrix and create moulding compound for injection and compression manufacturing techniques. Also, fleeces is considered a very fine fibre mat made from short fibres that is used on the external surface of the laminates. The last fibre type are the textiles. Textiles are widely used in the FRP manufacturing. They are arranged in plies and create a planar reinforcing material. The mechanical properties of products produced by textiles are poorer than long fibre, but the first ones are easier to work with and thus more preferable. [B.01]

After producing the FRP component the unnecessary part of the semi-finished components must be cleaned from the extra material. This can be done manually with a saw, but a lot of dust is created and thus the workers need to wear gloves, mask and uniform. An alternative solution that produces no dust is water jet cutting. [W.04]

C.1.1 Loading pattern

C.1.1.1 Tension

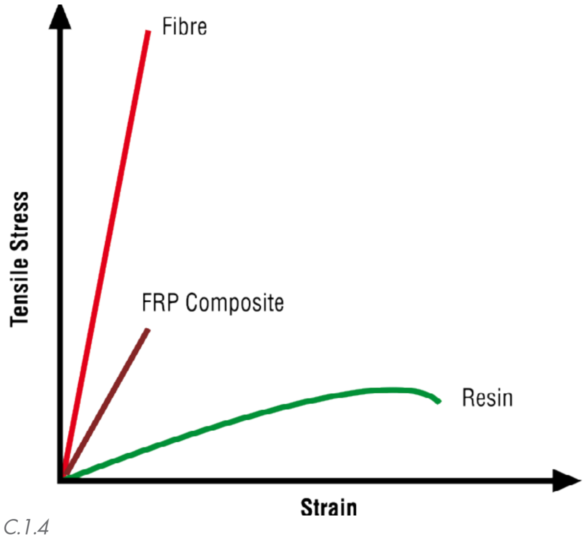
The response of the composite to tensile stresses is depended on the tensile strength and stiffness properties of the reinforced fibres. [W.01]

C.1.1.2 Compression

The resin will be responsible for the response of the composite to compression loads. Also the resin must keep the fibres in straight columns to prevent fibre buckling. [W.01]

C.1.1.3 Shear

During shear the layers of fibres try to slide to each other. In order for this to be prevented the resin matrix is responsible for the strength and stiffness of the composite in shear



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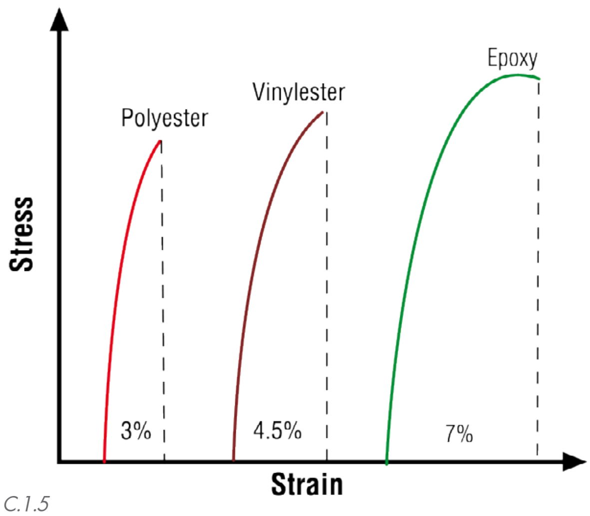

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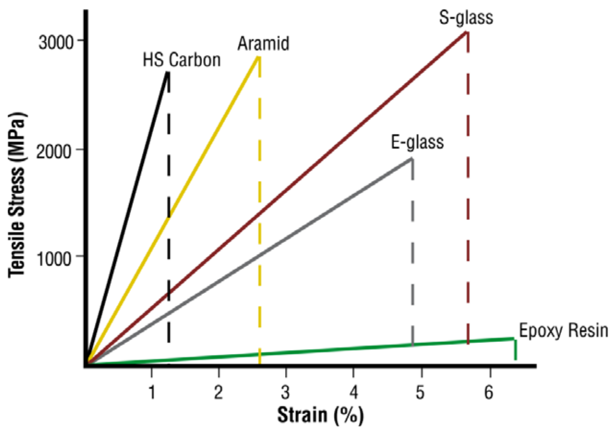


C.1.6

C.1.4 Tensile to stain diagram comparing fibre, resin and FRP composite
C.1.5 Stress to strain diagram comparing different polymer types
C.1.6 Tensile stress to strain comparing different fibre types

stresses. For the composite to perform well under shear loads the resin elements must not only exhibit good mechanical properties but also have good adhesion to the reinforcement fibres. [W.01]

C.1.1.4 Flexure

Flexural loads are caused from loads on both surfaces of the composite. During flexural loads the upper face is put into compression, the lowed into tension and the middle part into shear. [W.01]

C.1.1.5 Tensile strength vs. elongation

The strength of the laminate is considered as the amount of load that can be carried before the material fails. Tensile stresses are carried by the fibre of the composite element, but the service value is not only determined by the fibre. The resin also contribute to that value, since the shear stress must not exceed the resin's load capacity and traverse micro cracking appears. Instead of the strength, stain is a more accurate indicator of the materials internal mechanical behaviour. The elongation of the fibres must be taken care of the resin, otherwise micro cracks will appear on the material. These micro cracks will not lead to immediate failure of the structure, but in an environment with moist air and water, this part will absorb more water due to moisture than the un-cracked part. The self-weight will increase, the moisture will attack the resin and the fibres and eventually the stiffness of the structure will minimize and the failure possibility will grow. Increasing the resin fibre adhesion derives from the resin's chemistry and the fibre's chemical surface treatment. [W.01]

C.1.2 Stiffening methods

Because flat sheets can be too flexible extra stiffening is needed in the whole component, as a sandwich construction or in particular parts through ribs and its cross-section profile. Stiffening could also be achieved by its geometry, i.e. by forming shell. [B.01]

C.1.2.1 Profiling and ribs

This type of stiffening technique is mostly used for unreinforced polymers. For production reasons embedded materials, like metal, wood, or foam could be laminated on the finished FRP surface and strengthen the element. Alternatively, stiffening lamella or sections can be attached with adhesive, or by profiling the cross-section itself and create a rib. In the case of different material, use of different composite combination the restraint stresses and the different thermal behaviour must be taken into account. [B.01]

C.1.2.2 Edge strengthening

Unsupported edges are difficult in manufacturing and sensitive in deformations. For those reasons the use of a flange, also shaped in the mould permits the edge design and rib stiffeners in the edge deterring the deformation. The simplest way to stiffen an FRP sheet edge is by bending it 90° or wrapping a section of different material like timber, metal of foam around the edge of the FRP. This addition is better to take place during manufacturing, but it could be done afterwards as well. These material could be used instead of stiffening the edge also as supporting construction integration. [B.01]

Moreover, when direction of a member changes, change of lamination is needed as well. This can be achieved through a radius turn. This radius should be at least 5mm and not less than the thickness of the laminate for pultruded components and minimum of 20mm for manual laminated elements. [B.01]

C.1.2.3 Sandwich elements

Sandwich fibre reinforced polymer elements are frequently used, due to their small weight comparing to their load-bearing capacity. The low weight is due to the core -central zone of the component- that is usually less expensive and strong than the fibre reinforced polymer, but more flexible. Additional stiffness can be reached by adding FRP ribs inside the core zone. [B.01]

C.1.2.4 Integrating functions

Since fibre-reinforced polymer products can be processed in cold or room temperatures the integration of secondary functions in the main structural section is possible. Built-in light fitting, decorative features, thermal mass, sunshade control systems or even sensors to measure their mechanical performances like strain are some of the possible integrated functions in the initial production process. Even in a sandwich FRP element it is possible to incorporate electric cables or water pipes. This integration of functions in the main FRP component can be used as a stiffening method. In the case of need to access these ducts the accessibility need to be taken into account from the beginning of the design.

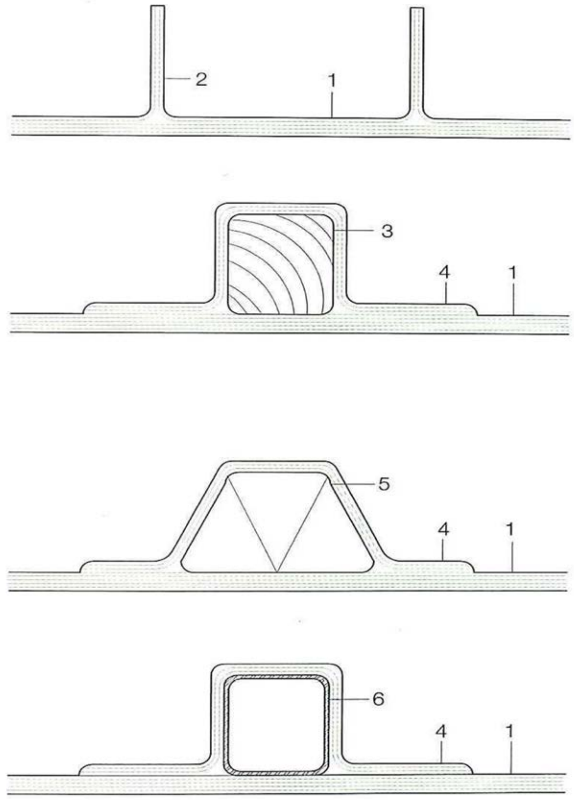
C.1.3 Connections

There is a big variety of joints for connecting fibre reinforced polymers (FRP) to each other and different materials. Some are visible like metal fitting and others almost invisible like laminated joints. It is possible to integrate lugs, splice plate, fittings or sockets into the material during the production. Such detailing improves load-bearing capacity of the joints, but create a thermal bridge. So, it is necessary for the designer to think about different parameters in order to design an appropriate detail for its FRP components.

C.1.3.1 Shadow-line joints

Shadow-line joint is a good type of connection in the case of big manufacturing tolerances, but inappropriate from climate point of view, because of thermal bridges. This problem is even more severe when the connecting sandwich components, because the thermal insulation is interrupted. This type of joint is ideal for connecting the FRP components with the ground, through installing an elastomeric strip in the join that also permits an even load transfer. Finally, this joint is accessible from the outside even after the construction is finished.

C.1.3.2 Laminated joints



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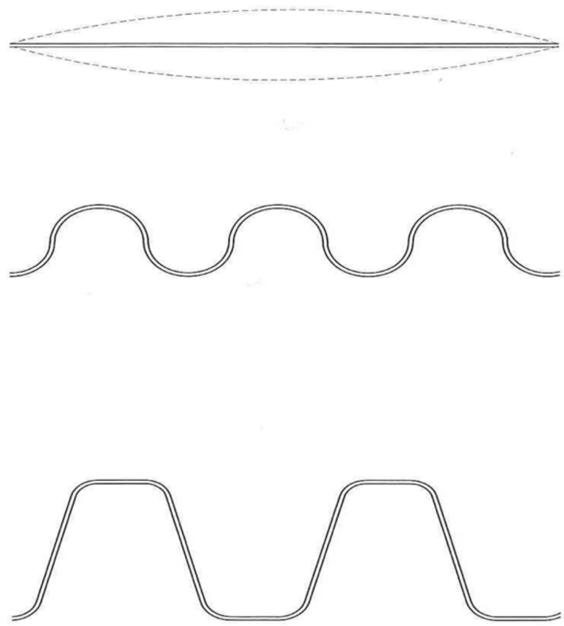


C.1.8

C.1.7 FRP stiffening via ribs and embedded materials examples
C.1.8 FRP stiffening via profiling examples

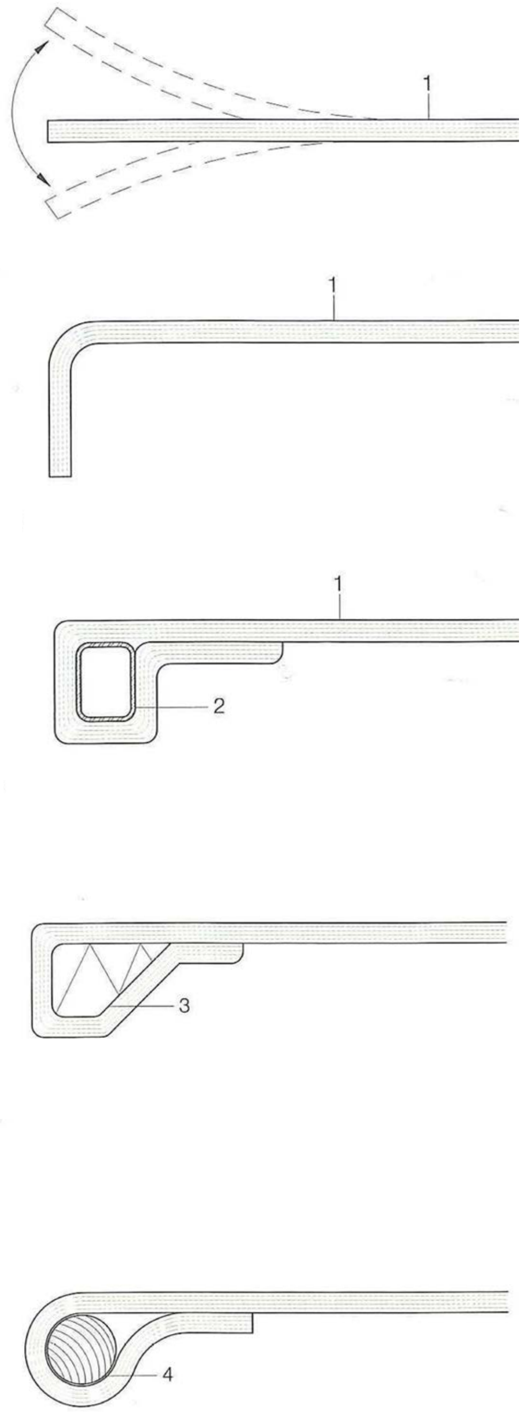
In order to join components through lamination the parts need to be butted together and then jointed by laminating plies across the joint. The additional fibres should be attached on both sides, so that even load transfer is ensured. A peel-ply fabric can be used as appropriate textile for the laminated joint. Otherwise, fibres could be left sticking out from the components and then used for the laminated joint. [B.01]
In the case of a sandwich construction the cores need to be connected through fit in system and after the lamination joint can take place. [B.01]

C.1.3.3 Built-in and bolted joints

Embedded steel, stainless steel or aluminium could be used as a concentrated load transfer joint. The metal lugs need to be thin enough, so that the lamination is not disrupted. If better coherence between the composite and the steel is needed a perforated sheet of steel can be used, where the long fibres can also be looped around the perforations. Moreover, screws and threaded sleeves can be integrated in the laminate as a built-in component. Lungs, plates and thin perforated steel metal have the best load transfer results.

In the case of a bolted connection, the position of the holes must be known beforehand. In order to prevent delamination the whole tension must be reduced [A.06] and the extra fibre plies must withstand the stress from the connection. By looping the fibres around the hole the necessary result is achieved. Also, by fitting a metal sleeve into the hole, the load carrying capacity of the joint will increase even more. In order to design the right hole reinforcement, the geometry and the direction of the force must also be known beforehand.[B.01]

Large build-in fittings are also possible to sandwich elements positioned inside the core. This joints result in a lower bearing capacity, lower thermal insulation value and is considered a hinge. In order for the material to compensate the stress concentration, extra lamination is needed around the joint. Otherwise, an internal



C.1.9

C.1.9 FRP edge stiffening examples
C.1.10 Shalowline joints examples
C.1.11 Laminated joints example
C.1.12 Bolted and build-in joints examples
C.1.13 Glued joints examples

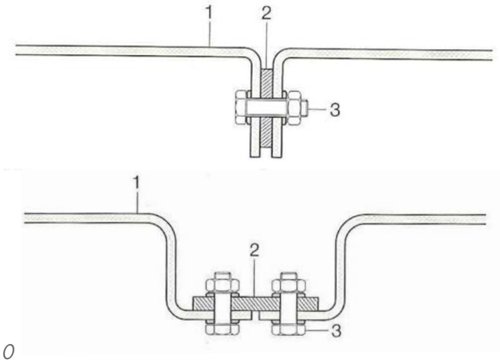
flange could be used as well as a stiffener. In any case, the thermal expansion co-efficiency for the joint material needs to be compatible with one of the composite. [B.01]

C.1.3.4 Glued joints

Steel lugs and angles can also be used as joints after glued to the FRP surface. Using this joint, high forces can be transferred through. [B.01]

C.1.3.5 Combining joints

Combining different types of joints is reasonable solution when high redundancy against failure is necessary. Such variety is responsible for the loads in different directions. For example, bolts can carry the tensile forces and the adhesive the shear stresses, while adding bolts on an adhesive joint is ineffective. [B.01]



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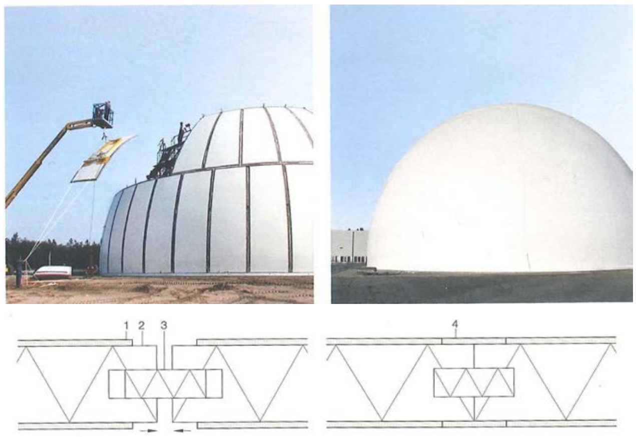

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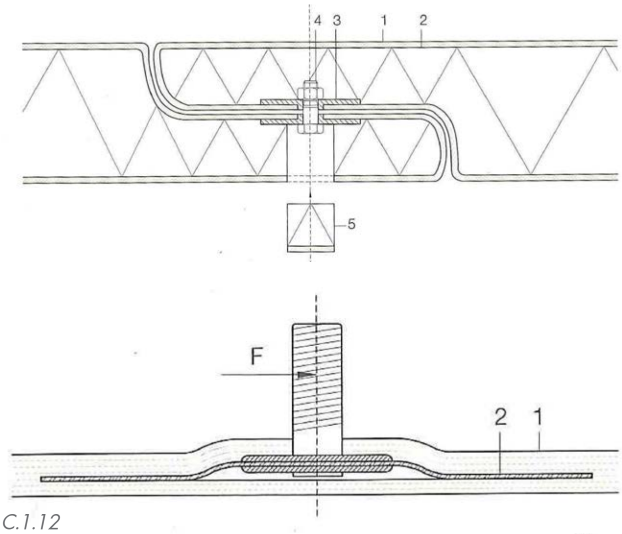

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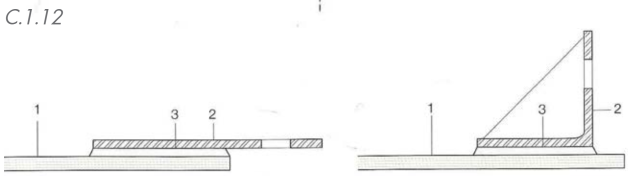


C.1.13

C.1.4 Composite failure pattern

The behaviour of the polymers and the fibres varies over time. The deformations increase, pre-stressed components are released in the long-term loading. In general composite's strength is lower for permanent load than brief ones. In addition to being time dependent, the mechanical properties of FRP composites are also temperature-dependent. As the temperature rises the elastic modulus and strength drops. Also, environmental aspects like water, salt solution and UV radiation can also influence the polymers and fibres performance. [B.01]

C.1.4.1 Debonding and Fibre out

The reinforcement/matrix interface has a crucial role in the performance of a composite material. The reinforcement is effective in strengthening the matrix only if a strong interfacial bond exists between the reinforcement and the matrix. The interfacial properties also influence the resistance to crack propagation in a composite and therefore its fracture toughness. The two most important energy-absorbing failure mechanisms in a fibre reinforced composite are debonding at the fibre/matrix interface and fibre pull-out. If the interface debonds relatively easily, the crack propagation is interrupted by the debonding process and instead of moving through the fibre, the crack moves along the fibre surface, allowing the fibre to carry higher loads. Fibre pull-out occurs because fibres do not all break at the crack plane. Since they break at random locations away from the crack plane, one of the broken fibres ends pulls out from the matrix as the two crack faces open up with increasing load. If the pull-out occurs against high frictional forces or shear stresses at the interface, there may be a significant decrease in the fracture toughness of the composite. [B.03]

In many polymeric matrix composites, increased interfacial bond strength is achieved by fibre surface treatment, which helps in forming a

C.1.14

C.1.15

C.1.16

C.1.14 Failed FRP aeroplane component
C.1.15 Failed FRP component due to fire
C.1.16 Example of creep phenomenon

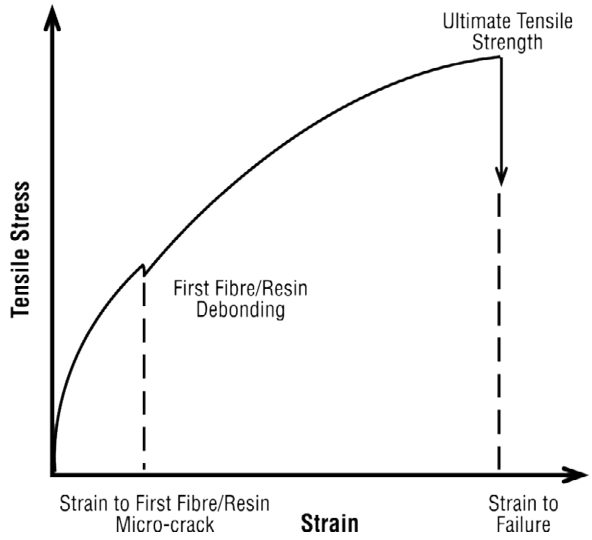
chemical linkage between the fibres and the matrix across the interface. Ordinarily, a mechanical bond is formed due to differential shrinkage as the polymer, matrix, with higher coefficient of thermal expansion than the fibres, cools down from the processing temperature. Higher shrinkage of the matrix around the fibre creates residual stresses in both the fibre and the matrix. At the interface, the residual stresses are compressive in the radial direction, but tensile in the hoop direction. The residual tensile stress in the hoop direction can sometimes initiate micro cracks in the matrix. Furthermore, if the mechanical bonding is disrupted at low stresses or by environmental attack, for example moisture, and the fibre-matrix interface debonds, the matrix will not be able to transfer stresses efficiently to the fibres and the strength of the polymer matrix will be lower. [B.03] The mechanical indicator for the failure of a polymer through a micro-crack mechanism is the stain of both resin and fibres. [W.01]

C.1.4.2 Delamination

Delamination is a critical failure mechanism in laminated fibre-reinforced polymer matrix composites and can occur from different causes. [A.06] The most relevant to the graduation thesis will be mentioned.

In principle, delamination is caused by high interlaminar stresses in conjunction with the typically very low through-thickness strength. It can occur due to the loading across the thickness of the laminate that is taking care of brittle and weak matrix. It can be related to debonding by allowing traverse matrix cracks to join up and produce a fracture surface, shedding down without fibres breaking. It can also occur on the same direction of the fibre lamination, when they are blocked together.

Delamination may occur due to overall interlaminar stresses due to FRP geometry or loading and localized interlaminar stresses due to a form of discontinuity or stress singularities.



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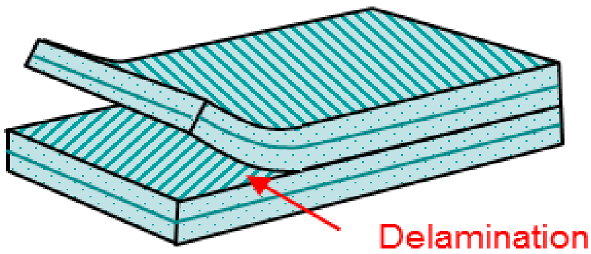

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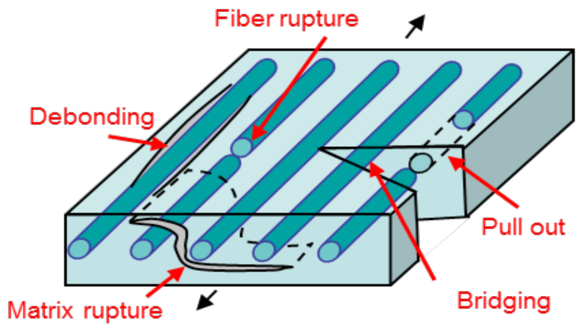

C.1.19

C.1.17 Tensile stress to strain of FRP showing debonding behaviour of material from micro-crack to failure
C.1.18 Illustration of FRP delamination effect
C.1.19 Illustration of FRP debonding and fibre-out effect

In the case of overall interlamination stresses the difference structural thickness, the free edge, the curved fibre paths are the most common causes. In the case of localized interlaminar stress discontinuities, cracks or joints are the most common causes. Localized stress but in big scale can also occur on big scale joint of different geometries. The connection area will be more sensitive to delamination, since there the fibres and the load path change. [A.06]

Impact load can also produce delamination on a component. During impact load there are two possible mechanisms of delamination. First, extra interlaminar shear stress in the mid-plane is produced due to the impact that reduces away from the contact force. Second, due to transverse tensile cracks that are formed by the back surface of the laminate owing to bending during impact. Different types of resin perform in a different way during impact, but also thicker laminates perform better in shear and thus this also is a possible measure against this type of delamination. [A.06]

C.1.4.3 Creep, creep rupture strength and relaxation

Subjected to a constant load, the individual molecular chains of the polymers slide past each other, increasing deformations and possibly lead to failure. This reaction of course is in a wicker cross-lincking thermoplastic, than in a denser molecular architecture thermoset. The enervation of the cross-linking is accelerated due to higher temperatures. [B.01]

The steady plastic deformation of polymers is called creep and occurs shortly after the application until it reaches its higher value. If the load exceeds a certain threshold the deformation increase disproportionally until it finally fails. This material property is called creep rupture strength of the material[B.01]

C.1.4.4 Degradation from water ingress and osmosis

Degradation from water ingress and osmosis can be caused when polymer is in a maritime environments, without necessarily be in direct contact to water. All resins are sensitive to moisture, but the absorbed water affects every type of polymer in a different way. This absorbed water will add to the laminate's weight and lead to gradual and long-term loss in their mechanical properties. [W.01]

Osmosis refers to the very low quantities of water that will pass through the polymer surface in vapour form. As the water will attack the surface of the polymer it will react with the hydrolysable components inside the laminate and tiny cells of concentrated solution will be crated and the fluid pressure will increase. The pressure will distort the laminate or the gel coat and the smooth polymer surface can turn into 'chicken-pox' surface. As hydrolysable components could be dirt and debris trapped into the polymer during fabrication. In order for osmosis to be prevented, resin with low water transmission rate and high water resistance must be used. Blisters can be eliminated as well when using reinforcement with similar properties. Epoxy have been proven to be an excellent choice for such applications. When epoxy is immersed into water for one year the loss of its inter-laminar shear was only 90%, while polyester was 65%. [W.01]

C.1.4.5 Fire resistance

Polymers lose their mechanical properties with high temperature. Even before exceeding the service temperature the polymer starts to soften up, losing its compression strength and as a result the structure could buckle. [B.01]

In the case of fire the consideration when designing with composites is based on the reaction of the material to really high temperatures in a small time. In the case of the polymer not only the actual material needs to be tested for fire resistance, but also the additional layers, the coatings and the fillers. In general, most of the polymers are flammable but still they can be used as structural materials. To increase the stability of a structure during fire, flame retardants could be used on the structure or the surface of the polymer. Another option would also be to increase the mass proportions in composites, so even a part of the thickness fails, the structure will still have the necessary structural thickness. [B.01]

Furthermore, important designing aspects regarding material selection based on fire resistance are the melting point and the flammability point, if toxic gasses produced and finally how the material fails. For example if holes are created and by-products. Unfortunately there is not a general rule for the behaviour of polymers during a fire, so individual data must be gathered for every polymer.[B.01]

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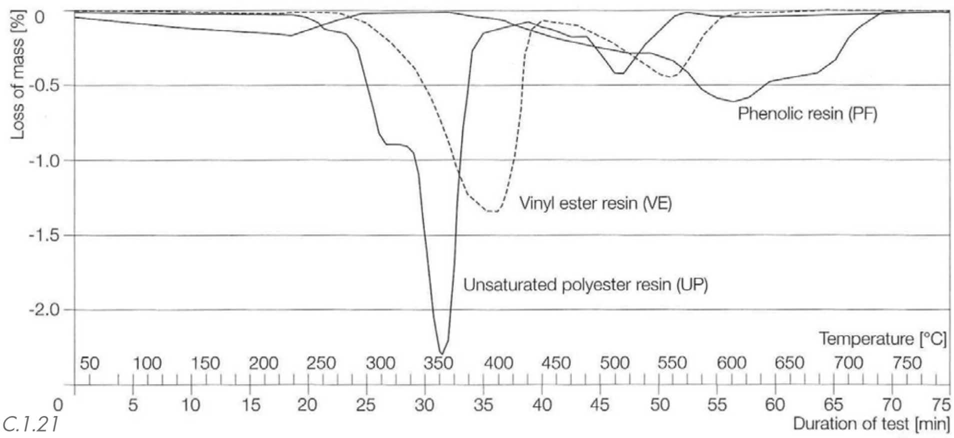

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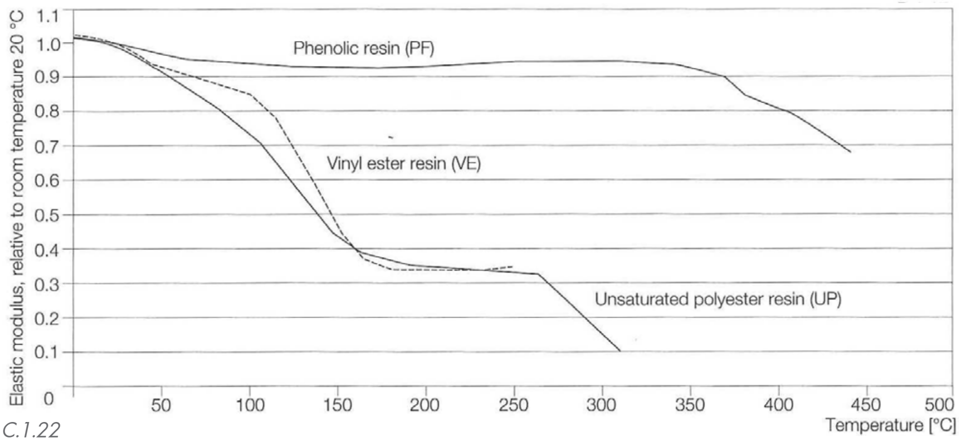


C.1.22

C.1.20 FRP degradation from water ingress and osmosis effect
C.1.21 Mass loss of different polymers to fire incident
C.1.22 elastic modulus reduction of different polymers to fire incident

C.2 Sustainability aspects of FRP

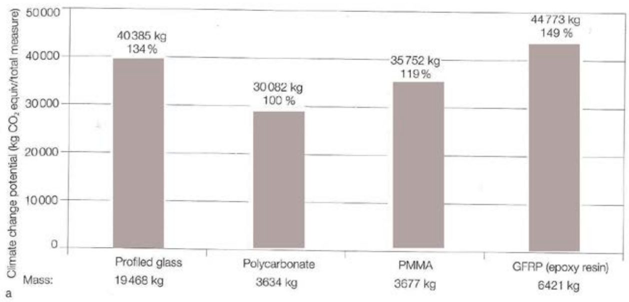
C.2.1 LCA

Fibre-reinforced polymers is a material with high manufacturing cost and difficulties on recycling, but with great strength, no maintenance need and long life span. On the first sight it is not proper in a sustainable design, but a Life Cycle Assessment (LCA) shows a different image. LCA criteria are based on the entire life cycle of a material and also the environmental impact during manufacturing or recycling, like energy consumption, CO_2 footprint and water contamination. LCA examination is a complex procedure which takes into account, not only the materials of construction, but the load-bearing system, the joining method and the dead loads. [B.01]

Sure outcome can be not given "Interpretation of LCA results can vary," confirms Bob Moffit, product manager at Ashland Performance Materials (Columbus, Ohio) but is always discussed in the terms of its surrounding and resources. This is also a reasons why there are more than one green labels that might be in conflict some times. For example there is the Leadership in Energy and Environmental Design (LEED) but also Environmental Product Declarations (EPDs). [W.02]

In general, with ordinary sustainability criteria FRP is not the most suitable material because is very cost and energy consuming during manufacturing. Although taken into account

C.2.1 Primary energy spans of individual materials groups per mass of material [kg]
C.2.2 Primary energy spans of individual materials groups per mass of material [kg]
C.2.3 Primary energy comparison of components (according to values from the ΦI<obau.dat database, cradle-to-grave, production and disposal, Germany, 2009). Comparison of steel and GFRP beams in bending for identical deformations and bending moment capacities



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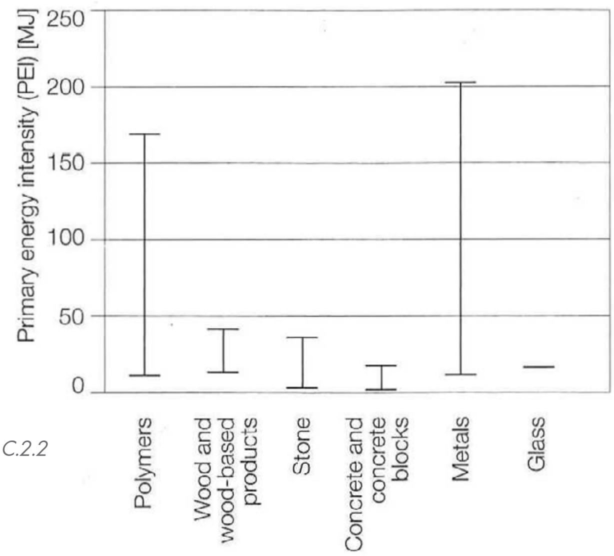

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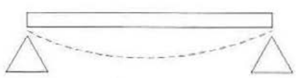
Identical deformation



		Steel beam IPE 200 g = 0.224 kN/m²	GFRP beam, pultruded IPE 360 g = 0.227 kN/m²
PEI non-renew.	[MJ]	421.30	1038.62
CCP	[kg CO_2 equiv]	47.98	161.17
ODP	[kg R11 equiv]	$1.32 \cdot 10^{-6}$	$2.36 \cdot 10^{-6}$
AP	[kg SO_2 equiv]	0.14	3.18
EP	[kg PO_4 equiv]	0.0135	0.0427
POCP	[kg C_2H_4 equiv]	0.0214	0.0906

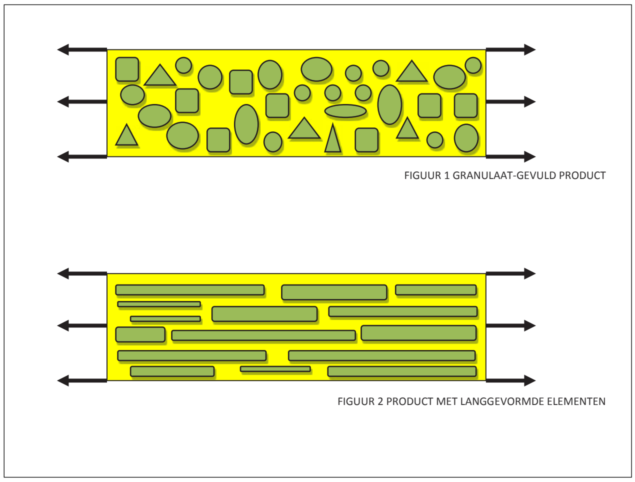
that it is a lightweight material, there is less water contamination and CO2 footprint during manufacturing, easy in-suit repairs, no need of maintenance and corrosion- impact resistance FRP becomes again an option for sustainable design. [W.05]

C.2.2 Recycling

Fibre reinforced composites is a material of long life span, but as already been mentioned in introduction of these thesis infrastructures stop being in used and need replacement even long before the end of their structural life span due to aesthetic or other criteria. So, FRP wastes are produced and it is a social responsibility of engineers to deal with those wastes, have knowledge of this when designing and find solutions in order to make reuse easier.

Recycling the FRP itself or the raw materials of it is a challenge. As mentioned before thermosets, as well as elastomers cannot really by recycled or reshaped, since their molecular cross-linking cannot break after being formed. On the other hand even if the raw material of an FRP element, like the vegetable fibres can be recycled, when mixed with the thermoset resin recycling is not an option anymore. [B.01]

Recent researches indicate new examples of example of up or down-cycling and reuse of existing FRP elements. For example, the research of Windesheim University of Applied Sciences in Zwolle, Netherlands conducted on May of 2016 entitled "Reuse of thermoset composites. Research of waste product types and collection Research waste products" [B.04] is based on the circular economy concept and part of FRP products with known fibre orientation are cut down and being reused as new FRP products to build new structures. Even if this is a university research still and not a practice of the market it indicates the further life extension of FRP structural products.



C.2.4 "Reuse of thermoset composites. Research of waste product types and collection Research waste products" research of Windesheim University of Applied Sciences in Zwolle

Manufacturing techniques
-
Mould technology

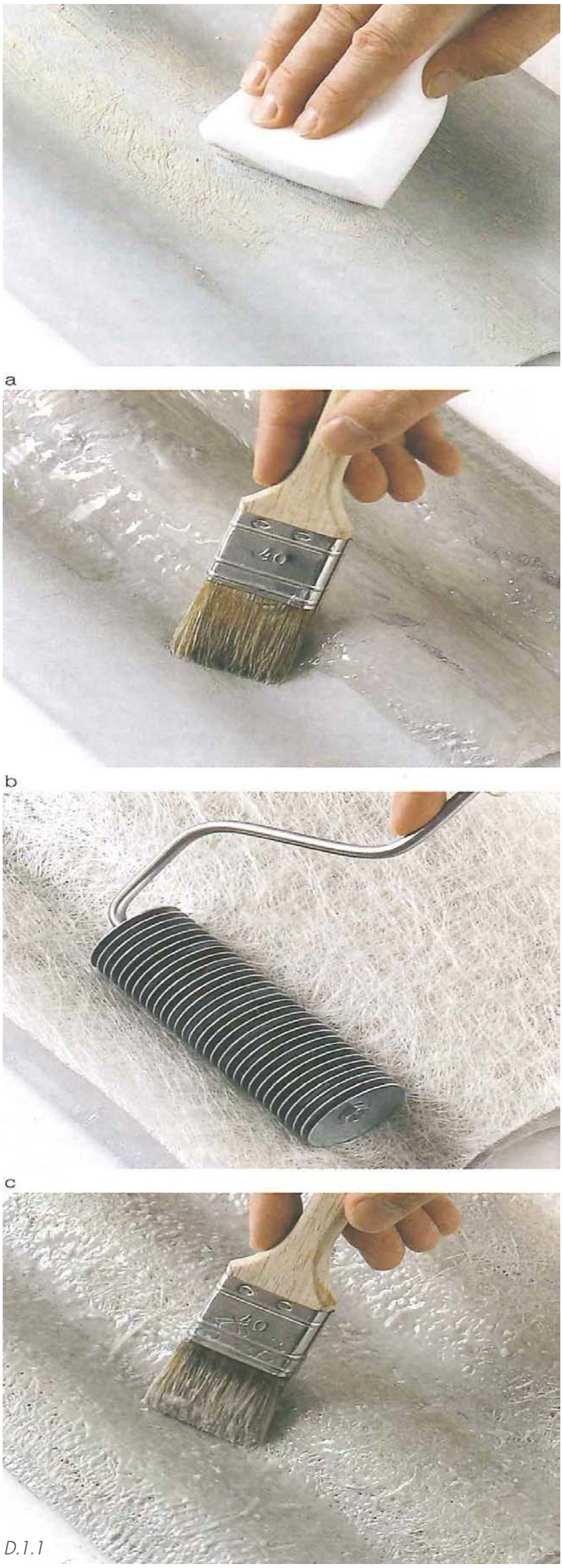
D.1 Manufacturing techniques

Different product techniques can be used to produce FRP structural products. The criteria for those techniques are based on the number of the batch and the cross-section of the product. In this chapter, all of the techniques will be mentioned and explained in order to highlight the material potentials best. Nonetheless manual techniques are more appropriate for the series of footbridges, since automated techniques might be cheaper, but suitable for massive production.

D.1.1 Hand lay-up

In principle, moulding techniques are suitable for elements in small batches, irregular shapes or large sizes. Depending on the geometry different material is used for the mould. For straight, simple geometries wood or steel sheets can be used, but for more complex items can be produced from rigid polyurethane foam moulds. Usually the foam is damaged during the first de-moulding, so not a lot of products can be produced from such a mould. Instead of foam a polymer mould could also be used that needs an initial mould to be produced from and thus more expensive, but nonetheless it can produce more products and is more durable in de-moulding and impacts that the foam one. Finally, the face contacting the mould has a smooth finishing, while the other side stays rough. [B.01]

In order to facilitate the de-mould phase of the product, the surfaces of the mould are coated with a release agent. In the case of the rigid foam mould, this first coating also prevents the resin from bonding with the foam. On the contrary, when the rigid foam mould is the core of a sandwich FRP element, then this layer is undesirable, because in this case, the shear bonding of the core and the resin is beneficial. The beginning of lamination starts by applying the gel coat, a coat of non-fibrous pure resin <1mm thick, to the mould. This coat of resin


a
b
c
D.1.1

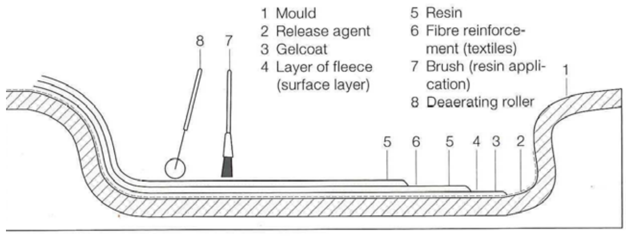
has a good hardness and impact resistance and practically is the protective surface layer of the laminate. Due to the runny form of this resin, thixotropic agent must be added. [B.01]

After this step, the textiles or fleeces are added, impregnated with the liquid resin and pressed down with a roller to remove any air bubbles and ensure the good contact of fibres and resin. Air bubbles cannot be removed after this phase and if not removed in time, the element is defective, most probably also structurally insufficient. [B.01]

To ensure a good finishing usually the first ply is fine fleece and then the suitable textile is used and orated accordingly to ensure the structural strength needed for load-bearing elements, while chopped stand mats are used for components requiring low load-bearing capacity. The maximum fibre content that can be reached is 45% by volume, because the diverse textiles cannot be fitted together more densely. This process is repeated until the desirable laminate thickness is achieved. Obviously the production quality of this manufacture technique is based on the rapidness and the skills of the manufacturing worker. [B.01]

D.1.2 Fibre spraying

This is an inexpensive method for the manual fabrication of large laminates with a complex geometry but low demands regarding load-bearing capacity. The method involves installing a roving in a spray gun which also chops the fibre into small pieces. These short fibres along with the resin are sprayed into the mould at the same time with a shot reaction time. Air bubble are subsequently pressed out with grooved roller like with lay-up technique. The thickness of the laminate varies considerable with this method, and it's not possible to control the fibre orientation either. However, the big advantage of this method is the minimum amount of work necessary and the option of being able to laminate vertical



D.1.2

D.1.3

D.1.4

D.1.1 Sequence of FRP hand lay-up manufacturing
D.1.2 Hand lay-up manufacturing technique diagram
D.1.3 Hand lay-up manufacturing technique in big structures
D.1.4 Fibre spraying manufacturing technique

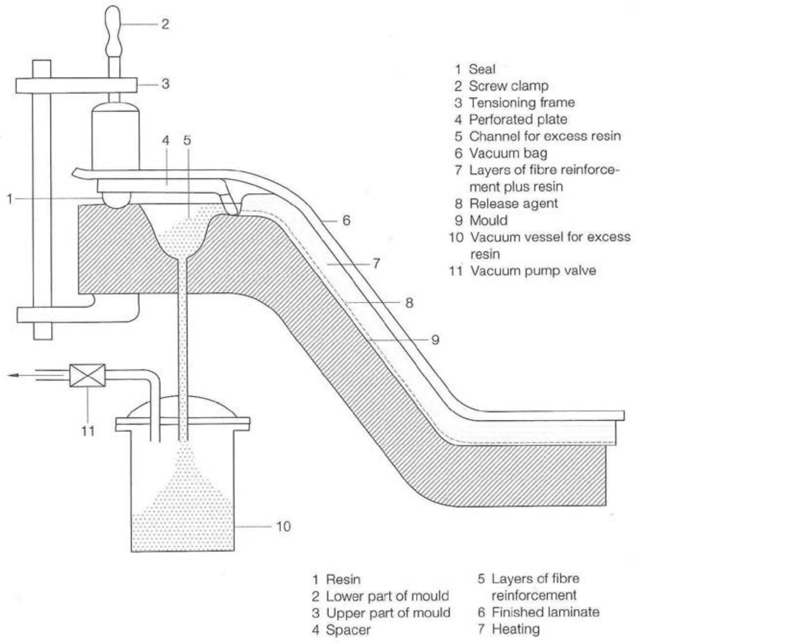
surfaces or membranes. [B.01]
This is a technique typically used for the bottom part of a boat, in the maritime industry, before the structural lamination take place.

D.1.3 Resin infusion (RTM) and vacuum methods (VARTM)

Resin infusion and vacuum methods are further developed methods comparing to the lay-up technique, which reduce the number of flaws and air-bubbles and increase the density of the laminate. Also, this technique provides a smooth face on both sides. In contrast to hand lay-up, in this method the resin is not applied to the mould before, but rather after all the fibrous plies have been laid in position to dry. The laminate is enclosed airtight in a porous release film and breather cloth in order for the resin to be poured. [B.01]

During the resin infusion method, the air is evacuated at one point and at the same time resin is forced in under pressure on the opposite site. This method is also known as Resin Transferring Moulding (RTM). If products with better mechanical results are necessary, during the vacuum method, the resin is sucked into the cloth by the low pressure. This method is also known as Vacuum-assisted Resin Transfer Moulding (VARTM), which is more time consuming that Resin Transferring Moulding (RTM). [B.01]

The curing of the resin could be accelerated through the use of autoclave, a heated pressure vessel. Through this procedure the temperature and the pressure cycles can be controlled exactly and reproducibly, resulting in products with a very high quality. Due to this precision this curing technique is used excessively in the aerospace industry. Components are cured at pressures of 2-25bar acting on all sides enables lightweight moulds to be used, even for complex and large structures. [B.01]



D.1.5

D.1.6

D.1.5 Resin infusion and vacuum manufacturing technique diagram
D.1.6 Resin infusion and vacuum manufacturing technique

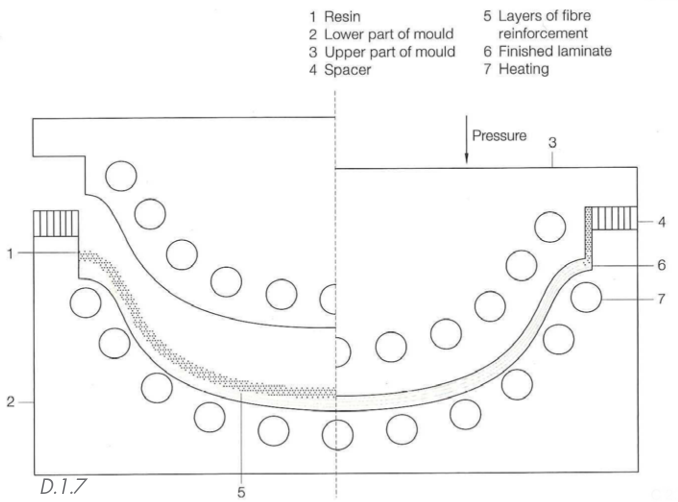
D.1.4 Compression- and transfer-moulding methods

Methods as such are primarily useful for the industrial manufacture of large series. The automated manufacture of moulded items made from fibre-reinforced polymers requires a relatively high initial investment in tools and moulds needed for the compression- and transfer-moulding methods that can be used. The moulding typically takes place in two-part metal mould. Sometimes the use of mould made out of synthetic resin can be used for compression-moulding. [B.01]

The best fibre content that can be achieved is slightly higher than the hand lay-up technique, approximately 50% by volume. Components that must comply with more demanding specifications are produced by transfer-moulding with steel or aluminium moulds. Fibre content of up to 65% by volume are possible with this method. [B.01]

<u>**Pre-impregnated textiles**</u>

Compression and transfer moulding techniques can be based on fluids as well as on pre-fabricated semi-finished products, so called prepregs. Prepregs are reinforcing fibres already impregnated with resin which cure under high pressure at high temperature. The prepregs are prepared on machines, in order to achieve a consistent wetting of the fibres with the resin, which is what enables a high-quality fibre composite to be produced. The fibre impregnation process is therefore separate from that of the actual moulding technique. Prepregs reinforced with short fibres, so-called sheet moulding compounds (SMC), are used for production of large series, as semi-finished product. The resin compound and the fibres are packed between polymer carrier foils and further processed to form endless rolls of material. This material is afterwards cut to size and moulded in two-part, heated steel moulds under high pressure (30-140 bars). The most typical applications are large batches of control cabinets and vehicle



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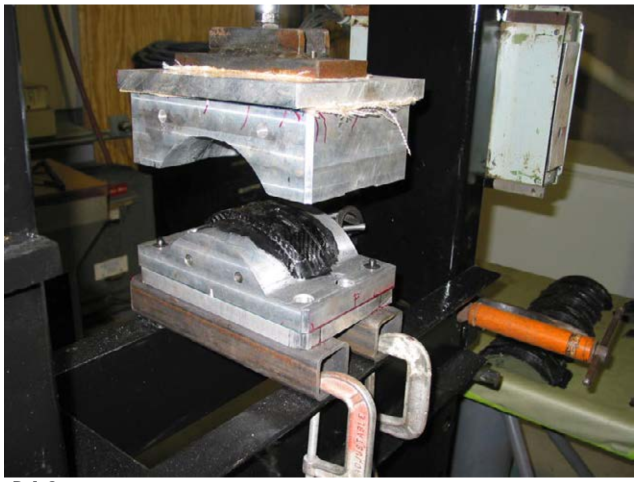

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D.1.9

D.1.7 Compression and transfer moulding manufacturing diagram
D.1.8 Compression moulding manufacturing
D.1.9 Transfer moulding manufacturing

components. In general automated methods are more economical than other methods, but it is only suitable for large series. [B.01]

D.1.5 Pultrusion

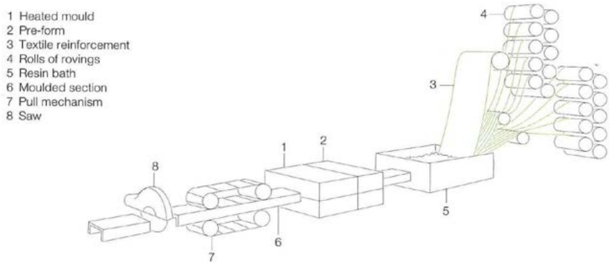
Pultrusion is currently a particularly significant method for semi-finished products in the building industry because it represents a relatively simple way of producing sections and sheets with a high fibre content and a low scatter of the mechanical properties. The products made from pultrusion have a homogeneous extruded cross section. Due to the cross section produced by this technique, it will not be considered further for the project manufacturing. [B.01]

D.1.6 Wrapping

Wrapping or filament winding, is the production method for pipes, vessels, tanks and other rotationally symmetrical hollow components. In composite wrapping, pre-tensioned rovings are wound around a rotating mandrel, mats or woven fabrics can be also be used due to the cross section produced by this technique, it will not be considered further for the project manufacturing. [B.01]

D.1.7 Braiding

The braiding method, which is similar to wrapping, requires elaborate, expensive machinery and is mainly used for highly stressed components in the aerospace industry. In this method, a large number of fibres from a braider are wound, one over the other, onto a mandrel. Either the mandrel or the rotation braiding head is fixed, the other part then moves and can lay the fibres continuously over the length of the component. Due to the cross section produced by this technique, it will not be considered further for the project manufacturing. [B.01]



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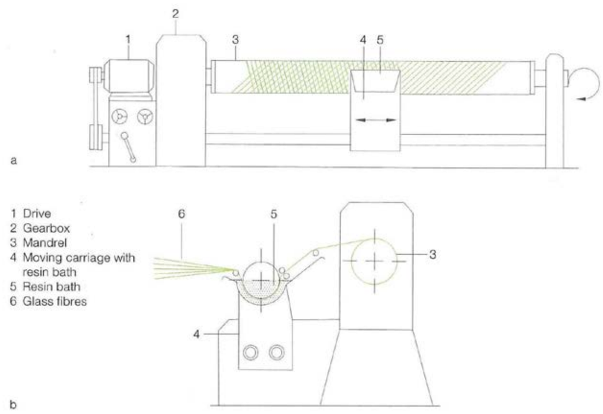

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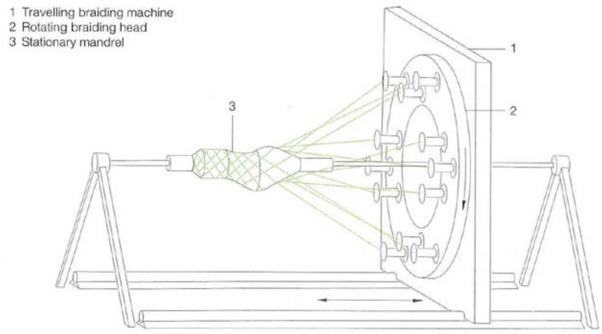


D.1.12

D.1.10 Pultrusion manufacturing technique diagram
D.1.11 Wrapping manufacturing technique diagram
D.1.12 Braiding manufacturing technique diagram
D.2.1 Mouldmaking process
D.2.2 Manufacturing of free-form elements
D.2.3 Final free-form element

D.2 Mouldmaking

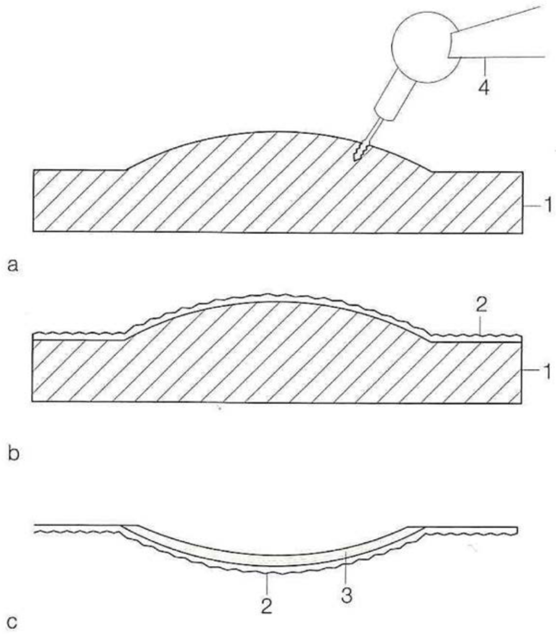
D.2.1 Moulding process

The moulding process normally takes place in three steps. Firstly, the original or master mould, i.e. the prototype, is produced. The original mould can be produced by additive or subtractive means, i.e. by respectively adding or removing material from the mould step by step. It is made from materials such as rigid foam, balsa wood, clay or gypsum, which although easy to work are unsuitable for multiple uses. A negative mould is produced from this original moulds in the second step. To do this, the surface of the original mould is coated with a release agent such as silicone oil or wax and the negative mould laminated or cast on this. Various robust materials- fibre-reinforced polymers or metals- can be used for negative mould depending on the size of the production run. The third step is the production of the actual component, with a surface geometry identical to that of the prototype, in the negative mould. Here again, a release agent is necessary in order to ensure easier de-moulding. [B.01]

Instead of three-stage moulding process, it is also possible to build the negative mould directly. Rigid foam shaped with a CNC milling machine can be used, for example, but negative moulds made from wooden beards are also worth considering for large-format laminates. One special type of mould is permanent form-work, which is coated with the plies of laminate material and remains as the core material in a sandwich element. [B.01]

D.2.2 Mould design considerations

The determination of the draft design required is mostly based on the material properties, the geometry, tolerance requirements, local shrinkage rate, and the parting line must also be taken into account. Shrinkage is the dimension to which a cavity and core should be fabricated in order to produce a part of desired shape and size. Basically, shrinkage is a function of material properties, mould



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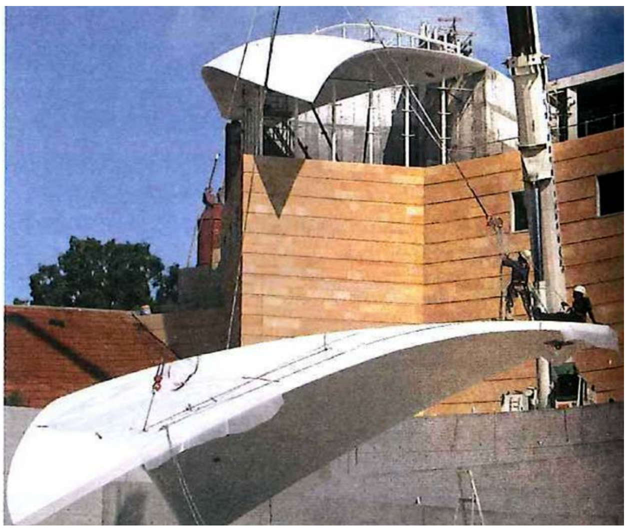

D.2.3

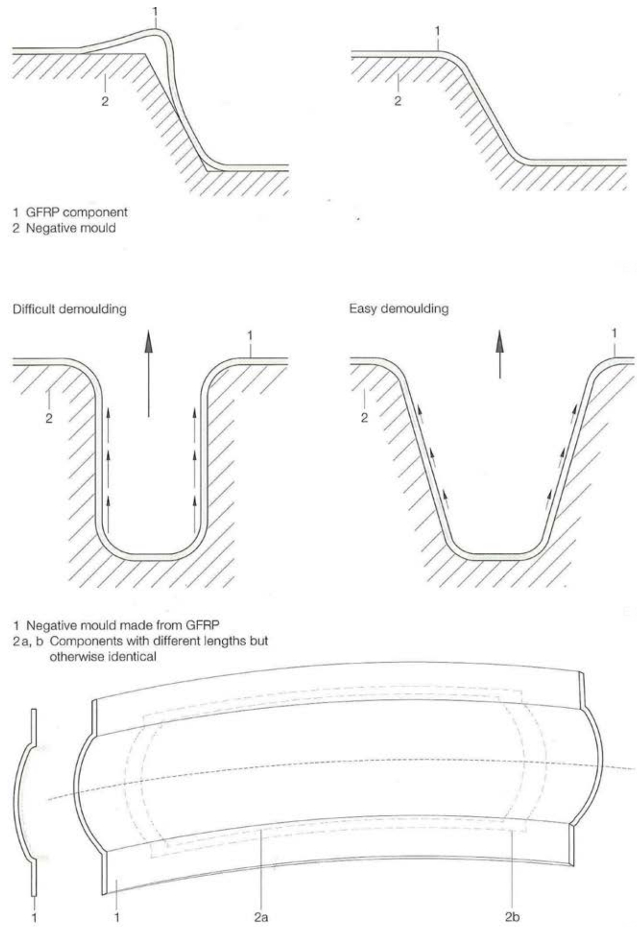
temperature, part thickness, injection pressure, and melt temperature. [B.02]

In principle, the polymer becomes viscous during the production of fibre composites components and so a sealed mould is essential. A one-part mould is sufficient for the hand lay-up of planar components, also for fibre spraying and the resin infusion and vacuum methods. On the other hand, the automated compression- moulding method requires a two-part mould. The surface of the laminate in contact with the mould is smooth, whereas the other surface usually has a rough or irregular finish. A foil can be laid over the surface not in contact with the mould when using the resin infusion and vacuum methods in order to achieve a smooth finish on this surface as well, but it is very important- and difficult- to lay the foil without folds or creases. [B.01]

D.2.3 Design principles for moulded parts

While developing a cavity layout, a decision must he made as to whether a single- or a multiple-cavity mould should be used. Factors such as period of delivery, quality control requirements, cost of the mouldings, polymer used, shape and dimensions of moulding, and capacity of injection moulding machine are considered. [B.02]

The mould can be developed from the component geometry, although it may be necessary to divide up the mould or component into several segments to suit production requirements. For example, at least two segments are required when laminating a circular cross-section. Considering the de-moulding aspects for a component are vital when designing a mould, e.g. for undercut geometries. Instead of dividing the components into pieces, it is also possible to divide the mould into several sections. The individual parts are fixed firmly together during laminating. To do this, the edges of the mould segments are provided with flanges that are bolted together. [B.01]



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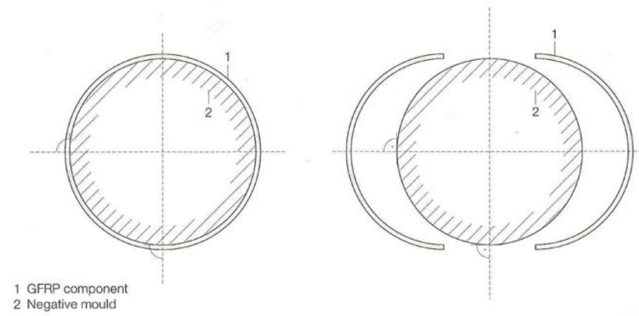
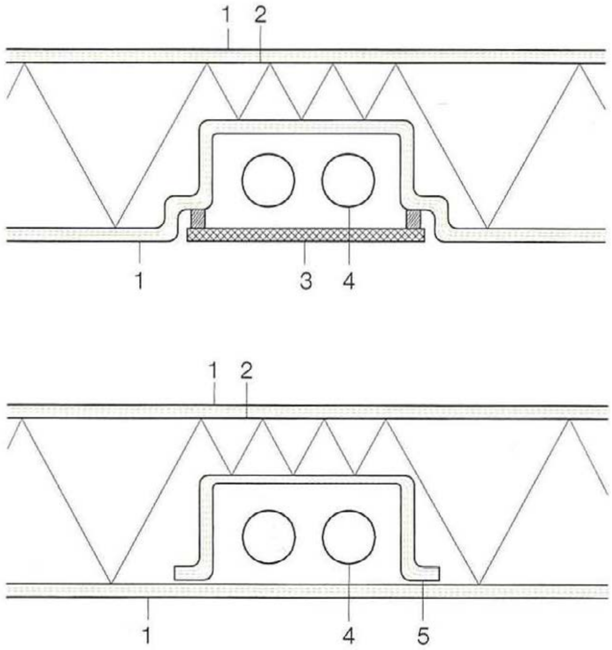


D.2.5

D.2.4 Geometrical considerations to facilitate demoulding process
D.2.5 Manufacturing of spherical geometries

The materials normally used for mould making result in negative mould and components that are comparatively stiff. The geometry should therefore be designed in such a way that there are no undercuts. If necessary, several segments must be combined to form a mould that is separated again afterwards. Surfaces parallel with the de-moulding direction must be avoided because they cause high friction forces when removing the component from the negative mould. Small moulds up to 20cm deep should be designed with an angle of minimum 2° to the vertical, larger moulds >1m deep with an angle of minimum 5°. Rounded arise with adequate radii must be included so that laminating with a consistent thickness is possible. [B.01]



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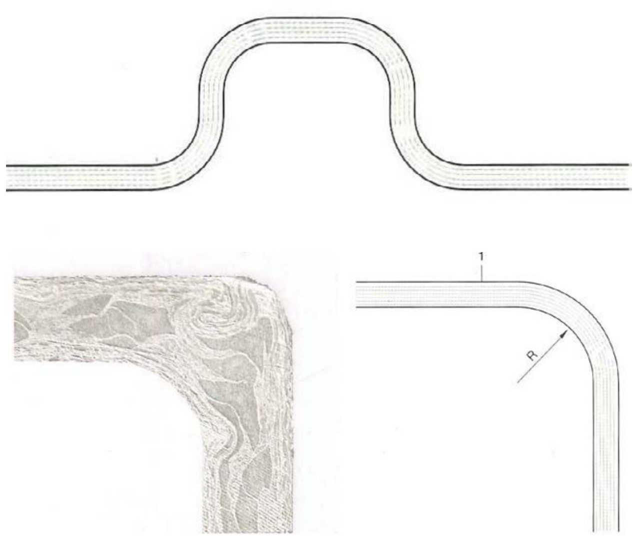
D.2.4 Materials

Moulds are expensive in terms of their materials and production, and can in some cases exceed the cost of the actual component quite considerably. The least expensive materials is therefore chosen depending on the dimensions of the component, the desired surface quality and number of reuses required. In addition, the cost of mould making should be minimized by designing the components geometry accordingly, e.g. by using the same moulds for components with the same shape but different dimensions. [B.01]



D.2.7

D.2.6 Accessible integrated element in FRP component/ Inaccessible integrated element in FRP component
D.2.7 Design of round direction change of FRP elements

<u>**Gypsum and clay**</u>

Gypsum is an inexpensive material that is easily formed into the shape required. It is suitable for both original and negative moulds. But its low strength means it is only suitable for small components and a few reuses. Dry gypsum absorbs water and release agent, which makes de-moulding difficult on many occasions. Gypsum moulds are fragile and are frequently damaged beyond repair during de-moulding. [B.01]

Clay is likewise an inexpensive, easily worked mould material. Under the right temperature and moisture conditions, it is easy to shape, and after drying, or rather cooling, it can be worked with simple tools. [B.01]

Rigid foam

The advantage of fine-pore foams (PVC, PUR, XPS) is that these can be shaped with a computer-controlled CNC milling machine. The cost of the material is comparatively high and so the quantity of rigid foam required must be reduced to a minimum. The rigid foam is frequently left in the finished component as the core material. But where it is required for moulding only, then must be sealed with a filling compound and wax. Moulds made from rigid foam are likewise only suitable for a few reuses. Although foams with larger pores (EPS, Styropor) are among the cheapest, they are difficult to work. EPS combined with gypsum or clay is suitable for simple moulds. [B.01]

Fibre-reinforced polymer

Fibre-reinforced polymers, mainly GFRP materials, are suitable for making negative moulds. Different resin systems are used depending on the number or reuses required, i.e. the durability demands placed on the mould. GFRP has established itself as a material for negative moulds where 100+ reuses are required. One advantage of GFRP is that it is possible to integrate additional handles, flanges and fixings in the mould to simplify handling and assembly. [B.01]

Metal

Casted moulds made from steel or aluminium are only relevant for very large production runs or demanding tolerance requirements. Such moulds are expensive to produce, but are stable and durable. [B.01]

In the case of simple cross section with straight surfaces steel plates could be used as mould. Due to low price of metal sheet, a mould as such is one of the less expensive options.

D.2.8

D.2.9

D.2.10

D.2.11

Wood
Moulds made from timber represent a reasonable alternative for especially large components and where moulds do not have to satisfy requirements regarding dimensional accuracy. The actual face of the mould can be made from thin veneer plywood or planed boards fixed in position by an orthogonal arrangement of framing members. These can be manufactured exactly in a computer-controlled process. [B.01]

Polymer
Polyurethane casting resin is used where high-precision moulds are needed. This material has an excellent surface finish and is relatively robust. However, the mould itself is comparatively heavy and expensive, and the resin cannot be reformed afterwards. Elastomers, e.g. silicone rubber, represent alternatives to casting resins for making moulds, but only for relatively small components. One advantage is that undercuts are possible with these extensible materials. In addition, no release agent is required when using silicone. [B.01]

D.3 Mould Types

For the basic compression, transfer, and injection moulding processes, a wide variety of mould types may be considered. Criteria for the mould type are the production volume, the allowable final part costs, the mould maintenance and amortization costs, as well as the hourly cost rates for moulding machine and labour. [B.02]

D.3.1 Single-Cavity Moulds

For low production quantities of a few hundred parts, single-cavity moulds may be feasible. Single-cavity moulds can be of the hand-moulding type, having no mechanical ejection mechanism, no heating or cooling provisions, but requiring a set of universal heating/cooling plates bolted into the press, between which the hand mould is placed and removed each cycle.[B.02]

D.2.12

D.2.8 FRP mould example
D.2.9 Rigid foam mould example
D.2.10 Metal mould example
D.2.11 Silicon rubber mould example
D.2.12 Gypsum mould example

D.3.2 Multi-cavity Moulds

Production moulds are generally multi-cavity, they have integral heating or cooling provisions and ejection systems. When they follow single-cavity hand moulds, cavity dimensions may be fine-tuned, and vents and gates can be repositioned, based on experience with the single-cavity moulds. Family moulds are multi-cavity moulds that mould one or more sets of a group of parts that are required to make up a complete assembly of the finished product. If sales require greater quantities of any size than are required for one or more of the other sizes, a second cavity insert could be made to fit into the mould base, enabling twice as many of the faster-selling size each cycle. For family moulds to be successful, all parts should have approximately the same wall thickness so that moulding cycles may be optimal for all sizes. [B.02]

D.3.3 Moulds with Removable Cavities

Some moulded parts have configurations that require portions of the cavity to be removed before they can be ejected. For fully automatic cycles, moulds for such a part may be constructed with cam-actuated or hydraulically actuated side cores that serve as the above-described mandrel. In each cycle, after the mould is closed and prior to injection of material, the side core is automatically actuated into place. Following the cycle, the side core is retracted automatically prior to mould opening and part ejection. [B.02]

D.3.4 Moulds with Inserts

Many plastic parts are produced with moulded-in inserts. After the mould is closed with the insert in place, plastic is injected or transferred into the cavity, where it surrounds the shaft end and fills out the cavity to achieve its shape as a handle. Following hardening of the plastic, the mould opens, and the finished part is removed. [B.02]

D.3.1

D.3.2

D.3.3

D.3.1 Single cavity mould example
D.3.2 Mould with removable cavities example
D.3.3 Mould with inserts example
D.3.4 Sandwich core as mould example

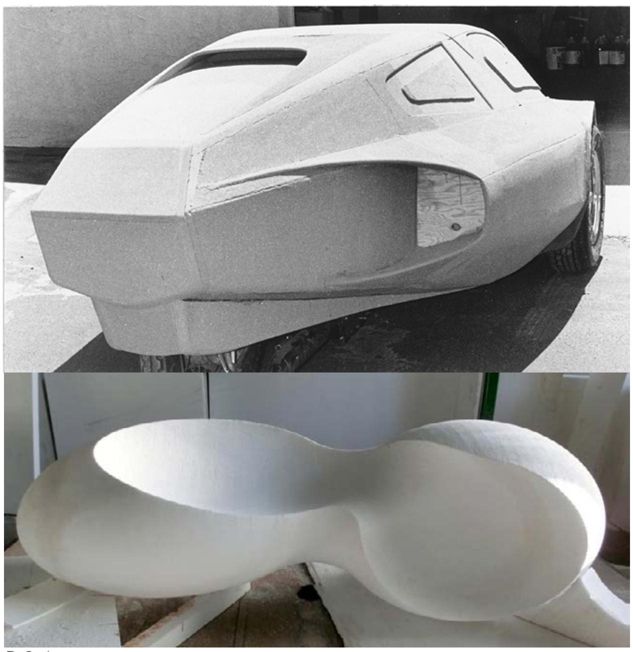
In many insert-moulding operations, fully automatic moulding becomes possible when mechanisms are installed to put the insert into place before each cycle and to remove the insert with moulded part following each cycle. [B.02]

D.3.5 Sandwich core as mould

Sandwich elements do not necessarily require a mould if the laminate material is applied directly to the core material. The core functions as mould, load-bearing component and thermal insulation. The use of CNC machining allows virtually any shape to be produced. [B.01]

To do this, the block of rigid foam must be cut first, e.g. with a CNC milling machine. The fibre-reinforced polymer is laid directly on the rigid foam without the need for a release agent and the laminate bonds with the foam through the resin. The amount of liquid resin absorbed by the foam depends on its porosity, this fact must be taken into account for production. Separate blocks of rigid foam can be glued together to produce large-format components. [B.01]

The high costs of such foam materials makes this form of construction relatively expensive. It therefore makes economic sense to integrate the mould into the component only in the case of irregular, one-off geometries. Another disadvantage is that the part is laminated on the outside, i.e. the comparatively rough and inaccurate final ply of the laminate forms the final surface. However, this disadvantage can be compensated for to some extend by using the resin infusion or vacuum method. [B.01]



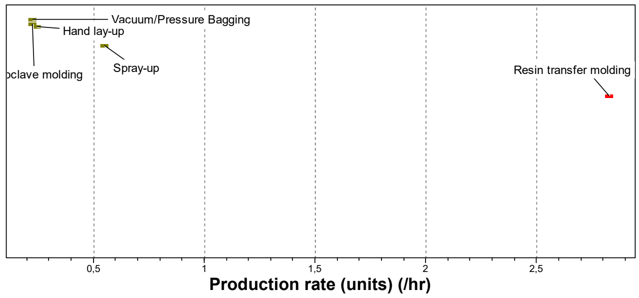
D.3.4

D.4 Resin transfer moulding

Through a CES analysis the most suitable moulding technique for the project was researched. In the beginning, the hollow 3D shape was set as geometrical limit, so that there is more design freedom on the connections of the modules. After this analysis six (6) possible choices were available. Autoclave moulding, Hand lay-up, Resin transfer moulding, Filament Winding, Spray-up and Vacuum/pressure bagging. Filament winding was excluded from the further analysis, since it does not belong on the mould-based manufacturing technique. As next step, the remaining five (5) choices were further analysed. The criteria for this analysis was based on the idea of a cost*efficient modular public infrastructure. Hence the tolerances, the surface roughness and the production rate was set as main criteria. Resin transfer moulding was performing best on all those criteria and so this is the selected manufacturing technique.

In general, Resin transfer moulding (RTM) is an easy and common way of manufacturing FRP complex components with low-rate cost tooling. It's an intermediate process between cold press moulding and contact moulding. The component is enclosed on two moulds and thus both of the surfaces are smooth. Apart from moulds, resin injection points and vent points are also needed to be integrated on the moulds for the RTM process.

Also, since the process is a closed mould process, the wastes and the emissions are less comparing to open mould processes. Additionally, the costs of the materials and the disposals are low and there is bigger consistency and repeatability on the process by reducing the cycle times, which results in higher productivity and lower labour costs. [W.06]



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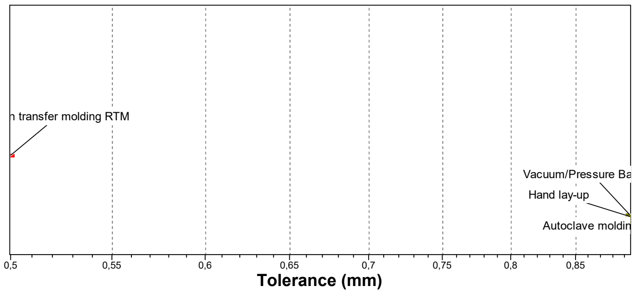

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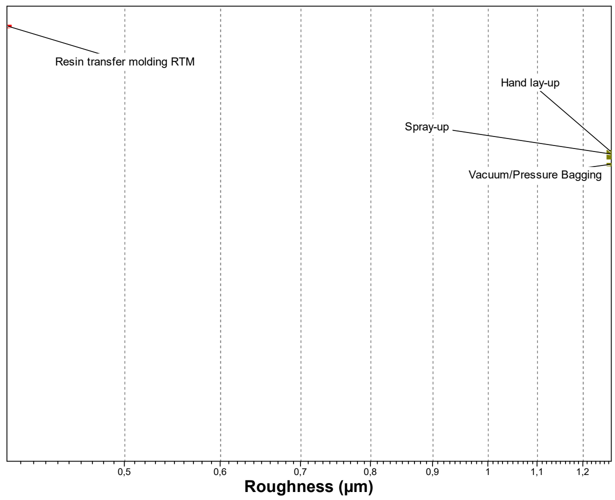

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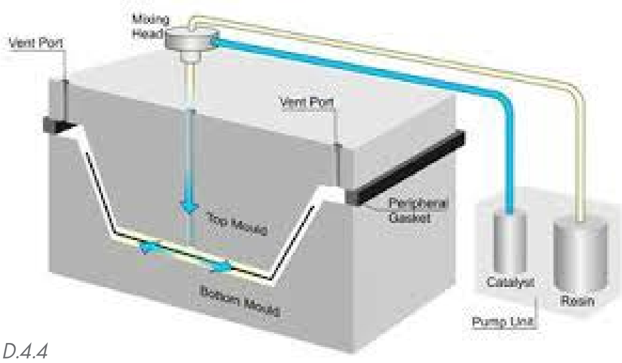


D.4.4

General advantages of RTM

- All dimensions, including part thickness are directly controlled by the tool cavity. Smooth surface is possible, but also more elaborate surface shaping, decorative and mat finishes are possible.
- Net shape parts can also be produced, eliminating some finishing operations
- All types of fibres can be handled through this method, even types like thick 3D woven fabric that normally is hard to mould by conventional means
- Is compatible with a broad variety of resins
- No prepreg process is necessary, cure scheduling is simpler and cure cycles shorter
- For fixed cavity tooling fibre, volume fractions are well controlled, accomplishing more consistent mechanical properties
- With correct mould design and sufficient process control very low voidage levels can be achieved, which means smaller rate of defect components
- Very complex geometries can be moulded on one set of mould that result in significant cost reduction.[B.05]

D.4.1 Requirements for RTM tool design

D.4.1.1 General considerations

When designing a mould set for RTM production several aspects need to be taken into account. The geometrical requirements of general moulding techniques have been already mentioned in previous chapter, but here a more specific considerations of RTM requirements will be elaborated.

First of all, loads arises from the resin injection pressure which is required in order to achieve the right Vf% (percentage of fibre volume fraction) and also from the resin expansion. Those loads are reached from the tool faces and need to be in the deflection range of the mould permitted deflection. Extra support

D.4.5

D.4.6

D.4.7

D.4.1 Comparative chart of production rate of different moulding manufacturing techniques from CES
D.4.2 Comparative chart of tolerances of different moulding manufacturing techniques from CES
D.4.3 Comparative chart of roughness final texture of different moulding manufacturing techniques from CES
D.4.4 Resin transfer moulding manufacturing process diagram
D.4.5 Examples of irregular geometries with RTM
D.4.6 RTM production of steel moulds
D.4.7 RTM production of FRP moulds

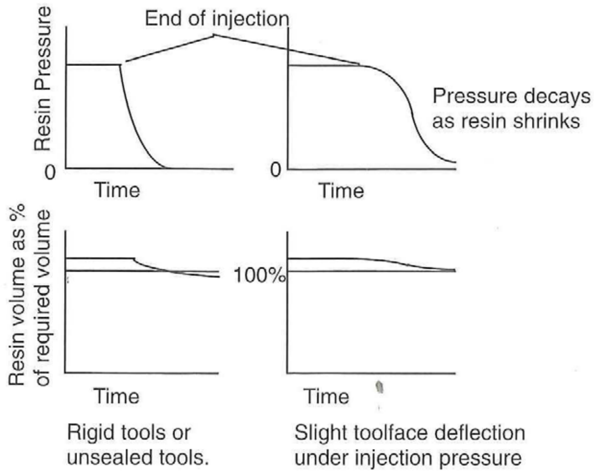
needs to be implemented in the mould design in order for the deflections not to exceed the allowable limits. Also, the tolerances of the sealing needs to be taken into account to prevent air and resin leakage. On the other hand, if the moulds are totally inflexible, then the decay in resin pressure as the resin cures and shrinks will be much more rapid, which can lead to shrinkage-induced voidage or poor surface quality. [B.05]

Moreover, also the thermal differences during resin curing need to be taken into account, where the mould face is also heated. For tools that are used at room temperature the heating strategy and thermal mass of the mould is not that crucial. High thermal mass or low thermal conductivity tools are advantageous since the temperature of the mould slightly rises, facilitating the production cycle. There is no waiting time in order for the mould to cool down after opening and reloading. On the other hand, for tools that must be thermally cycled the thermal response is very important and must be considered carefully. [B.05]

Furthermore, the differential thermal expansion of the resin also influence the tool design. During curing the resin expands inducing dimensional changes. If the resin is kept under pressure during cure, there would be a resin-filled gap between the tool and the layup resulting in trimming requirement even if the tool was designed as net shape. Components made from resins such as polyesters instead of thermal expansion show similar effects of resin shrinkage. In principle the relative expansions could be accommodated by the use of a strip of very high-expansions coefficient material around the periphery of the tool. [B.05]

D.4.1.2 Mould seals

Seals are used to control the flow of the resin out of the tools and permit evacuation of tools. When working with polymers, evacuation is not necessary, so the seals are mostly in charge of the resin not to contaminate the



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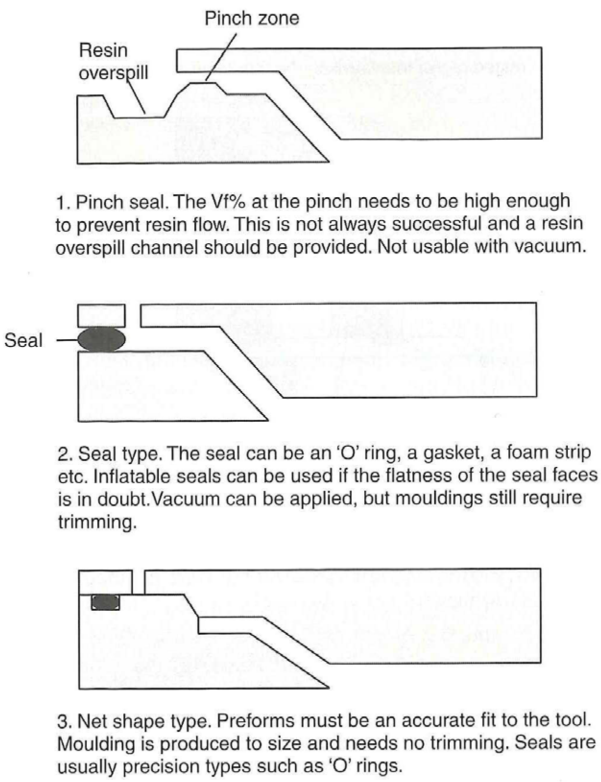


D.4.9

D.4.8 Diagrams of pressure loads and thermal expansion during polymer curing
D.4.9 Different examples of mould sealing
D.4.10 Example of mould with flanges
D.4.11 Moulding of extra collet mould element
D.4.12 Example of experimental modular mould
D.4.13 Different mould clamping options

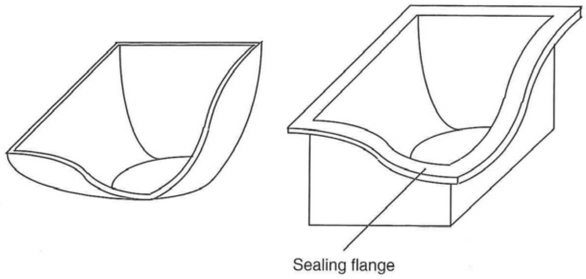
working area and control the wastes. As seals foam, rubber gaskets and rubber strip can be used in a flat flange around the mould. The design of the seals is very straightforward. The only requirement is for the two halves of the moulds to match each other. Also, sealing tools need to be vacuum tight to a few mbar they require much closer seal tolerances and better surface finish for the seals to seat against. In the case of tool being needed in more than two moulds, then a collet type mould can be used or a modular mould that its pieces connect through the seals as has been used in prototypes. [B.05]

D.4.1.3 Mould clamping and closure

In a RTM production the moulds need to open, get cleaned and then be reused. Then the moulds need to be brought together and close against the resistance of the reinforcement and lock so that the injection pressure does not cause excessive deformations of resin of vacuum leakage. There is a big variety of clamping and closure choices. Simple bolds can be used to clamp and lock the moulds. For long-cycle-time tools, the time to fasten the bolts is not a major issue and the use of bolts will be cost-effective. For tools that quickly need to be fastened the use of hydraulic actuators can provide both closing and locking forces. Also, normal clamps can be used or other similar tools designed for RTM processes. [B.05]

D.4.1.4 Ejection of moulding

After the resin has cured, the component need to be demoulded. Some times this procedure is really easy due to the geometry of the component itself. If the component cannot be demoulded easily an ejection mechanism can be added on the mould. There Is a large variety of standardized ejection mechanisms.



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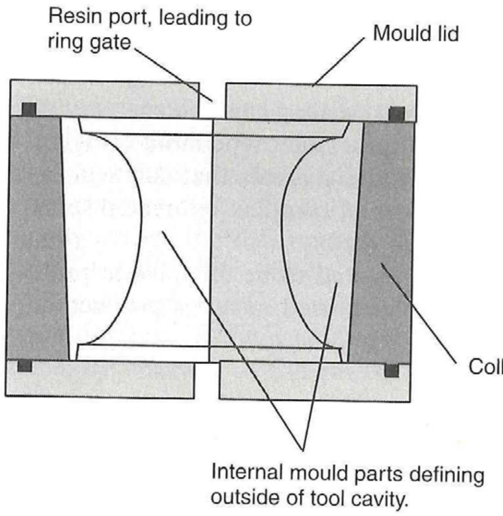

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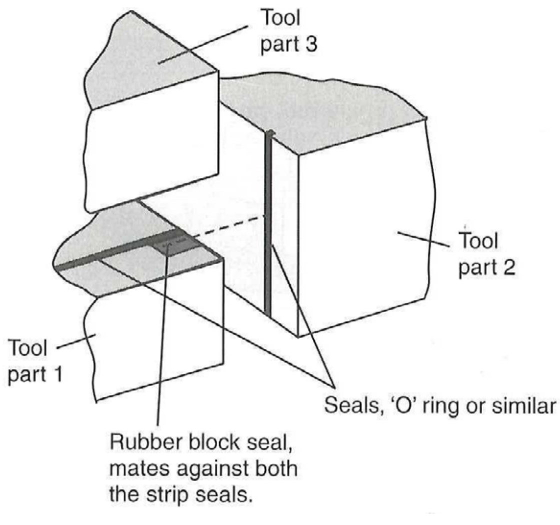

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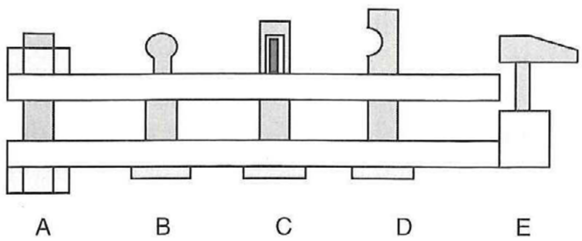


D.4.13

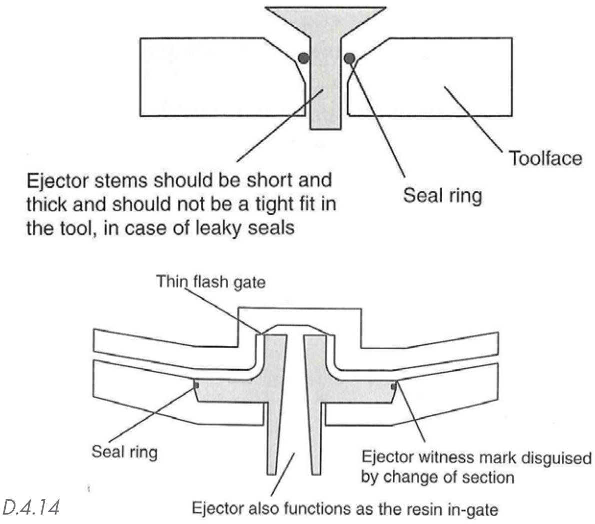
When implying such a mechanism on the mould it needs extra care so that the ejection does not damage the component. Also, the designer needs to acknowledge that this part of the mould will be shaped on the component as well. This might determine the position of the mechanism on the mould. Moreover, the mechanism itself needs to be sealed and protected from resin going on the component and damaging it. Finally, when colleted mould is used, there is no need for extractors since the mould parts fall away when the collet is opened.[B.05]

D.4.1.5 Integration of inserts into RTM moulding

Integrating inserts on the component during its manufacturing can lead to more complex mould, and mould loading, nonetheless it is possible to be done through RTM process. Typical inserts could be metal plates or threaded inserts, big-head type fasteners, tubes etc. Also moulding a hole on the component also is succeeded via similar approach. Integrating inserts and usually connections on the mould might be structurally more beneficial than post-moulding operations or drilling, but more aspects need to be taken into account, such as the compatibility of the materials, due to the high temperatures that occur during resin curing.[B.05]

D.4.1.7 Resin distribution

The correct place of the injection and vacuum system can determine the quality of the component, in terms of homogeneous resin to fibre rating and creation of air gaps. When the shape is simple there is much of such danger, but as the shape of the component gets more and more complex the chances of defects rises. On the other hand, these problems are not so severe when the moulds can evacuate to very low absolute pressures prior the injection and the seals guarantee no resin leakage during injection. Also the vacuum will ease such problems of uneven flow but will not eliminate them completely. For those



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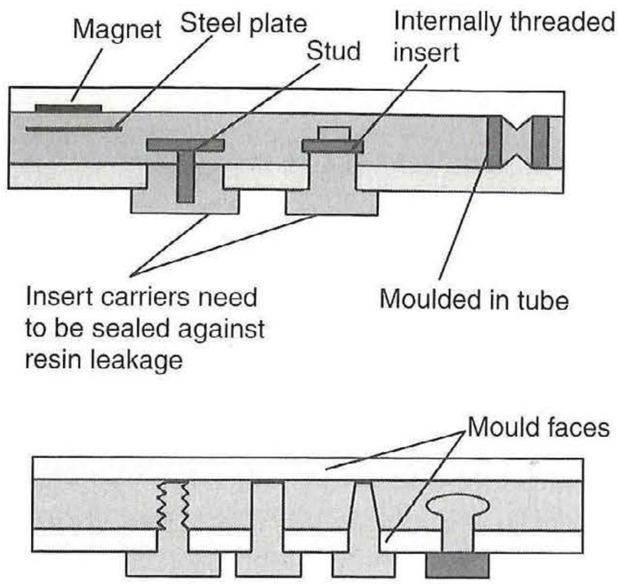


D.4.15

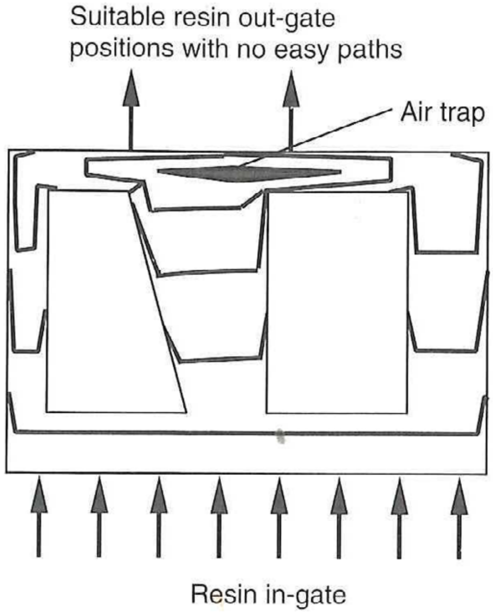
D.4.14 Injector examples for demoulding facilitation
D.4.15 Examples of insert integration in the mould and hole design
D.4.16 Graphical study of proper resin gate design for irregular shapes
D.4.17 Resin gate design example for boat-like geometries
D.4.18 Fibre warping around core for sandwich FRP production

reasons, it is essential to predict beforehand the resin distribution and decide upon the position of the injection and vacuum systems. Typically in circular or rectangular shapes the injection is done from the perimeter of the mould and the vacuum is placed on the centre. For high aspect ratio of rectangular parts the resin gate is placed centrally and the vacuum on the perimeter to avoid voidage. In that case also a line gate along the long axis could be used to ensure that the flow length is close to equal to all the points.[B.05]

D.4.1.8 Sandwich panel design for RTM

When manufacturing foam core sandwich components the resin is flowing on both surfaces. During this manufacturing the upper and lower surface need to have the same resin flow, otherwise an internal force is created that pushes the foam towards one side of the mould. This will result in uneven mechanical properties of the component on the different surfaces. In order to overcome this problem the permeability of the core need to increase, so that the different surface pressure will even during the entire process. A common solution is to implement fibre-reinforced ribs on the core, which will also reinforce the mechanical properties of the component.[B.05]

RTM process is frequently used from the automobile and aeroplane industry due to the good mechanical properties it offers, the good control of the reinforcement orientation along with the high fibre fractions, the potential resin and void-rich areas rate and finally the well-controlled surfaces finishing. Such examples are the entire self-supporting body of the Swedish all-terrain military caterpillar vehicle no. 206, which uses E-glass fibres and polyester resin along with PVC foam core. And other application of producing FRP sandwich with RTM process are the propeller blades Fokker F50, Saab SF340 and Bell LCAC hovercraft, where preformed layers of carbon fibres and fabric held together with a binder



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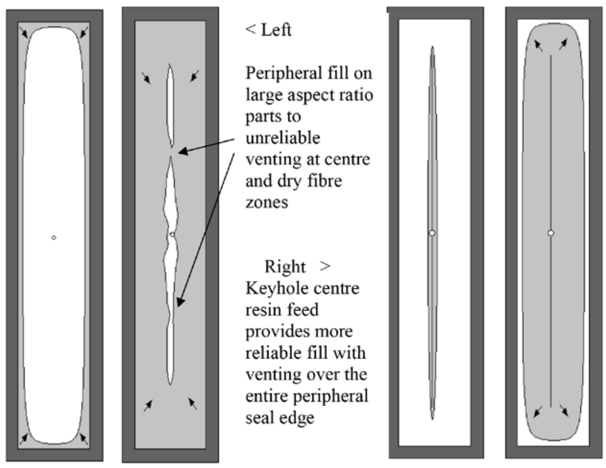

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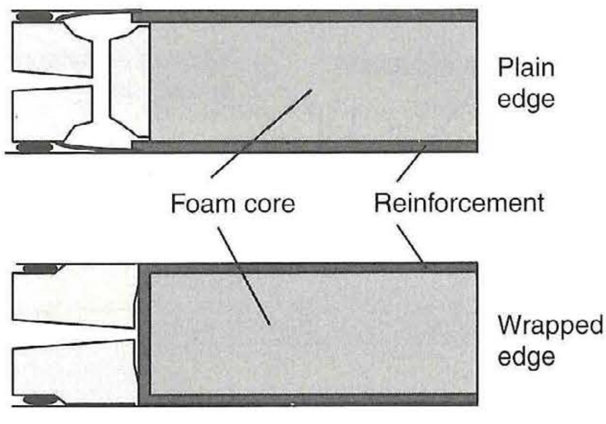


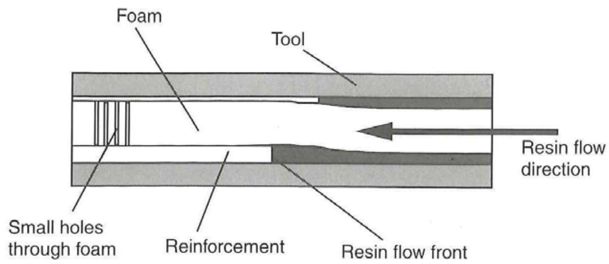
D.4.18

are stacked and inserted into the blade mould where a PUR core is foamed in situ. The metal fittings are added together with leading edge reinforcement layers and an aluminium braid for lightning protection. Those different parts are assembled together on the RTM mould, which is heated to reduce the epoxy resin viscosity during vacuum-assisted injection.[B.05]

D.4.1.9 Light resin transfer moulding

Light resin transfer moulding is an improved version of resin transfer moulding, where one of the two moulds is made as light weight sheet composite and can be reused, unlike Film infusion. After clamping the moulds under vacuum, catalysed resin is then injected at low pressure. The resin follows the injection path around the product cavity which converges to a central vacuum point. The two moulds are clamped to each other via the perimeter flange of both moulds, as in RTM process. Today the flange is much simpler than the beginning of the RTM process. It is enough for a parallel gap of no more than 1mm to be built into the matched mould flange and the necessary clamping vacuum force is produces. As a result of this evolution less evacuation is needed in the beginning of the production cycle and hence less building cost and energy is required. [A.07]

Furthermore, sealing the moulds around a perimeter flange is essential for LRTM as well. Big variety of seals exists for LRTM process, similar to the ones for traditional RTM. For LRTM two seals are necessary. The primary seal is positioned as close as possible to the mould cavity and the secondary vacuum seal on the outer edge of the flange. In order for the necessary vacuum and resin management connection to be achieved to the LRTM closed mould a pipe attachment needs to be considered. For that reason inserts could be used on the moulds that are not standardized but are used broadly from manufacturing companies.[A.07]



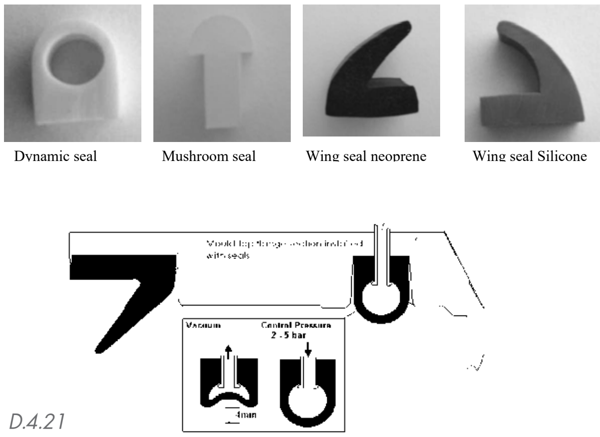
D.4.19

D.4.20

D.4.19 Moulding production of sandwich FRP elements
D.4.20 Example of light RTM manufacturing production
D.4.21 Different sealant examples
D.4.22 Different flange clamping examples
D.4.23 Mould requirements for light RTM mould design

Moreover, as in traditional RTM mould clamping is needed for the initial clamping of LRTM moulds and then the vacuum pressure to take over in order to fully close and clamp shut the moulds. For the clamping normally "G" clamps are used, but also a vertical sealed flange.[A.07]

Finally, with LRTM net shape moulding can be produced more accurately, with faster trimming operation, which means also less dust, less wastage and less cost. This is achieved through the gap between the resin feed and the mould cavity. Now this gap has been reduced to 1mm or less and thus the extra resin does not interfere with the fibres and is also easier to trim. In addition to that, the perimeter resin injection and the central vacuum that are normally used for this process can augment the quality of the final product even more.[A.07]



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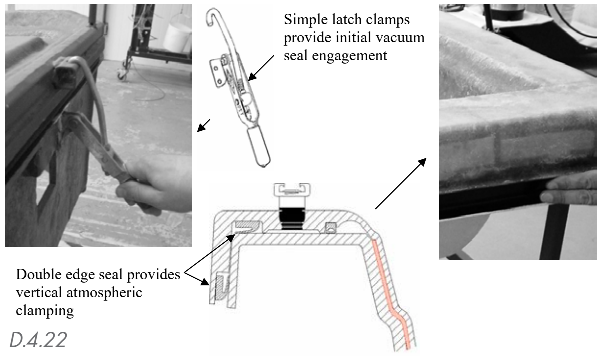

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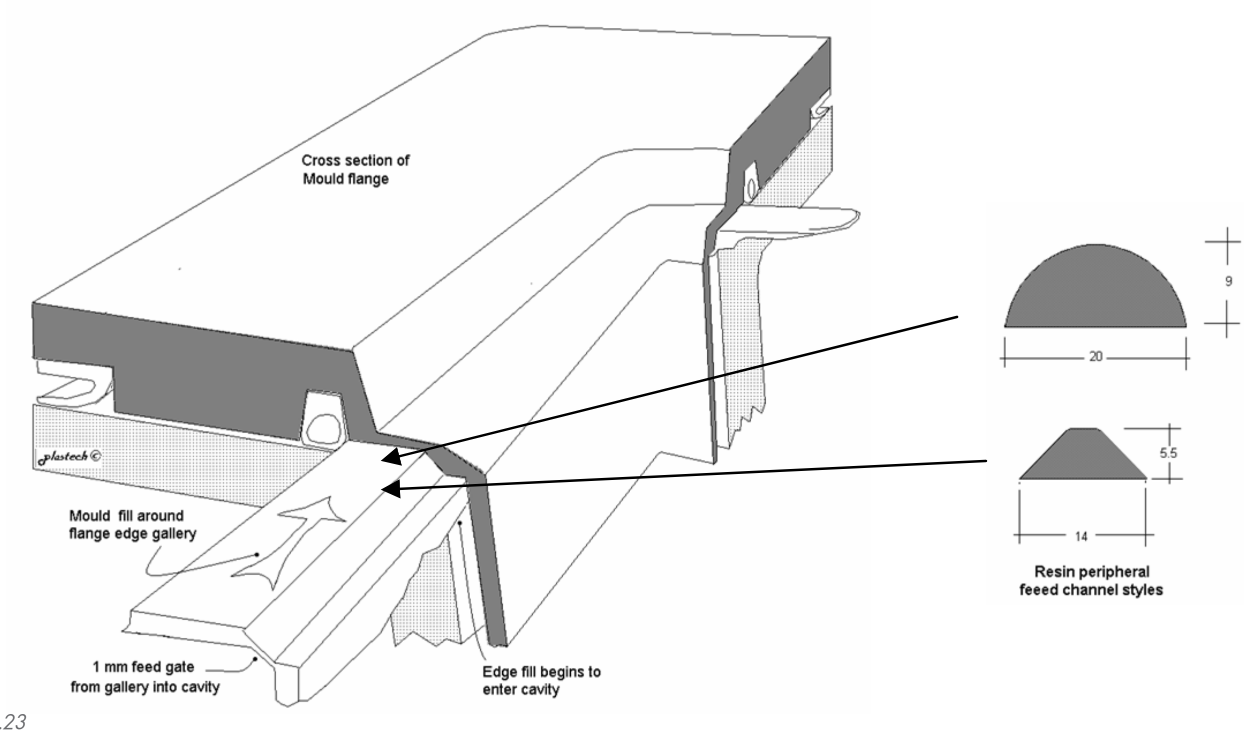


D.4.23

Modularity

E.1 Modularity

Modularity derived from dividing a product into independent components. This independence allows a firm to standardize components and to create product variety. Apart from design principle, product modularity also rationalize the product lines and hence minimises the production cost while in the same time increasing the different product variations. [A.08]

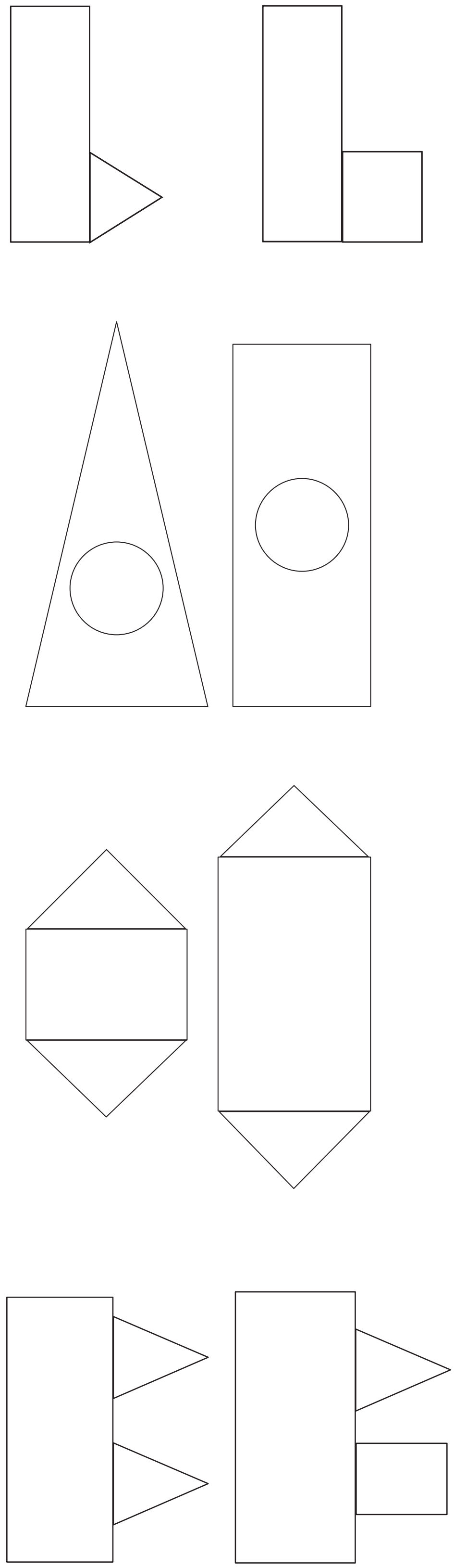
Moreover, modularity in principle intents to identify the independent, standardized, or interchangeable units, in order to cover a broad spectrum of functions. Hence, it extends to modular design process, product and manufacturing. In an ideal methodology all three aspects of modularity would be involved. So, a modular design process would be used to design modular products and to produce them using a modular production system or modular manufacturing processes. [A.9]

Furthermore, according to Erixon [8] the benefits of modularity extend to product life cycle, product development and design, variance, production, quality, purchasing, and after-sales. Namely:

- Economy of scales
- Increase of feasibility of product/ components change
- Increase of product variety
- Reduction of lead time
- Decoupling of tasks
- Ease of product upgrade, maintenance, repair, and disposal [A.10]

Finally, the characteristics of modularity methodology are generalised as follows:

- Use the finite set of components to meet the infinite changes of the environment.
- Establish the module by reviewing the similarities among the components.
- Keep as much independence of the resulting cells as possible.
- Use different modules for different varieties of assemblies. [A.10]



E.1.1

E.1.1 Modularity in products

Product modularity also implies the identification of physical structures and functional structures. Such decomposition allows the standardization of components and the creation of product variants. This results in components of modular products that have functional, spatial, and other interface characteristics that can create a variation of final products. The mixing and matching of different modular components generates a large variety of modular products, where each product would have a distinct combination of the modular components. As result these products have distinctive functionalities, features, and performance levels. [A.09]

E.1.2 Modularity in design problems

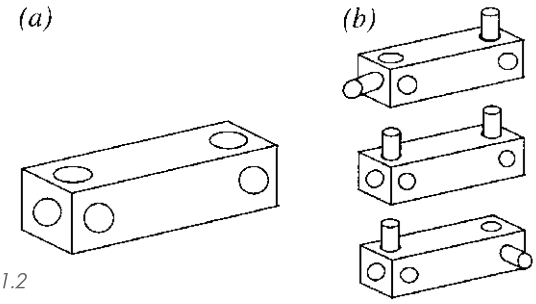
In this case modularity focuses on the decomposition of a complex problem into subproblems. By resolving these subproblems a solution to the main problem is also found. The broken down subproblems are strongly connected to the main problem and thus a different solution to the main problem could lead on a different main solution. [A.09]

E.1.3 Modularity in production systems

Modularity in production systems targets on standardizing modular machines. There are no standards for modular machinery, in order to build a modular production system, production machinery must be classified into functional groups from which a selection of a modular production system can be made to respond to different production requirements. [A.09]

E.1.4 Flexibility in modularity

The same modules can be arranged in different configurations and thus producing a variety of products. This flexibility is allowed via the connections of the modularized components. The system topology can be altered by changing



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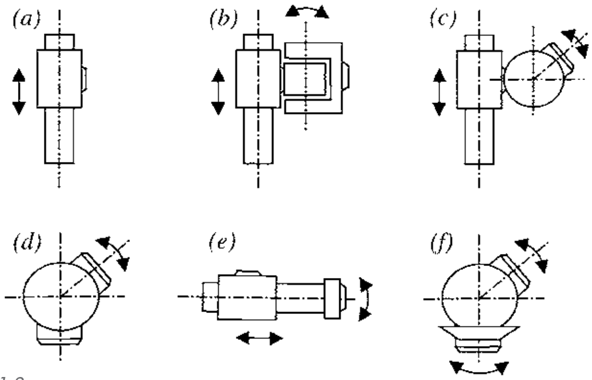


E.1.3

E.1.1 Module variations
E.1.2 Modular connection design placement
E.1.3 Modular connection design of different degrees of freedom

the number of modules according to different purpose. A characteristic example is the robotic systems, where different configuration of modules (joint and link) produce different result. [A.10]

E.2 Modularity principle

As has already been explained modularity has many different applications in different part of the design. For the specific project of bridge design a suitable modularity principle had to be determined in order for manufacturing the bridge series via the use of the same modules.

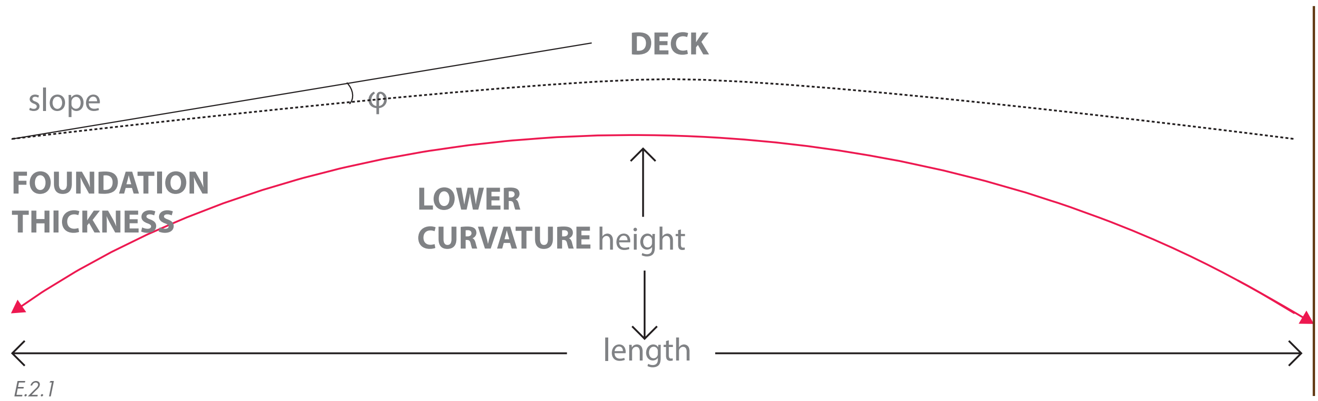
What was understood from the literature research of modular designed was that in order for the modular bridge to be designed firstly the bridge should be analysed according to its main elements, namely height difference, type(movable, arch etc), span. These parameters will determine the modules principles depending if they consist of a boundary condition for the final bridge design or not.

More specifically, Tanthof Delft that is used as case study, have shorted bridge lengths than the general area of Delft. Thus it was decided that the length of the bridge to be set as not-fixed in order to permit production of longer bridges for the rest of the areas in Delft. Also, in order to better facilitate the elongation in combination with no supporting elements on the canals design principle, an arch /curved beam shape was decided to be used as primary bridge shape.

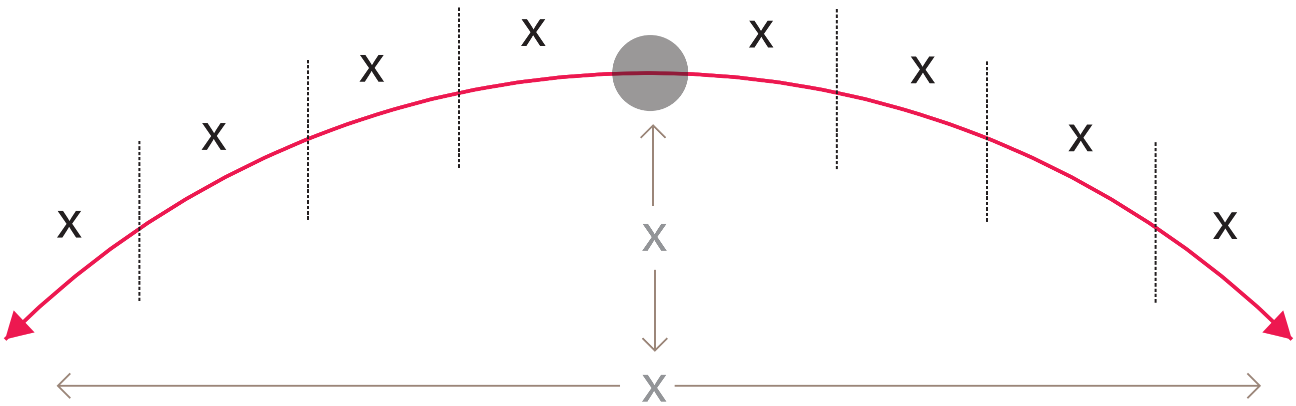
Furthermore, in the general Delft area demanding bridges concerning the free height below the bridge is demanded only on the central rivers, where commercial boats also use these water routes. For Tanthof Delft on the other hand there is no boat activity and only animals use the canals as water routes. Such a characteristic permits for shallow short bridges to be designed. As *Figure E.2.1* indicates the foundations height enlarges as the height curve and the deck curve disperses from each other. In that case the ending of the bridge would create an obstacle for the animal passing that is unwanted. Hence, a smooth curve, of low slope in between the permissible limits of 7-8% that would integrate both the bridge structure and the deck is ideal for the bridge series.

Lastly the module dimensions need to be decided as well. As shown on the Figure E2.2 a linear rhythm is decided for the project in order to permit further extension by adding more modules on respect of the bridge's curvature. In such a way, a range of bridge length would be covered through the re-use of the modules.

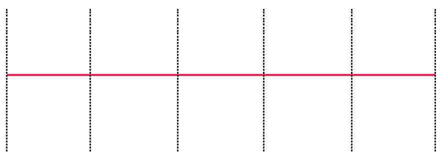
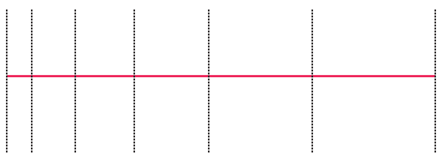
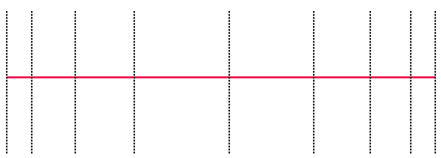
After setting the variables and the constants principles of the modularity pattern for the bridge series it is be explained how the specific data from the municipality where used in order to specify the module matrix of the bridge series.



E.2.1



E.2.2

	CRITERIAS	RESULT
	possible length expansion less modules possible	+
	fixed length more modules	–
	fixed length more modules	–

E.2.3

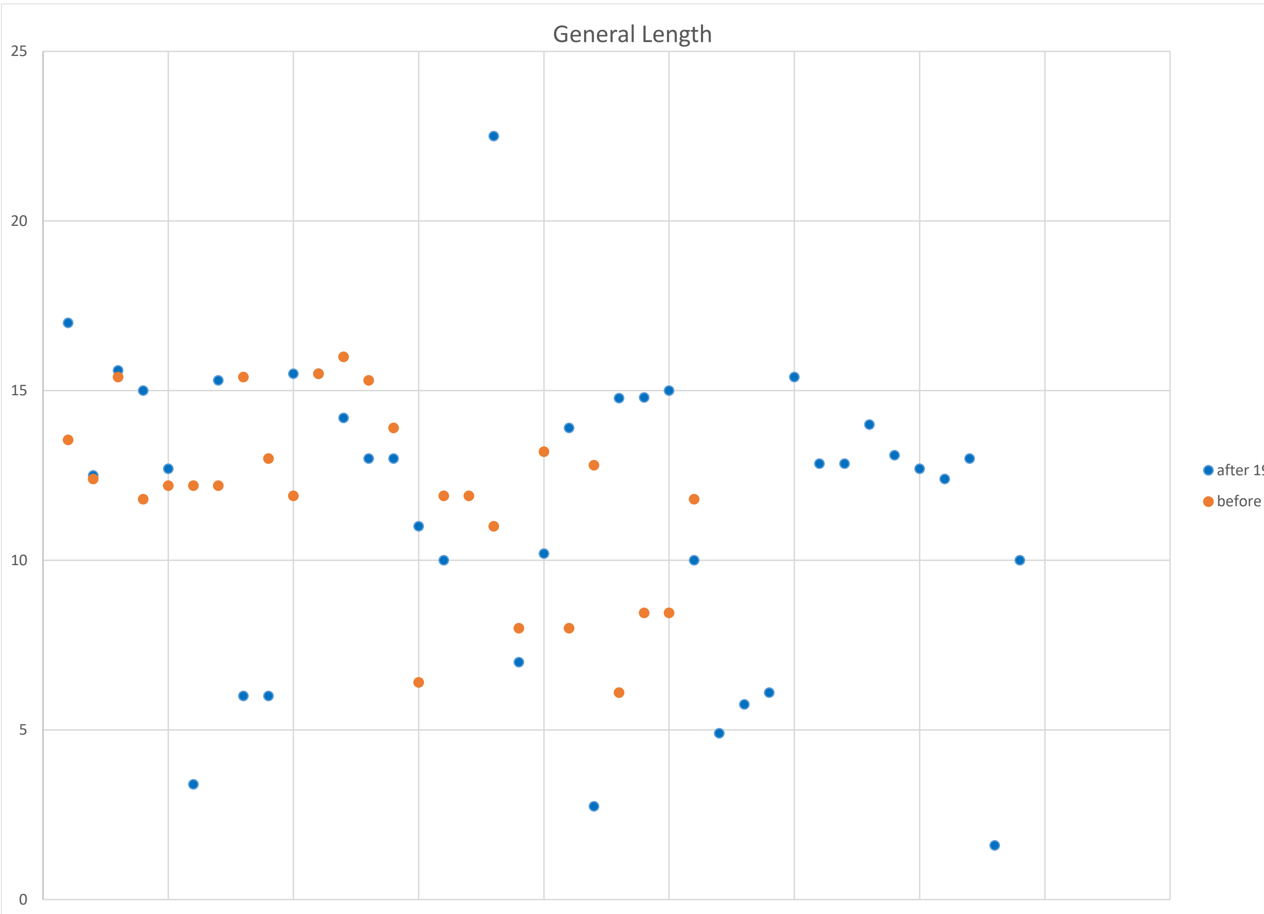
E.2.1 Analysis of bridge design elements
E.2.2 Final module sequence
E.2.3 Comparative table of different module sequence

E.3 Municipality data

In order for the modular design of the series of pedestrian bridges to be designed an area-case study needed to be found. In the beginning the area of Delft was selected due to its massive number of pedestrian bridges and its proximity to my working place. After a first try listing the bridges of city centre of Delft two important conclusions were made. First of all, it was realised how well integrated the brick bridges were in their surrounding and gave some guidelines for designing an integrated bridge in Delft area. Also, the bridge recording is an extremely time consuming process and an already recorded list needed to be found, otherwise there would be no sufficient time for recording the existing bridges and designing a new series.

After meeting with the Municipality of Delft a new solution was given. There is already a plan of replacing the wooden pedestrian bridges of Tanthof Delft, due to material aging or steep slope. Through their record of pedestrian bridges a further data processing would form the necessary modules. Unfortunately the pedestrian bridges of Tanthof are not subjected in some modular pattern and hence the designer should set its criteria by grouping.

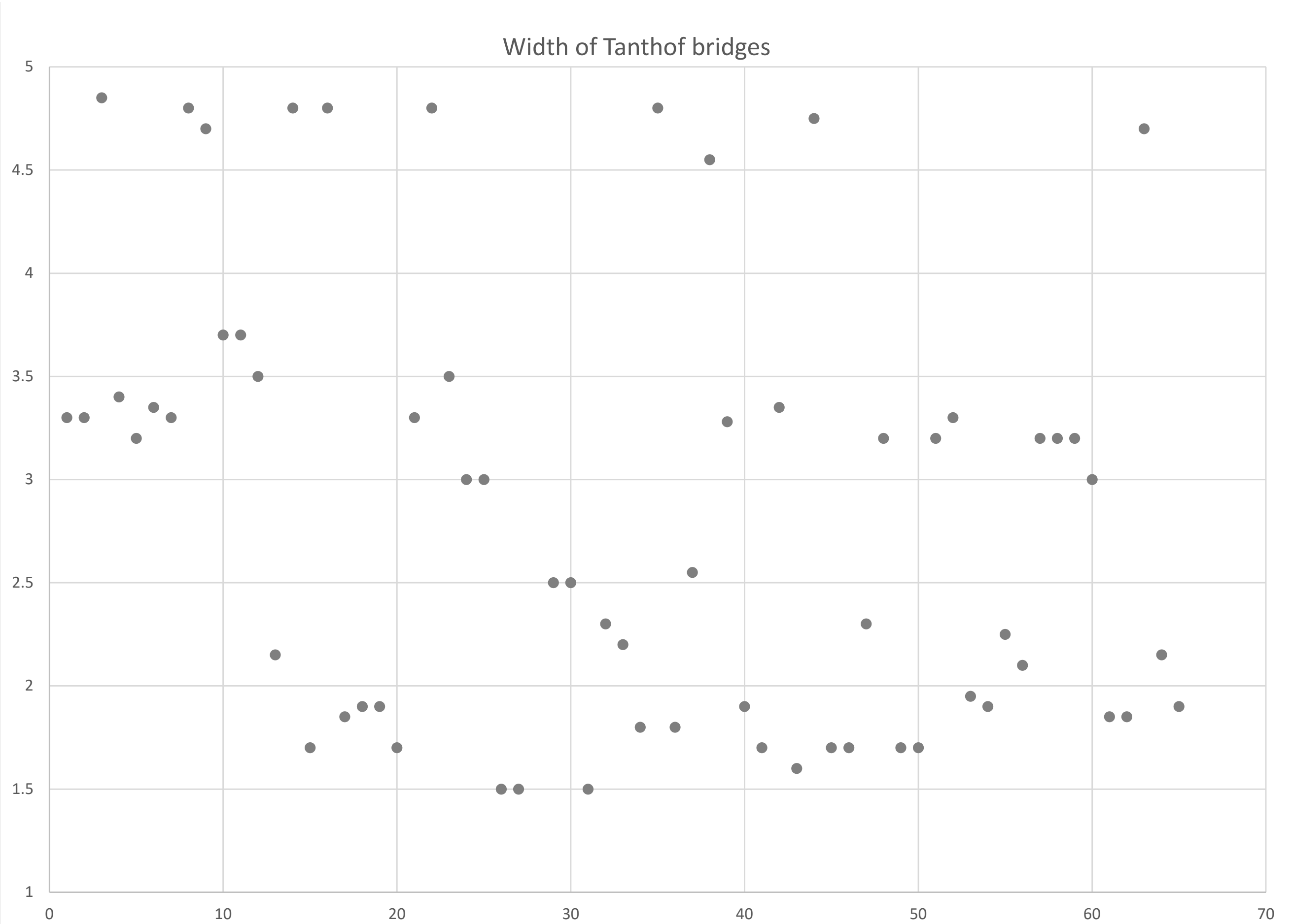
More analytically, the record from the municipality include information about the length, width, age, material and position of each bridge in the area. Those data are a general collection of information and need to be processed further in order to be used as scientific data.



E.3.1 Graph of all wooden bridges in Tanthof Delft according to length

To begin, the wooden bridges that need to be replaced needed to be separated from the rest population. Thus, according to the material criteria 10 were eliminated. The priority of replacement is be given to the ones made out of wood and steel and wood, due to material failure due to moisture. Thus the remaining population is 65 bridges. The next step is to separate again those bridges according to age and look into their general differences in dimensions and area locations. After plotting the necessary charts it was realized that this limit was insufficient, since there is a similar scatter of width and length throughout the ages of the bridges. And also, newer and oldest ones are placed throughout the neighbourhood. Even although the age did not eliminate the bridge population further, it needs to be taken into account for a cost-efficient infrastructure replacement schedule.

Furthermore, another interesting result from the first scatted chart was that except from the variable length that was expected, also the width of the bridges varies significantly. Even if the use of the bridges are similar: pedestrian use and pedestrian/cyclist use the standard deviation is almost 1m in an average width of 2,8m. The height of those statistical indicators revealed the need of focusing more on the width variation and explore the reasons for that enormous deviation. Moreover, due to the geometry of the shell-like mould, the width consist of one of the geometrical boundary conditions of the shape. Thus the existing bridges will be grouped into different width groups and be treated also differently. In order to create the different groups again the first



E.3.2 Graph of all wooden bridges in Tanthof Delft according to width scattered graph will be used, in order to check and delete any outlier.

To sum up, the existing Municipality data gave all the necessary information in order to form the necessary modules. From the existing data it was shown that the bridges should be grouped depending on their widths and vary on their length. For that reason three new width categories were proposed according to width needs of every group. More analytically the series of footbridges would offer the option of two (2), three (3) and four (4) lines. The total population of the bridge series will be 64 bridges, since one more was eliminated as length strongly deviated from the general population.

E.4 Module matrix

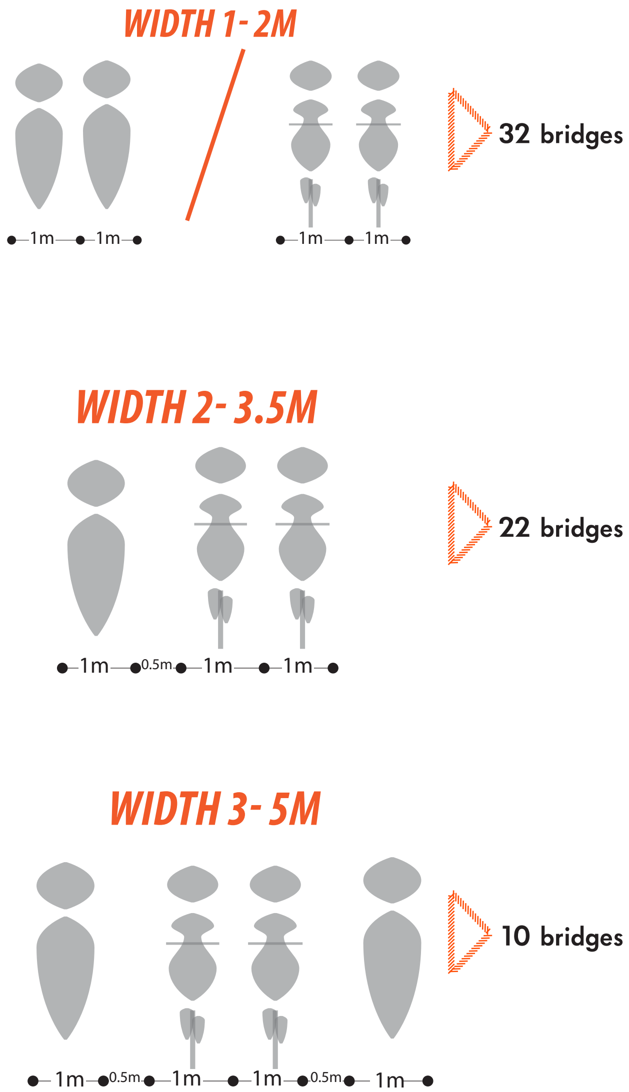
After analysing the Municipality data of the wooden bridges that will be replaced, the existing data was grouped in three different categories according to their width. The new width groups are of 2m with population of 33 bridges, width of 3.5m and population of 22 bridges and last width of 5m and 10 bridges population. The bridges are spread all over the area and mixed together, without an urban logic of bridge placement per width. What can be seen from the charts is that "Width 1" is spread across all length range, "Width 2" from 10m to 17m length and "Width 3" extends to 12m and 16m length bridges.

Even if some width categories extend in different length ranges than others, for the simplification of the project the design of the bridge series will still be considered to include all the possible length ranges. Also, as mentioned before the length range is spread along the possible bridge length without some specific pattern and thus the designer needed to rationalise the length that the series of pedestrian bridges would include.

Moreover, the given lengths would be determined from the mould modules that would

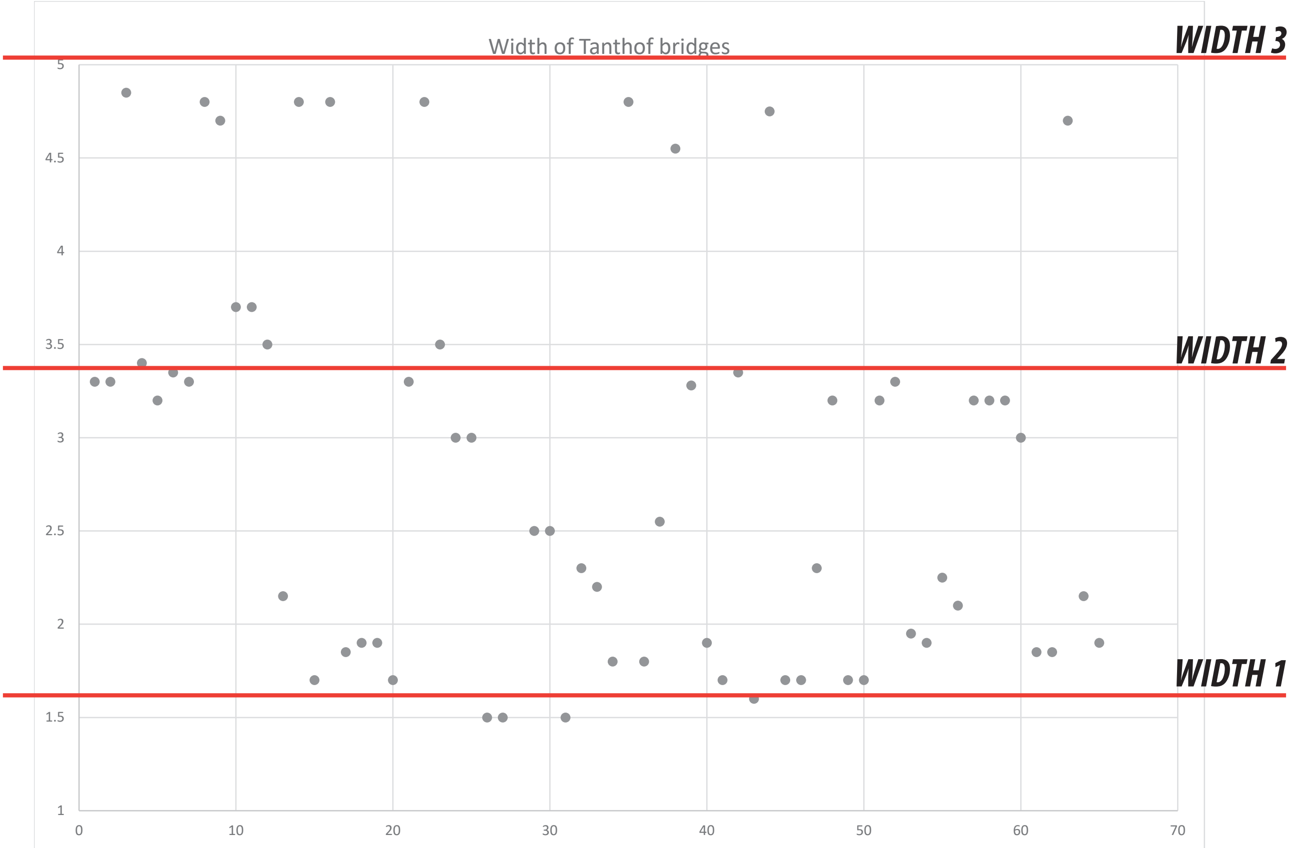
GENERAL BRIDGE NUMBER	75
WOODEN BRIDGES	65
FINAL BRIDGE POPULATION	64

E.3.3

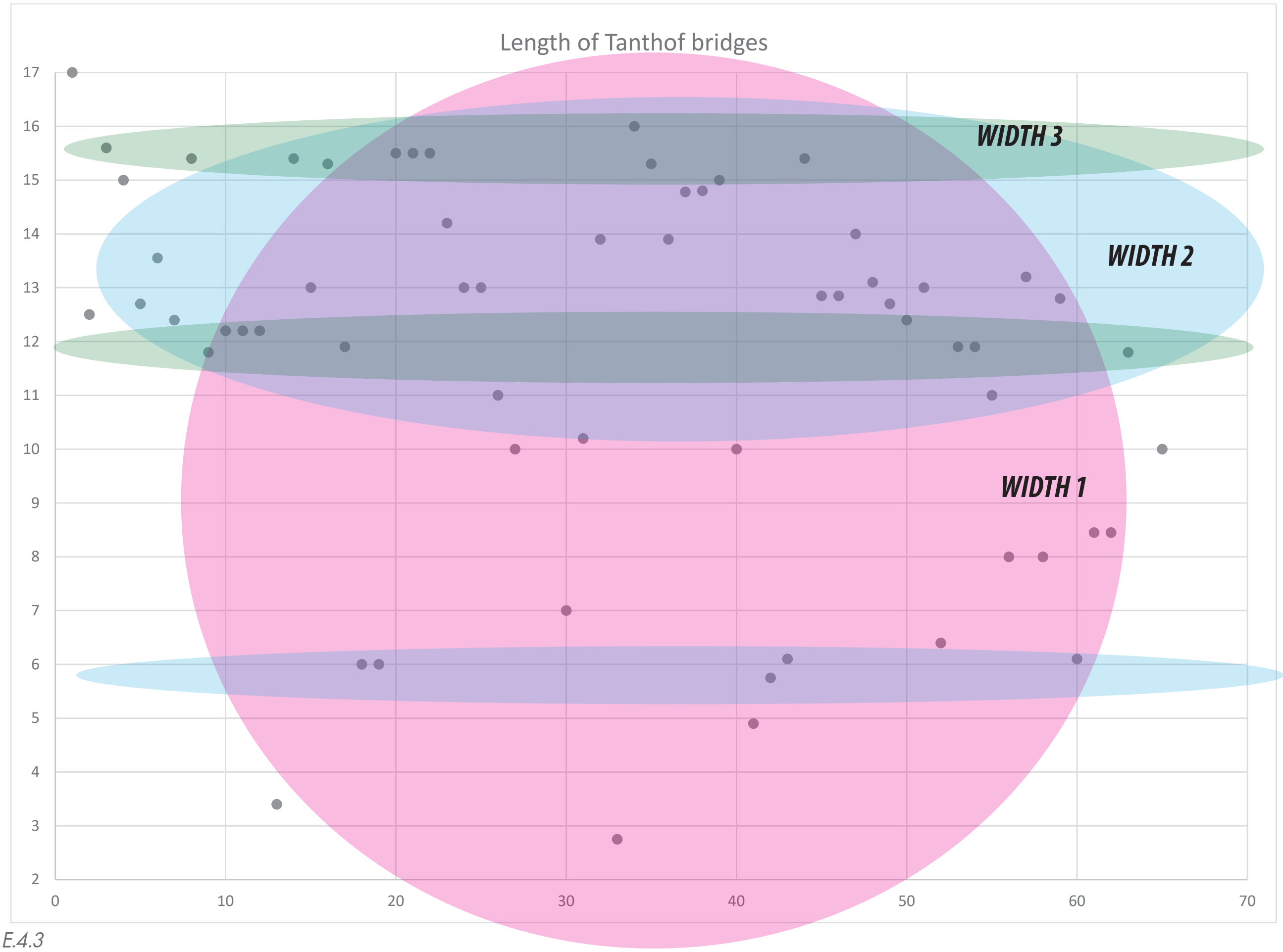


E.4.1

E.3.3 Table of bridge population
E.4.1 Width categories
E.4.2 Graph of new width categories
E.4.3 Existing width groups spread


Width of Tanthof bridges
WIDTH 3
WIDTH 2
WIDTH 1
5
4.5
4
3.5
3
2.5
2
1.5
1
0
10
20
30
40
50
60
70

E.4.2

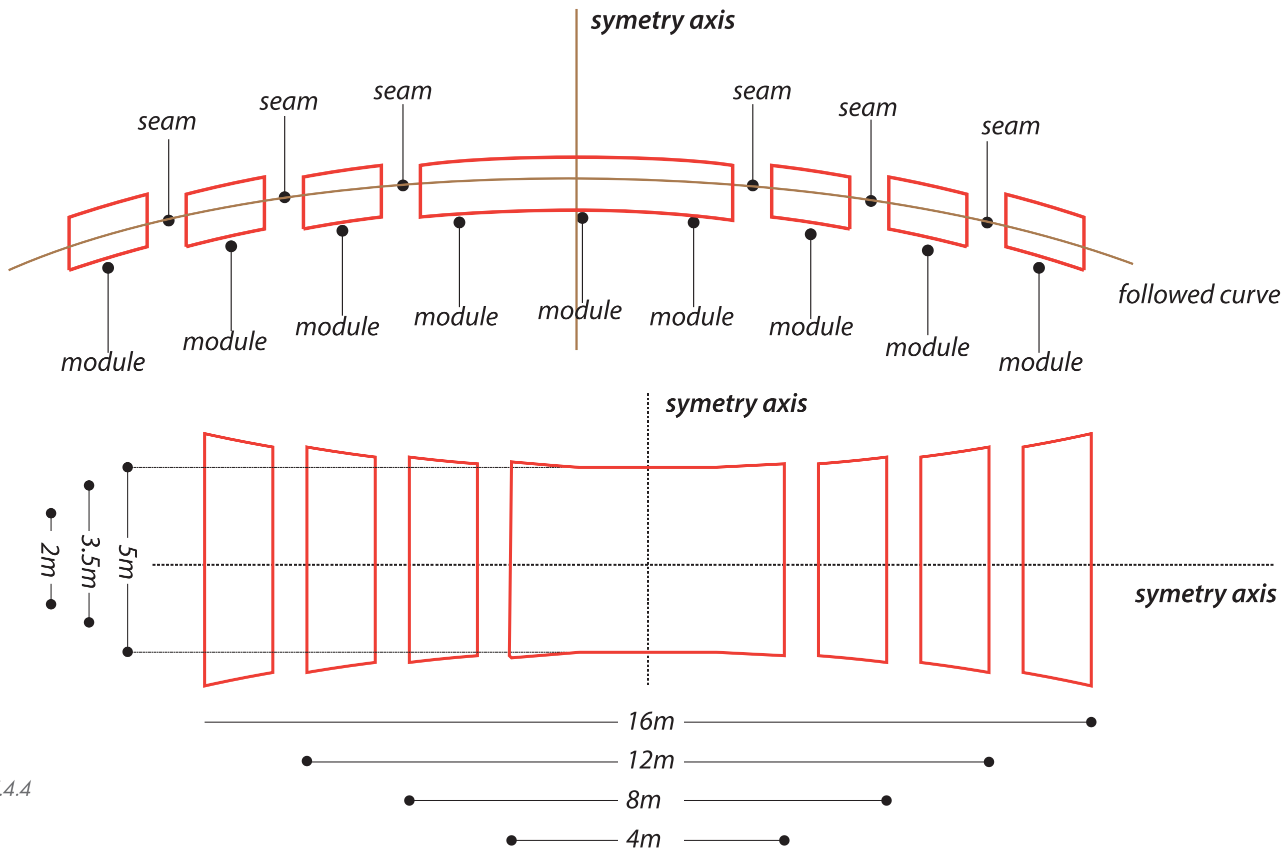

Length of Tanthof bridges
WIDTH 3
WIDTH 2
WIDTH 1
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
0
10
20
30
40
50
60
70

E.4.3

manufacture the FRP bridge structures. After the previous research it was decided that the mould would have a main centre point and the different lengths would be determined from symmetrical parts that would be added left and right of the main mould. Two end moulds would complete the manufacturing mould and would include the foundation connection requirements as well.

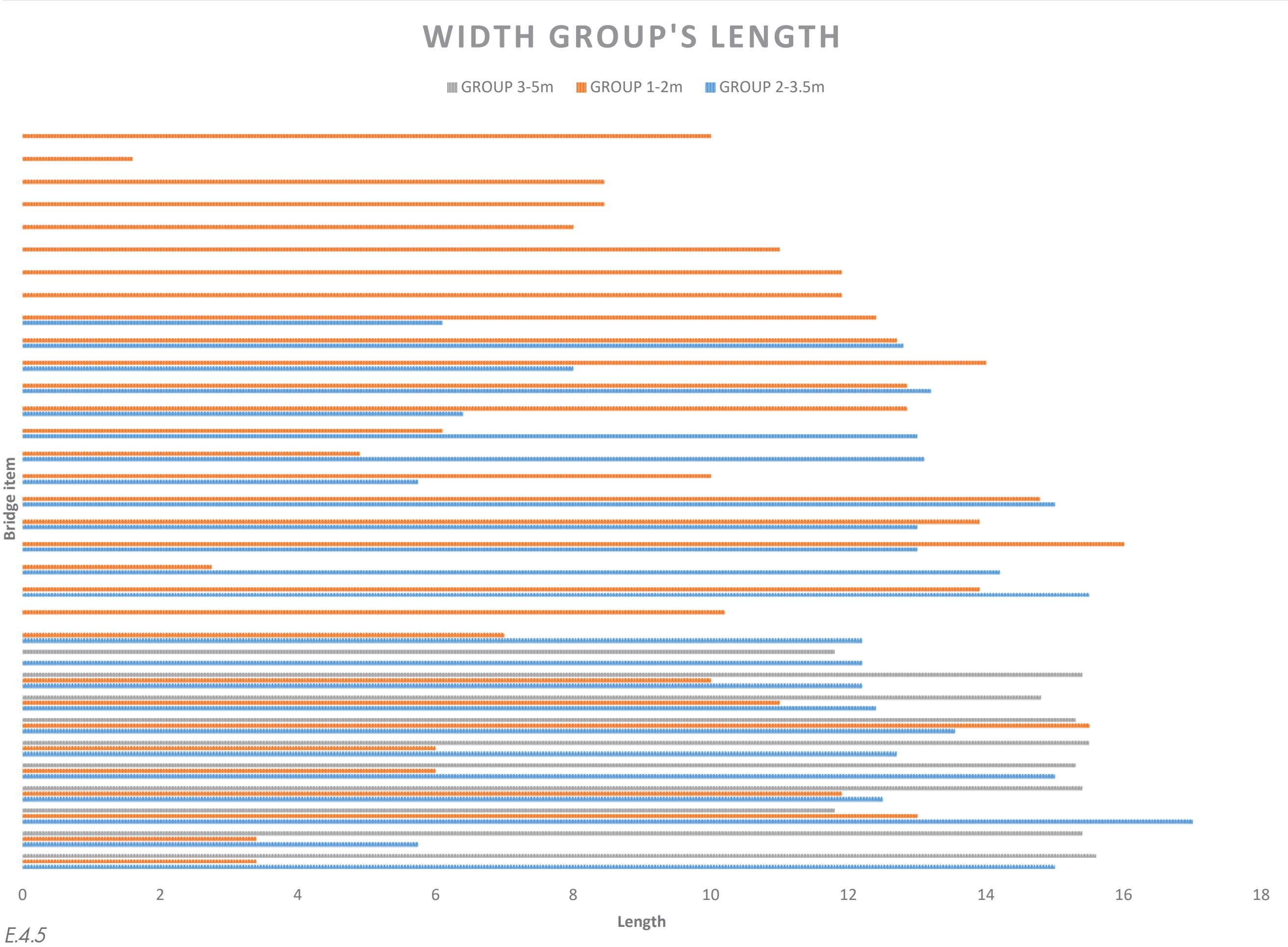
As starting point, the manufacturing mould would be able to produce structures with non strictly determined lengths, but the manufacturing method of Resin Transfer Moulding (RTM) that was selected as more appropriate manufacturing technique, would not allow for such dimensional freedom, due to the fixed shaped upper and lower mould parts. Afterwards, as an alternative, it was decided that more fixed length dimensions would be determined for the products of the bridge series. In order to minimize the mould numbers and their connections the dimensions of the mould parts were optimised to the larger possible. Hence, through studying the length values where more bridges are concentrated and creating a new repetition patter the following lengths were determined: 4m, 8m, 12m and 16m long. Those lengths would be available for all the three different width groups.

Finally, since there is no strict restriction of the canal width, a tolerance of ±1,5m, meaning ±0.75 from every side is permitted due to foundation area manipulation.

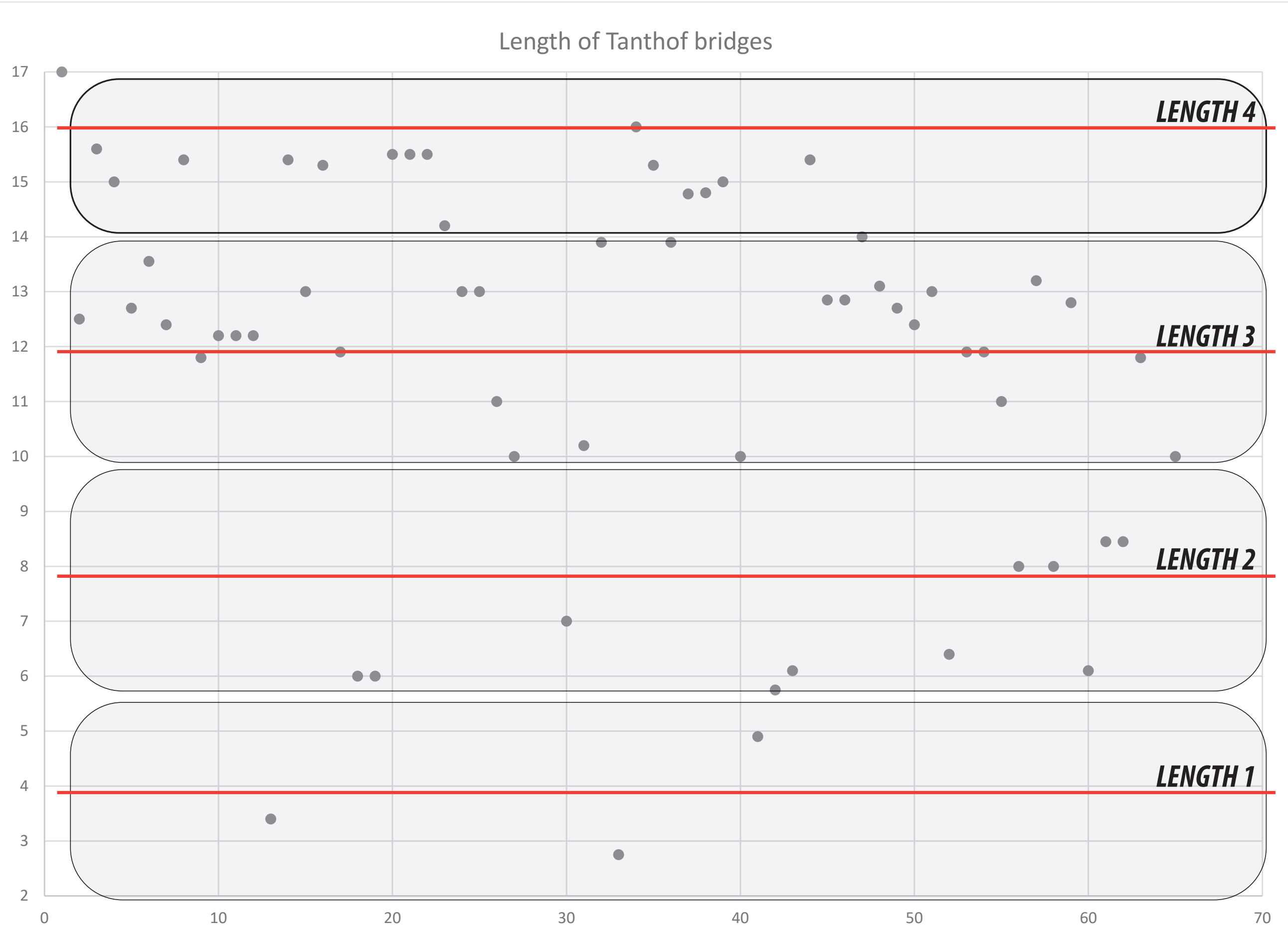


E.4.4

E.4.4 Module matrix
E.4.5 Graph of length per new width group
E.4.6 Graph of new length categories with tolerance of +/- 1.5m


WIDTH GROUP'S LENGTH
GROUP 3-5m
GROUP 1-2m
GROUP 2-3.5m
Bridge item
0
2
4
6
8
10
12
14
16
18
Length

E.4.5


Length of Tanthof bridges
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
0
10
20
30
40
50
60
70
LENGTH 4
LENGTH 3
LENGTH 2
LENGTH 1

E.4.6

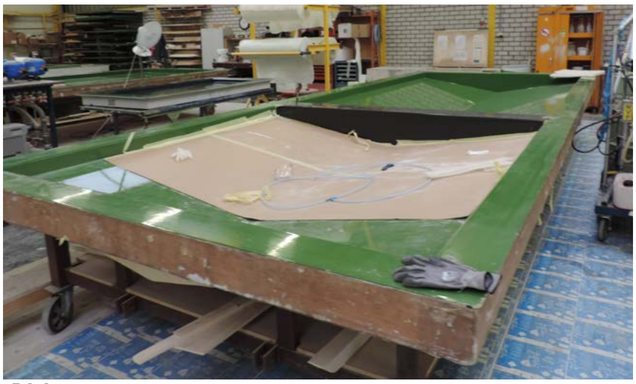
Bridge design

F.1 Case studies

F.1.1 PolyProducts

During the research I had the chance to visit PolyProducts facilities and discuss with Mr. Jeroen van der Vlis on the moulding technology for fibre-reinforced polymers. In general, PolyProducts is a manufacturing company of third party. Their clients come from a broad spectrum of composite applications. Their expertise and flexibility derives from their collaboration with different industries and from products of different scale, as it will be explained later. Here, some of their projects are mentioned to explain the broad spectrum of mould applications.

Firstly, the bus steps project consists of big batch and thus more moulds were used in order to produce more final projects by the hour simultaneously. Since this project is not a load-bearing structure that need excessive structural calculations, plywood is used as an



F.1.1

F.1.2

F.1.1 Adjustable mould with linear stop
F.1.2 FRP prefabricated house
F.1.3 Metal scale adjustable mould for FRP chimney
F.1.4 FRP chimney
F.1.5 FRP step mould
F.1.6 FRP translucent facade

F.1.3

F.1.4

F.1.5

F.1.6

embedded stiffening element. Furthermore, for the translucent canopy they imitated the structural logic of the sandwich FRP, were the core was also FRP honeycomb shaped. The use of FRP in such a geometry offered the translucency that was desired by the Architect, and also provide the necessary structural capacity. Of special interest was the kitchen range product. The company had a specific design as order, but since they saw potentials for further orders, they made a mould of adjustable analogies and "head" orientation. More specifically, the kitchen range they divided the geometry into 3 moulds. 2 out of polymer for the curvy "head" and one for the main straight surface body. The separation of the "head" (with the square outline base) along with the adjustable outline of the "body" mould gives them the ability to produce 3X4=12 different products. Finally, the prefab house of PolyProduct is another example of massive production with adjustable dimensions. Every element is produced via Vacuum Injection moulding, for cost-efficiency reasons and using a linear stop the dimensions are determined.

F.1.1.1 Footbridge Harlingen technique

The Harlingen footbridge is the first all FRP footbridge in the Netherlands. It has 16 meters length and 2 meters width, produced by PolyProduct in 1997 for the Rijkswaterstraat and is placed as the way to the ferry on Harlingen. For this product Polyproducts also used a mould and produced the one-piece monocoque bridge with no extra connections, easy to transport and install. The architectural design was based on the structural design, thus a U-shape FRP section with embedded core ribs as stiffeners. The railing was integrated on the structural scheme (U-shape section). Furthermore, the bridge was produced by the mould technique. The mould was placed on the inner surface of the bridge, so that it would facilitate the placement of the ribs. According to the manufacturer "*To obtain extra stiffness in the lengthways, the surface of the bridge and the railings have been equipped with polyester shafts that are filled with PVC foam. As the bridge must be able to support a pressure of 750 kilograms per square meter, the strength was of course extensively tested prior to, during and after its construction. In a cooperation with a local water company, over 30 tonnes of water was put on this bridge, and with a deflection of just a few centimetres, the bridge easily passed all parameters*" Finally, the downsize of that is that the external surface was not as smooth as the internal (parapet) and the railing could not be replaced, restricting the bridges appearance on the existing one. [W.07]

F.1.7 Harlingen footbridge installation
F.1.8 Harlingen footbridge transportation

F.1.7

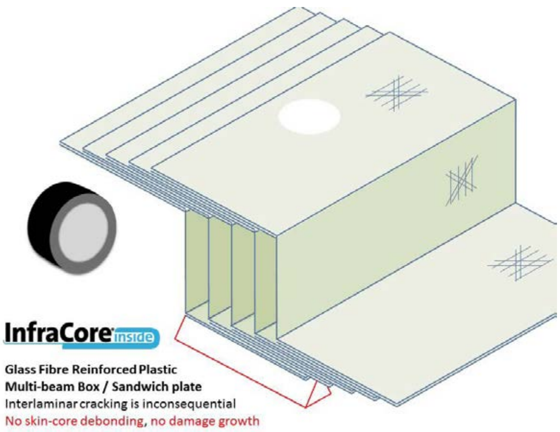
F.1.8

F.1.2 FiberCore

FiberCore is a company of expertise on FRP bridges. They are currently cooperating with the municipality of Rotterdam for placement of series of FRP footbridges across the area. FiberCore uses the adjustable-table technique, in order to produce the curvature of the bridge deck. This mould is a long table, which has retractable members that give the ability to produce the curve. The bridge is produced upside-down. Extra elements can be placed on that table, like the edge of the railing connection to the deck. After the placement of the fibres and the core, the injection moulding starts. The bridge cures during the night, so the next morning the product is ready for further processing. According to FiberCore, the production of a footbridge lasts 1-1,5 weeks.[W.08]

F.1.2.1 InfraCore® technology:

The Infracore® technology was developed from FiberCore and is a construction method for heavy load bearing panels. The essence of InfraCore prevents premature debonding of the skins from the core in sandwich-like structures. As shown below, Infracore® panels may be viewed as multi-web beams or plates, but without the drawbacks. This technology has also been implemented on pedestrian bridges achieving extremely slender decks, as The bridge is on the Excercitiestraat (Crooswijk), which deck is only 25cm. [W.08]



F.1.9

F.1.10

F.1.11

F.1.9 InfraCore deck architecture
F.1.10 FiberCore FRP footbridge designs
F.1.11 FiberCore FRP footbridge intallation
F.1.12 Exercitiestraat bridge railing
F.1.13 Exercitiestraat bridge railing failed test
F.1.14 Exercitiestraat bridge railing production mould

E.1.2.2 Series of bridges for Rotterdam

During 2014 FiberCore announced a second batch of 28 footbridges for Rotterdam. Their length varies (22.5m to 4.5m) but their layout is always the same. FRP deck with metal railing. The FRP deck is produced with the adjustable mould and the InfraCore technology. An important element of that layout is the replaceable railing, thus this gives the different character of every bridge. By making the railing removable the bridges can be renewed, by changing their fanade, ormaintained, in case the railing gets damaged.[W.08]

Furthermore, the newest footbridge of FiberCore had also FRP railing, manufactured by Jules Dock. The bridge is on the Exercitiestraat (Crooswijk). It is 20 metres long and 1.9 metres wide and yet its thickness amounts to a mere 25cm.[W.09] This is possible because the bridge and its railings are made from fibre-reinforced polymer. This exceptionally strong material is light in weight, making the building of super-slender bridges possible. The railings of this particular bridge are unique- never before has a bridge been styled with an intricate yet slim line composite railing construction. Even though it was not designed beforehand, the railing benefits structurally the bridge, since it increases significantly its stiffness. On the other hand the use of adjustable table for the manufacturing of the deck restricts its shape into no organic shape and more connections are needed comparing to the PolyProduct design, since the railing can be replaced.

F.1.12

F.1.13

F.1.14

Footbridge Harlingen			
Criteria		**ADVANTAGES(+)**	**DISADVANTAGES(-)**
DESIGN:	*All FRP footbridge*	unified appearance	
		Monocoque piece with no extra connections	• Non replaceable hand railing • Difficult renovation in the future (nonadjustable design)
		Visible structure	• Resembles of steel construction • Repetitive monotone facade
STRUCTURE:	*U-shape beam*	Integration of railing on the shape of the structural scheme	Impossible maintenance of the hand railing
		Straightforward structural shape	• Heavy appearance • Non organic free form shape • Use of only one cross-section
	Foam rib reinforcement	Clear-orthological design based on structural behavior	• Morphologically monotone design • No optical qualities(solid surface)
		Adjustable length and height (change the rib dimensions and amount)	Re-estimating the rib dimensions
MANUFACTURING:	*Use of one mold*	Place the mold on the inside face, changeable outside outline	• Inner surface polished. • Non polished Façade
	Use of lay-up technique	Manufacturing more bridges as the same time	• More working hours • Appearance of the bridge based on the of the worker
TRANSPORTATION-CONNECTIVITY-ASSEMBLY	*Truck Transportation*	One piece no extra connections(less installation time)	
		Easy transportation and installation(light weight)	
		Simple foundations	
Conclusions:	• **Architectural design is outbalanced by the Structural design** • **The placement of the mold on the inside face gives the possibility of reproducing the design for different structural requirements(different placement of the ribs)** • **No extra workability is needed after the finish of the molded piece**		

F.1.15 Polyproduct manufacturing philosophy comparative table

Series of footbridges for Rotterdam			
Criteria		**ADVANTAGES(+)**	**DISADVANTAGES(-)**
DESIGN:	FRP slab with metallic railing (FRP railing for Excercitie Bridge)		• Non-unified appearance • Appearance like steel bridge
		Economic (material+manufacturing) railing	Different material, parts with different mechanical behavior
		Different façade per railing	• Extra connections after molding • Embedded connections on the mold-detailing
STRUCTURE:	InfraCore technology (composite sandwich curved slab)	Different cross section	• Limitation on structural scheme of the footbridge
		Slim composite sandwich thickness	• Use of technique (InfraCore) for high load traffic to footbridges.
	Nonstructural railing	Easier maintenance of the railing- no extra support for the self-height of the bridge	• Extra connections • Post processing of the bridge
		Variety of railing-different architectural design	Extra time for manufacturing and designing
MANUFACTURING:	Use of adjustable mold (adjustable curve)	Easy adjustment of different curves	• Inner surface polished. • Non polished Façade • One bridge at the time
	Use of injection molding technique	No extra working hours	One bridge per injection machine
		Precision on material use	One bridge type per curve
TRANSPORTATION-CONNECTIVITY	Truck Transportation	One piece slab no extra connections(less installation time)	Railing extra piece (more time to connect it to the slab)
		Easy transportation and installation(light weight)	
		Simple foundations	
Conclusions:	**• Architectural design not integrated with the Structural design. The railing and the slab are not integrated.** **• The use of the InfraCore restrict the overall design using a design that imitates more a steel welded construction than a free form composite architecture** **• The separated hand railing facilitates the renovation-maintenance and provides a variety on the bridges façade, even with the same structural scheme.**		

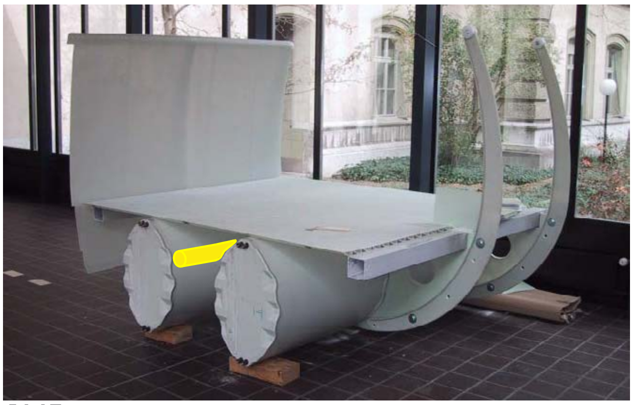
F.1.16 FibreCore manufacturing philosophy comparative table

Two more projects were selected in order to investigate also the experimental stage of FRP footbridge design. Both of the following academic projects were build, but not in terms of massive production.

F.1.3 Swissfiber, ZHAW (Zurich University of Applied Sciences)/ Staubli, Kurath & Partner AG, Variocell 02, Zürich, 2001

Zurich University of Applied Sciences designed and build a modular FRP footbridge in 2001. The modular footbridge unites detachable and fixed connections for moulded parts. Each oval main beam section has end plates with multiple integral interlocking joints which are simply butted together and tightened against each other with integral steel cables. The design resembles more of a steel design with flat connecting plates between the modules. Also, the connectivity of FRP modules shows to be insufficient, and thus it is also necessary to use steel cables through the whole construction, in order to tighten every piece together. On the other hand, the idea of the design for the railing is innovative for their time. The FRP plates also have integrated the main railing elements. The gap between them is then covered by a curved sheet of FRP. This principle of rib railing could give great freedom on the design of the railing. The same design was used later for the Swiss National Exhibition on 2002, where the bridge itself was turned into a module and via middle extra connections those modules managed to create a straight footbridge for a lot of meters. [W.09]

F.1.17 Variocell 02 cross-section
F.1.18 Variocell 02 bridge



F.1.17

F.1.18

F.1.4 3TU, Bio-based composite footbridge, Eindhoven campus, Netherlands, 2016

The newer experimentation with FRP is the Bio-based composite 13m span bridge that was designed and build by TU Delft and TU Eindhoven, in the context of 3TU project, in 2016. The design is based on a sectional deck with non-structural railing. The walking surface of the structure is a low arc with a radius of approximately 50m with a maximum 6 ° slope angle. Important element of the deck are the fillet (rounded) edges of the geometry that add value to the smoothed appearance of the whole construction. Also, in order to express the bio-based content of the structure the railing resemble the organic form of the grass blades. The railing is manufactured as a, amount of flat elements that are attached on the side of the deck.[A.11]

Moreover, the innovation on this bridge is the use of bio-based composite material, nonetheless, the manufacturing and design also show importance. This design tried to exploit the free form potentials of FRP and also the geometrical freedom given by the mould technique, producing a natural-aerodynamic shape. For manufacturing that design also Vacuum Injection moulding was used. The mould technique gave the designers the necessary freedom to use different deck cross section enhancing the aerodynamic shape of the overall design and permitting to construct the cross-section optimized deck.

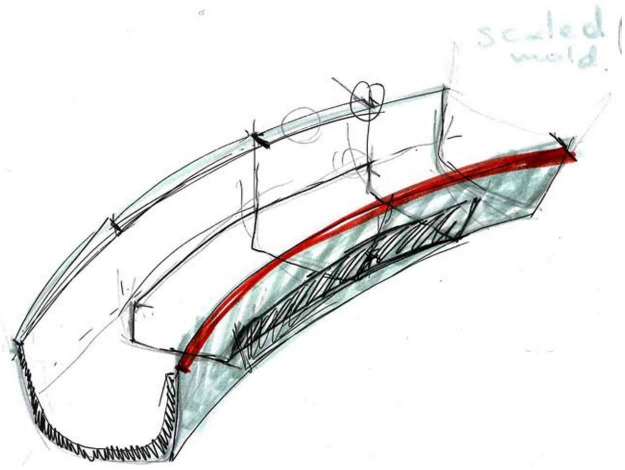
F.1.19 Bio-based composite bridge cross-section
F.1.20 Bio-based composite bridge

F.1.19

F.1.20

F.2 Design principles

After the literature review on the Fibre-reinforced polymer material and the technology on the moulding manufacturing technique a series of visits on Dutch manufactures relevant to pedestrian bridge manufacturing with FRP followed. During this period, discussion with experts gave me the opportunity to set the design principles for the bridge design of the series of bridges for the area of Tanthof. Also, this period was beneficial in order for the design limitations to be set as well. The principles and the limitations that derived from the discussions with FRP experts, footbridge manufacturers and case studies evaluations.



F.2.1

F.2.1 Design principles for the bridge design

In order for a series of bridges with integral architectural and structural aspects to be designed, both those aspects need to be set as design principles. Hence the design contains the following principles:

- Organic shape. In order to integrate on the natural environment by taking advantage of the geometrical assets of FRP and taking advantage of the stiffness of the double curved shapes, an organic double curved shape is attempted as the bridge and railing design.

- Bridge structure consists of one moulded piece. FRP is a material that will low maintenance need and thus ideal as infrastructure material. The commonly vulnerable areas of such structures are the connections and thus a one-piece structure is proposed.

- Modular design. A variations of lengths and widths are demanded for this project and thus a modular design where elements are re-used is proposed.


F.2.2

F.2.1 Modular mould primary idea
F.2.2 Sketch idea of Tanthof bridge
F.2.3 Project design principles

- Renewable facade. The railing is the most vulnerable part of a pedestrian bridge. Not including this part on the main structure of the bridge allows the easier replacement of the member in case of damage of renovation of the bridge facade of the entire series. In any case, the bridge as structure will be active and functional even without railing.

- No elements on the water and free space around the foundations for small animals to be able to cross over.

- Integrated functional requirements on the cross-section. Lighting and suitable flooring could be part of the cross-section, in order to provide an integrated result.

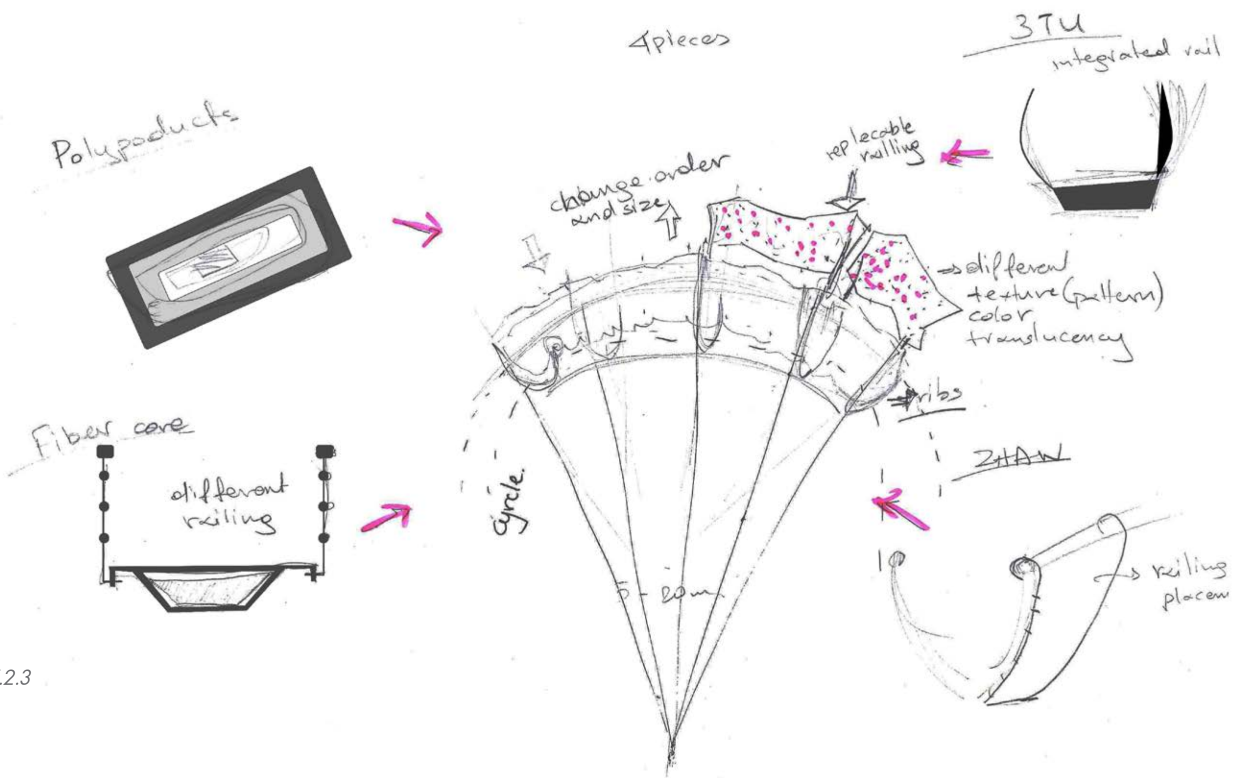
F.2.2 Limitation of bridge design

- Use of conventional material for footbridge manufacturing. As mentioned before there are special material like carbon fibres that have excellent mechanical properties, but are highly costly and thus are used in special aerospace applications. For this project special material will be eliminated from the selection and a more conventional one will be taken into account.

- Bridge dimensions suitable for Tanthof. Length variation between 4-16m with 4m step. Width variation based on functional criteria (number of lanes)

- Consider of no height difference between the covering span, in order to simplify the different sites.

- Examined on one load case. The structure will be simulated under 5kN/m^2 as proposed on Eurocode 0.



F.2.3

F.3 Tanthof Delft

The neighbourhood of Tanthof is located in the south of Delft, between Ruiven and Schipluiden. In the perimeter of the area the A4 highway, Kruithuisweg street and the railways can be found. The neighbourhood itself is divided in west and east Tanthof via Abtswoude street.

Tanthof is one of the old "family" neighbourhoods of Delft and consists mostly of housing areas of small scale. Also, nature is a very dominant element of the area and connecting element to Tanthof and the rest of the neighbourhoods of Delft.

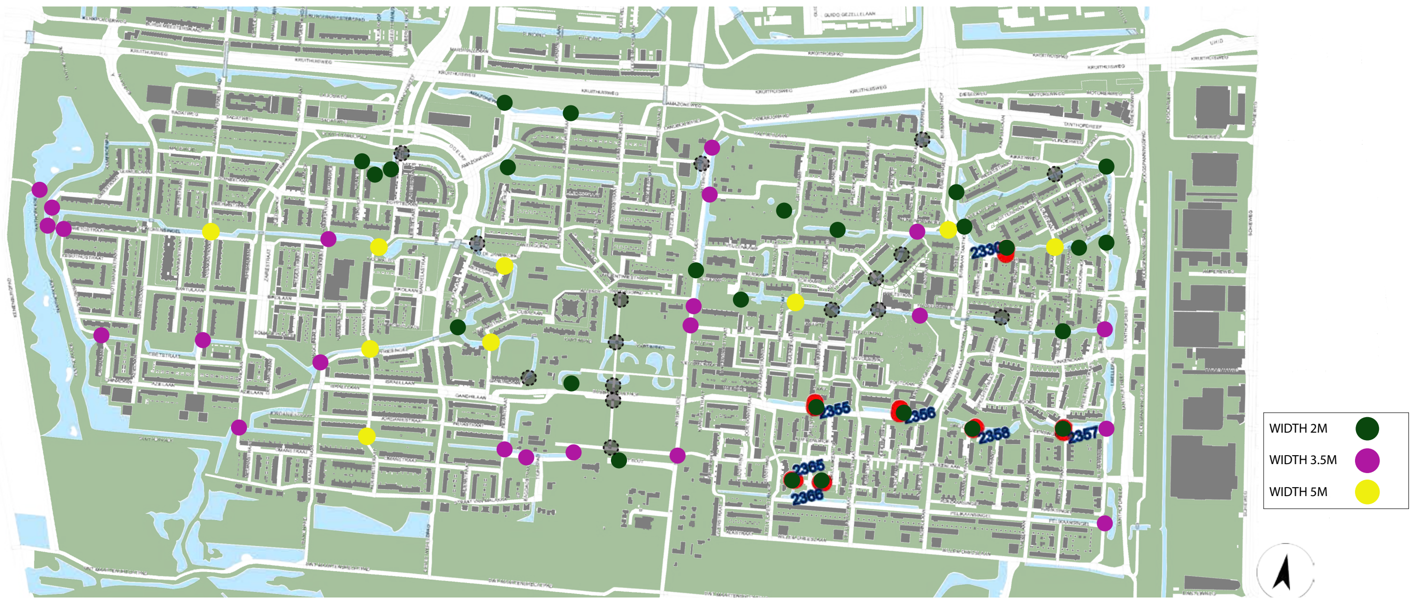
Moreover, the area has numerous canals and thus numerous footbridges. Most of them are old and made out of wood, thus the material shave aged or are very steep for bicyclists and need replacement. For this specific area there is no height limitation, since only animals use the canals as routes and the landscape is flat with no significant height difference between the river fronts.

F.3.1 Housing on Tanthof area
F.3.2 Bridge aspect of Tanthof
F.3.3 Bridge variations of Tanthof Delft
F.3.4 Indication of wooden bridges in Tanthof area

F.3.1

F.3.2

F.3.3



F.3.4

F.4 Primary structural analysis

F.4.1 Bridge series design simplifications

After analysing the Municipality data it was found that the population of the bridge production consisted of 64 bridges. Those bridges extend in different widths and lengths. Hence, every bridge should be structurally examined, in order to optimise every bridge separately. This process would be an extremely time consuming process, leading to an non-productive analysis. In order to overcome this difficulty a more engineering solution should be given by grouping the bridge population and examine a representative sample of every group. A first grouping of bridge population has been done according to three (3) new proposed widths as explained beforehand. Also, those bridges extend on different ranges of lengths and will be considered to extend to all the possible lengths from 4m to 16m per 4m length step. Since the bridge with the bigger span will also deform the most, the representative bridge sample of every width type will be the one of bigger length. For the structural design of the bridge only the stiffness (deformation) will be examined and not the strength (stresses), since FRP is a highly strong material.

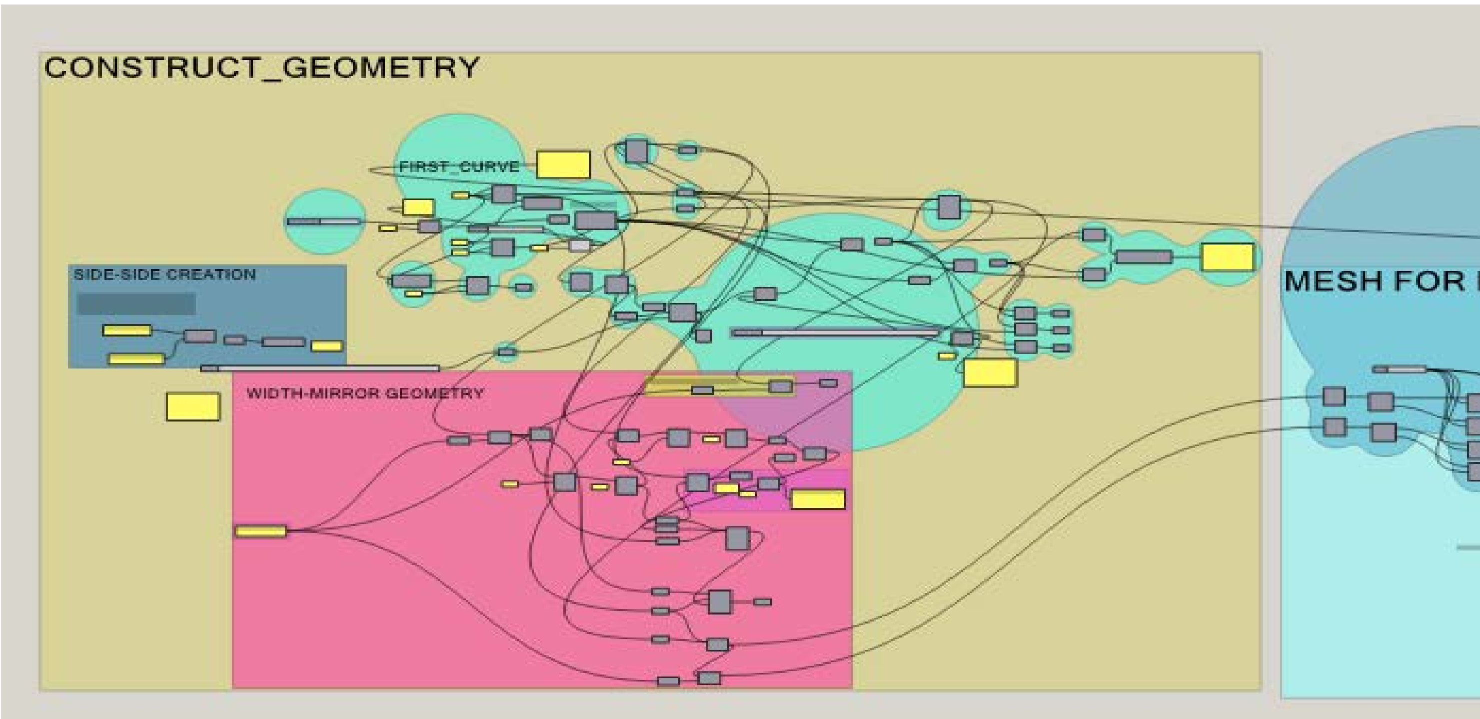
F.4.2 Preliminary analysis

F.4.2.1 Simulation models architecture

The structural analysis of the different bridge structures was a parallel process along the bridge cross-section design. Through the use of Karamba, a structural analysis plug-in for Rhinoceros and Grasshoper the different variations of bridge structures were designed and analysed under specific parameters each time. The aim of this process was to identify the parameters of every structure that influence the most the structural behaviour of the bridge and hence would determine the final optimised shape of the series. Moreover, deformation was set as structural criteria.

Furthermore, the dimensions of the structure is representative of the bigger dimensions of

F.4.1

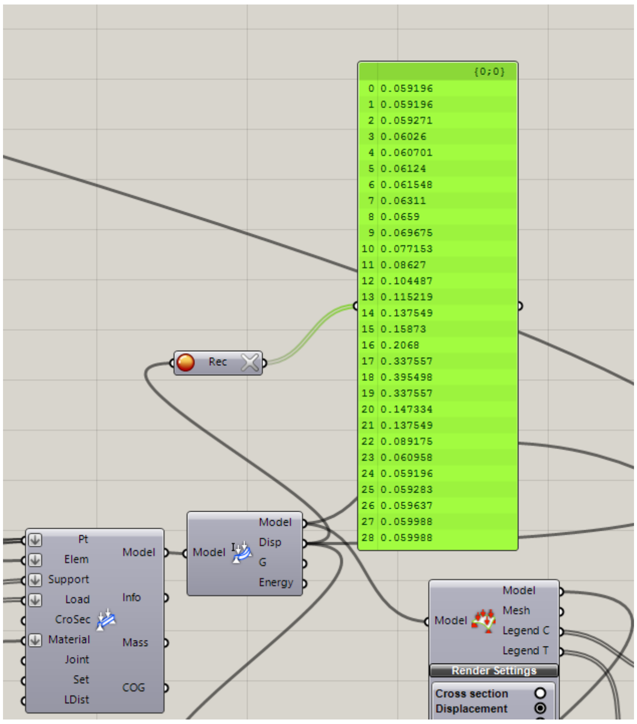


the bridge of the series of bridges. Hence, the dimensions are 16m length and 5m width. Also, for this primary analysis the material has been set as concrete and hence the deformation performance should be taken into account only quantitative and not qualitative.

Moreover, in order to simplify the form finding process, a homogeneous thickness is proposed throughout the items of the bridge series. In such way, only the shape parameters affect the structural behaviour of the bridges. Finally, the edges of the shape were set as pin-supports to simulate the real support of the structure and the load cases were set as the self weight and an extra pressure load of 5kN/m^2, as instructed from Eurocode 0:NEN-EN 1990.

Moreover, using a parametric design and structural simulation program like Grasshopper and Karamba was beneficial for the design at this point. Through the different range of the sliders and the use of Python those results were processed and comparative simulation graphs were plotted.

F.4.1 Karamba work-flow
F.4.2 Multiple data collection



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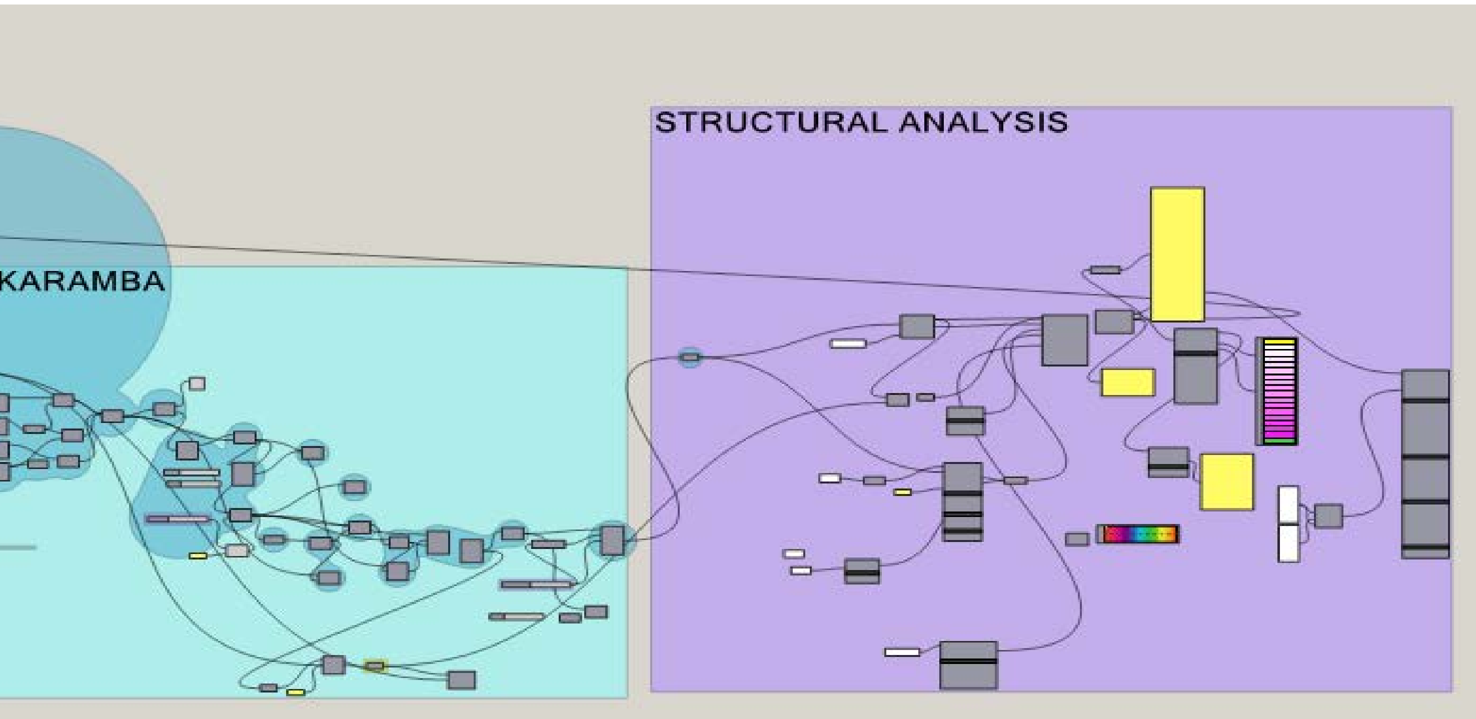


F.4.3 U-shape bridge

F.4.3.1 U-shape cross-section design

The first version of the bridges cross-section is a U-shape cross-section similar to the one used for the first FRP bridge in the Netherlands manufactured by Polyproduct. Since the railing is not structural, the parapet of the structure (flange) is lower than the railing. In such a way, the bridge structure and the railing blend in a more natural manner increasing the structural and aesthetic quality of the design.

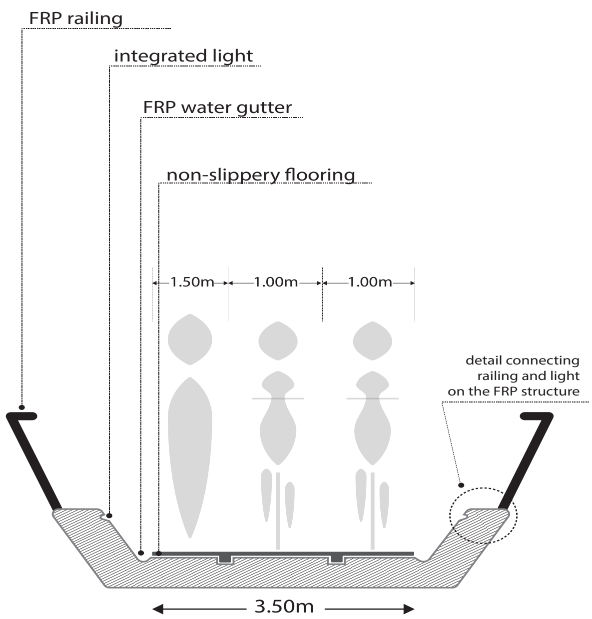
Furthermore, the lighting, water gutter and non-slippery flooring, are integrated on the bridge structure. Such integration demands of sculptural treatment of the cross-section. This decision was made based on the free-form shape that FRP can reach, given the limitations of the CNC milling on the PVC core and moulds. An additional design decision was to higher the structural cross-section and making it part of the bridge facade.

F.4.3.2 U-shape bridge structure

As shown in the previous chapter the first attempt to design the bridge design was based on the U-shape cross-section bridge. Its flange is higher on the middle of the length and becomes smaller as we get further from the middle to the edge. The initial design was based on the bridge design of Joris Smits "The Delft Bridge" which is based on the optimum shape according the general bending moment of the structure.

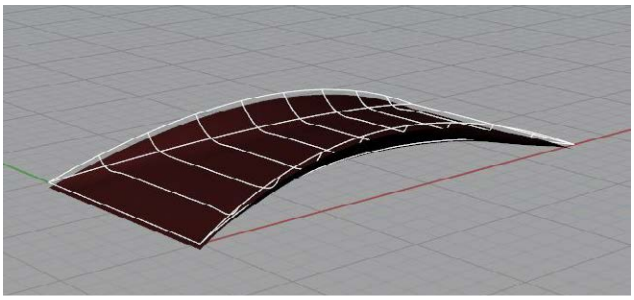
This shape is based on U-shape cross-sections of different flange height lofted, in order to create a smooth surface. Also, for the better stress distribution, the face between the flange and the deck is curved. This curvature is not significant comparing the general dimensions, but creates a more smooth and fluent shape.

The proposed shape was structurally analysed based on its geometrical parameters. More analytically, the parameters to be examined are the side curvature, the plan curvature, the



F.4.3

F.4.4



F.4.5

F.4.3 U-shape bridge cross-section
F.4.4 "The Delft Bridge" by Joris Smits
F.4.5 Illustration of U-shape bridge geometry
F.4.6 Geometrical variables
F.4.7 Graph of plan shape deformation
F.4.8 Focused graph of plan shape minimum deformation
F.4.9 Graph of side height deformation

flange height and the flange rotation angle. Finally, as the U-shape cross-section shows the walking plane is the same as the plane of the deck.

F.4.3.2.1 Simulation Conclusions

After running the relevant structural simulations and plotting the necessary graphs based on quantitative deformation the following outcomes were exported.

Plan shape

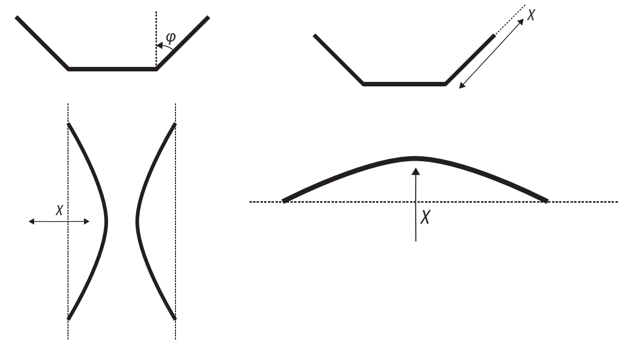
The general plan shape of the bridge design is parametrised in order to examine the structural behaviour of the structure in three positions. "Zero curvature" is positioned on 0m value, "negative curvature" on -1m to 0m value and "positive curvature" on 0m to +2m.

As shown on Figure F.4.7 the deflection between positive curvature and zero curvature position performs better, while the deflection steeply rises as the curvature turns into negative. Characteristically, the inclination of the positive curvature is almost 0°, while in positive position is almost 60°.

Finally, concerning the negative curvature position the deformation does not differentiate significantly and thus this behaviour permits for other criteria to determine the exact curvature of the plan, as the facilitation of traffic flows.

Side height

Another important element of any bridge design and thus for this geometry as well consists of the side height of the bridge deck. In some cases this element is crucial for a bridge, since it permits or not for boats to pass below the bridge. The side height could also determined if the bridge would be openable or not. In this project the height is not subjected to such criteria, since there is no need of boats to pass below and thus an opportunity to experiment with this parameter is being given as well.



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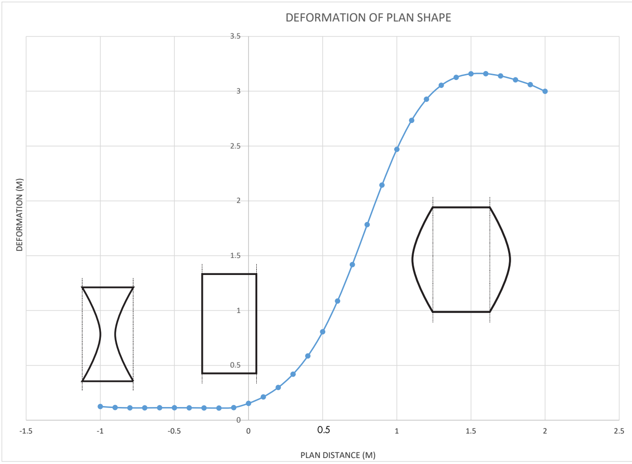
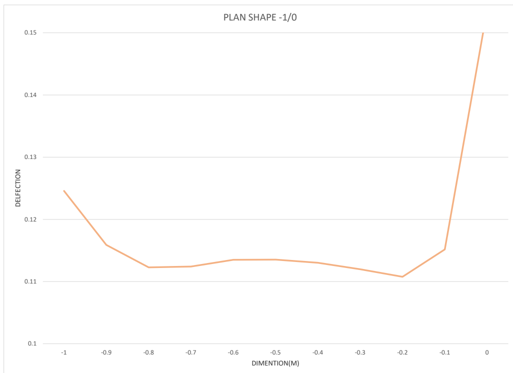


F.4.7



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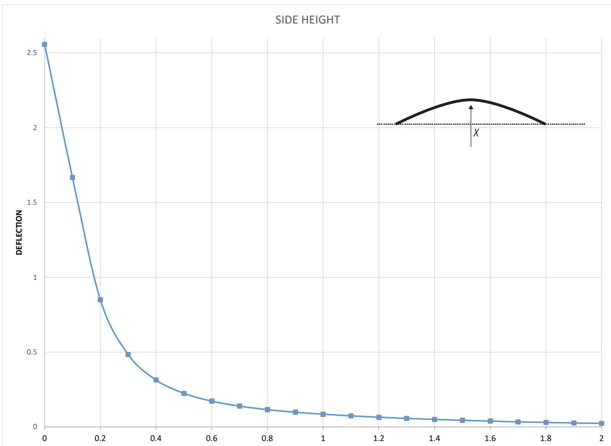
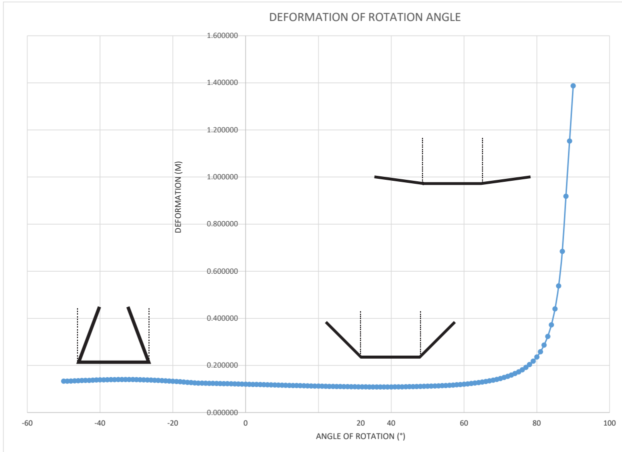


F.4.9

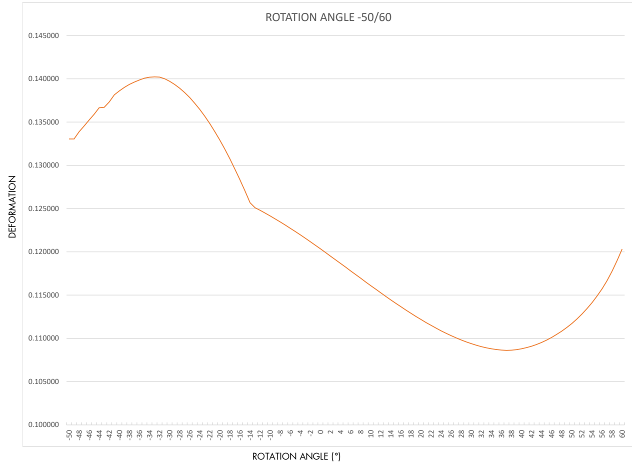
As can be seen on Figure F.4.9 there is significant decrease of the deflection from the straight position of the bridge to the curved one. However, there is no great differentiation of the deflection value after 0,4m height. Nontheless, the deflection decreases as the height of the side increases reaching 0 deflection in 2m height. It needs to be highlighted that this design aspect can influence the general height side focusing on the smaller bridge, since there must be a non zero height for the smaller bridge of 4m. Concluding, even 0.2m height decreases the deflection, no matter if this ratio is really small to the general 16m of the structure.



F.4.10

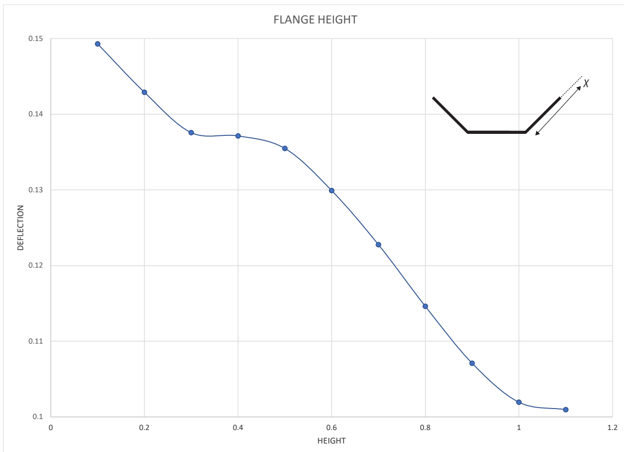
Flange rotation angle

An other important element of the U-shape cross-section is the flange rotation angle. For the simulation, 0° of the flange is set on its perpendicular position. Positive rotation is set outwards the 0° position and negative rotation inwards the 0°. Of course the shape of negative rotation, where the flanges bend inwards the centre could be challenging in terms of demoulding and thus be eliminated as a possible shape, but for this simulation this difficulty will be neglected and this variation will be included as well.



F.4.11

As can be seen on Figure F.4.10 the rotation angle ranges from -50° to +90°, but the general deformation performance does not depend strongly on the different rotation positions, but on the existence of the flange itself. An enormous difference in deformation between the existence of flange in angle and straight position is noticed. On a second chart of the rotation degree of -50°- (+60°) more beneficial information can be retrieved for the deformation of the structure between the positive and negative rotation of the flange. As can be seen on Figure F.4.11 the deformation fluctuates, but around 40° the structure deforms the least. It has to be mentioned of course that this rotation also influences the inclination of the railing as well that could create safety



F.4.12

problems and hence better care needs to be taken concerning the rotation angle of the parapet on the final design.

Flange height

The last simulation of this structure concerns the flange height of the cross-section. As already mentioned the flange height differentiate on the design from 0m at the edges of the structure to x height on the middle of the length. During this simulation the biggest height is parametrised from 0m to 1m.

As can be seen on Figure F.4.12 the decrease of the deformation is almost inversely proportional to the flange height. As a result, the flange height is highly important for the optimisation of such structure and minimization of deformations.

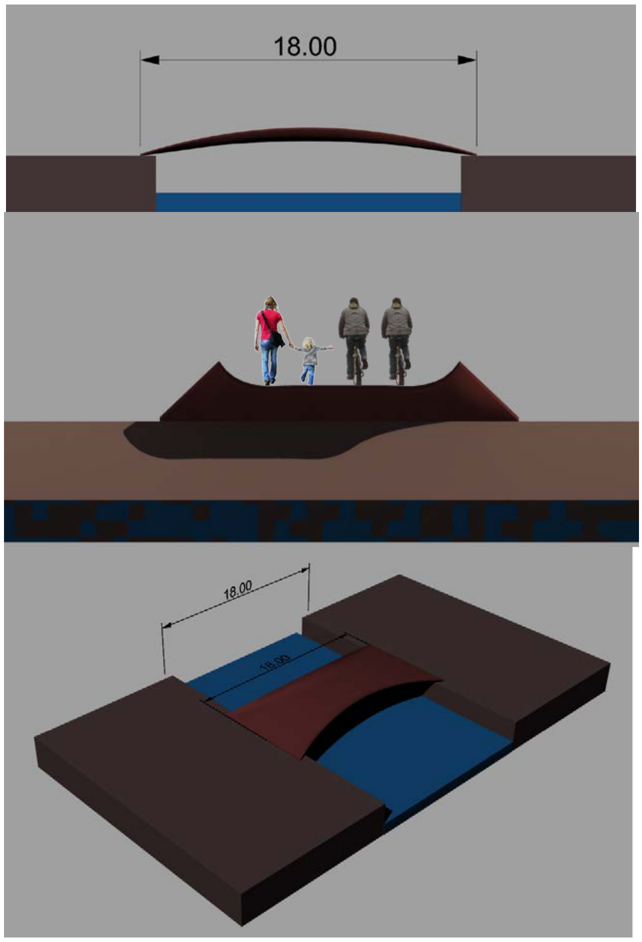
General conclusions

After the explained simulations a better understanding of the shape's structural performance was grasped. More specifically, the design aspects that influence more significantly the structural performance of the structure are:

- the plan shape
- the side height
- the existence of the flange
- the flange height

As expected, an optimised bridge design would have negative curvature, since then most of the mass would concentrate on the supports and the central area of the bridge, where the deformation is the biggest and the mass would be less and thus also the load. This plane shape is common in the traditional bridges of the centre of Delft and hence this is an extra reason to be persevered on the new bridge design of Tanthof.

Concerning the side height of the shape, less than one (1) meter height is sufficient, since there are no height limitations due to boat passage. What need to be borne in mind though is that



F.4.13

F.4.10 Graph of flange rotation angle deformation
F.4.11 Focused graph of flange rotation minimum deformation
F.4.12 Graph of flange height deformation
F.4.13 Illustrations of U-shape bridge structure

the inclination should avoid a steep curvature that would disturb the bicyclists way.

Finally, concerning the last shape optimisation element, meaning the flange, its existence contradicts with one of the main design principles of the bridge design. Through the structural simulations it was shown that the existence of the flange is tremendously important for the performance of the shape. Also, the higher the flange the better the performance of the bridge. But, as mentioned on the design principles the railing will not be part of the structure and hence the flange needs to be low.

Since this design aspect contradicts with the general design principle of the series a new shape needs to be designed that is stiff enough, but not based on a flange element.

F.4.4 Boat-shell bridge

F.4.4.1 Boat shell cross-section design

This cross-section follows a shallow shell design with an additional piece of deck in order to create an horizontal walking plane.

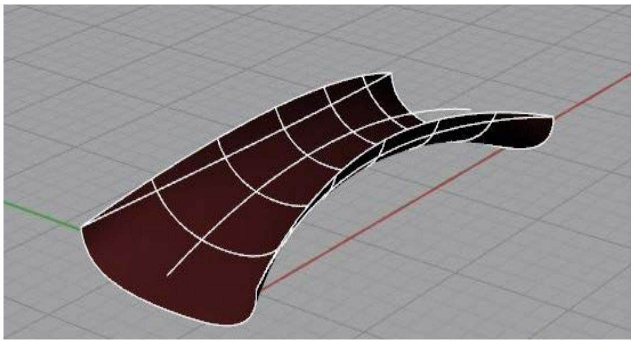
Furthermore, the side join of the shell structure and the deck will shape the rain gutter and also the lighting will be integrated on the FRP parapet as well. Epoxy resin with gravel on the top of the deck will provide the non-slippery demands of such project.

Moreover, the railing consists of the repetition of the same element providing a modular solution that easily get replaced. In order to achieve a homogeneous result the railing blinds in with the main structure creating the bridge parapets.

F.4.4.2 Boat shell structure

After the previous structural analysis was clear that an other bridge shape needed to be designed. This time a design that would follow the stiffening principles that a potato

F.4.14



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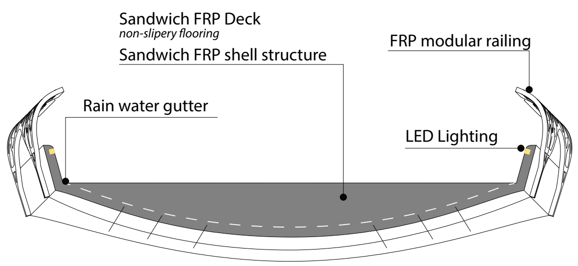


F.4.16

F.4.14 Potato chips using surface stiffness
F.4.15 Illustration of boat-shell bridge geometry
F.4.16 Boat-shell cross-section

chip is using. So, now the structural height that would provide the equivalent moment of inertia would be found underneath the walking level and not above it. In that way, the general shape would resemble more of a boat shape and the flange element would minimise its stiffening importance allowing this member to be more of an aesthetic tool.

On this model the flange height is set at 0,5m, representing more of an harmonic analogy of 1/2 since the total height, from the walking level would be 1m maximum. The side curvature was set to 1m allowing for a smooth curvature to be created on the side view of the bridge and at the same time permitting the smooth passage of bicyclists though the bridge. Also, the length of the bridge is 16m with width of 5m in the centre, while on the edges the width reaches 7m, shaping the bridge on a negative curvature. Now the deck height and the rotation angle of the flange are being parametrised, aiming to grasp the degree of structural influence of those members in order to design an optimised shape for the bridge series.

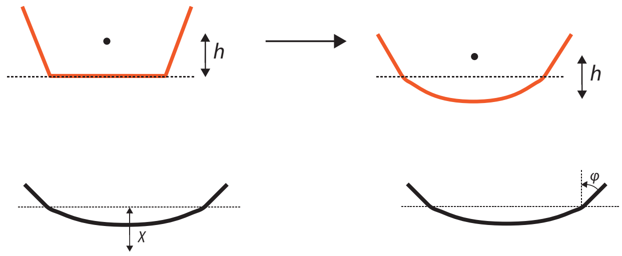
Finally, as in the previous model, concrete has been defined as the structure's material and thus the deformations need to be taken into account as qualitative values. The edge supports are defined as pin-supports. The load-cases are self weight and pressure uniform load of 5kN/m^2. The thickness of the shell is 0,1m homogeneously.

F.4.4.2.1 Simulation Conclusions

Through the same procedure as in the first model simulation graphs were plotted, in order to grasp the structural behaviour of the proposed shape.

Flange rotation angle

On this design the flange is set in a fixed maximum height of 0,5m, but the rotational angle has being parametrised in order to find an optimum shape. The boat shell



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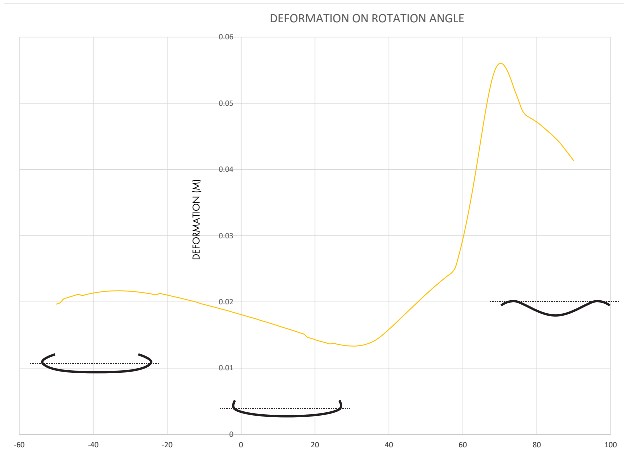

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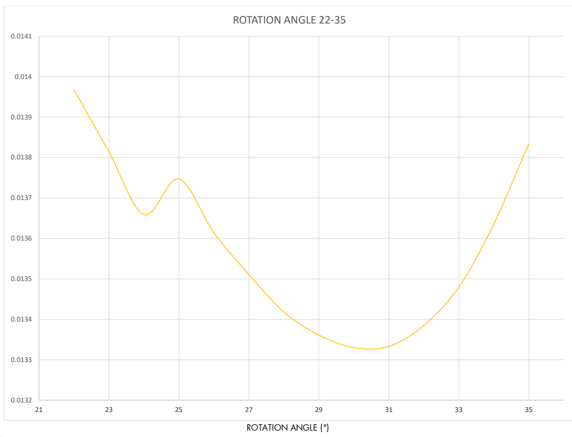


F.4.19

F.4.17 Alteration of structural stiffness
F.4.18 Graph of flange rotation angle deformation
F.4.19 Focused graph of flange rotation minimum deformation

shape simulation outcome is different than the respective chart of the U-shape cross-section. Again the rotation value fluctuate from -50° to +90°, while 0° is set when the flange is perpendicular to the walking plane. Furthermore, as the angle changes, also the general shape of the bridge changes in three (3) variations. The first variation includes the positive rotation of positive degree values, the second variation of negative rotation includes the negative degree values and the last one is set to 0° of rotation angle.

As can be seen on Figure F4.18, the negative rotation position shows continuously decrease of deformation, while the positive rotation position fluctuate from the lower deformation value to the higher value. This difference is caused, due to the geometry via the surface has been built. The augmentation of the deformation value is caused due to the irregular cross-section that is shaped after 50° of rotation angle.

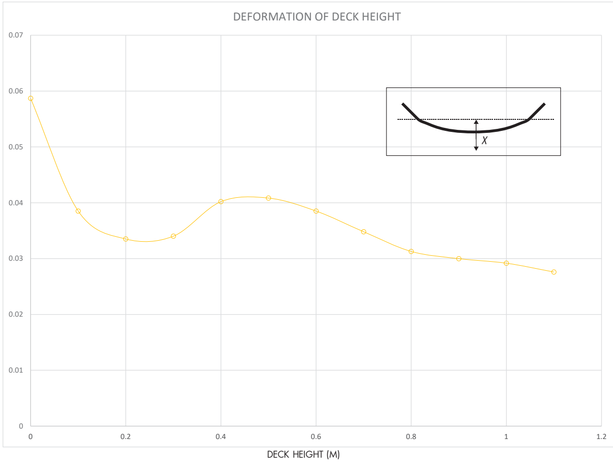
Finally, the plotted chart of the area with the lowest deformation value shows the range of degrees that the shape performs best (22°-35°). Between those degrees a more smooth shape is built.

Deck height

Last simulation concerns the deck height of the structure. As was expected this parameter influences significantly the deformation of the bridge.

Figure F.4.20 is similar to Figure F.4.12. This proves that the initial assumption of equivalent structural stiffness was correct and thus this shape would be the basic shape on which the final structure will be based.

More analytically, the graph declines almost proportionally to the deck height, which ranges from 0m to 1m. Also, the steep decrease from 0m to 0,1m height proves that the structural performance of the bridge improves drastically



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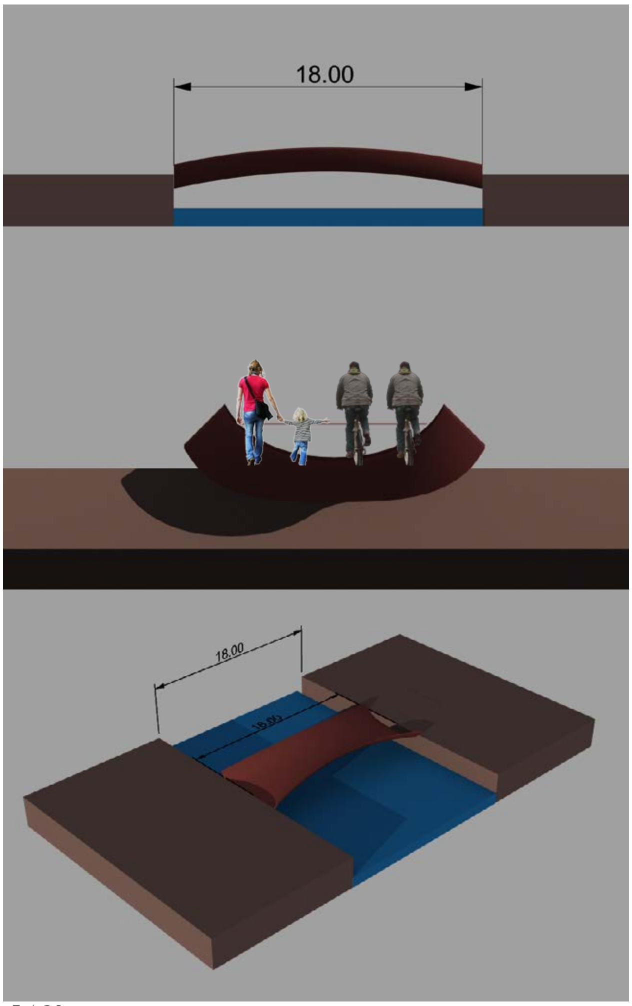


F.4.21

F.4.20 Graph of deck height deformation
F.4.21 Illustrations of boat-shell bridge structure

only by the existence of the additional height. This result is caused for two reasons. Firstly, by increasing the structural height, also the moment of inertia of the cross-section increases drastically ($I=(b*\mathbf{h}^3)/12$). And secondly the shape behaves more like a double-curved shell than a curved U-shape cross-section.

General conclusions

After analysing the structural behaviour of the U-shape bridge it was shown that a new design needed to be made. Nevertheless, the outcome of this structural behaviour depending on the geometrical parameters of the shape set the base for the new design. On the second version, the important aspect was to rethink the geometrical stiffness of the U-shape due to the flanges and translate them into a curved deck underneath the walking plane. Like this the design principle of low flange could be satisfied by a structurally optimised bridge shape.

More specifically, on this variation, the rotational angle is less important than the previous model. Also, the deck height now is the aspect of equivalent importance to the flange, since the rest of the important design aspects (side height, plan curvature) were the same.

Concluding after this preliminary analysis, the basic geometrical shape of the bridge series was decided and also its structural behaviour of different parameters was tested, allowing for more conscious geometrical design decisions for the final shape.

F.5 Parent bridge structural analysis

F.5.1 Simulation models architecture

After the preliminary structural analysis process a better understanding of the structural behaviour of the different bridge variations was grasped. The initial structural U-shape bridge cross-section had evolved into a boat-shaped shell structure in order to provide the bridge with structural depth and at the same time with a non-structural railing.

The final bridge design of the preliminary structural analysis will be simulated under the correct material conditions and will further be optimised. Parameter of optimisation will be again the deformation of the bigger bridge design of the series subjected under the correct boundary conditions, load cases and material properties.

Boundary conditions and load case

This simulation process share the same philosophy as the preliminary structural analysis process, so similar conditions have been introduced. More specifically, the structure is pinned supported on the edges, but with the parapet (flange) free of support conditions, since it stands above walking level. Furthermore, the load case of the simulation is similar to the former one, meaning self-weight (gravity) and 5kN/m^2 equally distributed load across the entire structure, resembling the active pressure load that is delineated in the case of pedestrian bridges by Eurocode 0:NEN-EN 1990

Material and sectional thickness

For this simulation process, the material properties of the proposed FRP should be determined accurately along the exact thickness of the proposed shell bridge design. From the material research the selected material was epoxy resin and glass fibres as the ply materials and PVC foam as the foam

SANDWICH FRP	
MATERIAL PROPERTIES	
VOLUME	0.106 m^3
DENSITY	112.00 kg/m^3
PRICE	2.35E+01 EUR/kg
YOUNG MODULUS E	1.586E+01 GPa
YIELD STRENGTH fy	574 MPa
SHEAR MODULUS G	6.95 GPa
MOMENT OF INERTIA	0.019 m^4

RESIN- epoxy/E-glass, UD prepreg, UD lay-up	
MATERIAL PROPERTIES	
DENSITY	1.77E+03 kg/m^3
PRICE	26.5 EUR/kg
YOUNG MODULUS	39.7 GPa
YIELD STENGTH	574 MPa
TENSILE STRENGTH	574 MPa
ELONGATION	2.45 % strain
COMPRESSIVE MODULUS	39.7 GPa
COMPRESSIVE STRENGTH	563 MPa
FLEXURAL MODULUS	39.7 GPa
FLEXURAL STRENGTH	520 MPa
SHEAR MODULUS	16.4 GPa
BULK MODULUS	22.8 Gpa
POISSON'S RATIO	0.141
SHAPE FACTOR	6.8

FOAM- PVC cross-linked foam (r i gid, closed cell, DH 0.030)	
MATERIAL PROPERTIES	
DENSITY	2.99E+01 kg/m^3
PRICE	14.7 EUR/kg
YOUNG MODULUS	0.0299 GPa
YIELD STENGTH	0.299 MPa
TENSILE STRENGTH	0.849 MPa
ELONGATION	3.87 % strain
COMPRESSIVE MODULUS	0.0182 GPa
COMPRESSIVE STRENGTH	0.299 MPa
FLEXURAL MODULUS	0.0299 GPa
FLEXURAL STRENGTH	0.849 MPa
SHEAR MODULUS	0.014 GPa
SHEAR STRENGTH	0.15 MPa
BULK MODULUS	0.0299 Gpa
POISSON'S RATIO	0.32
SHAPE FACTOR	2.6

F.5.1

of the sandwich FRP. By using the material properties of "Epoxy/E-glass, UD prepreg, UD lay-up" and "PVC cross-linked foam (rigid, closed cell, DH 0.030)" found in CES it was possible to calculate the material and geometrical properties of the sandwich FRP.

Moreover concerning the thickness of the plies it is assumed that the composite function as an isotropic material and thus should cover all the possible directions of loading and stress. Such behaviour also serves the plate action of the shell structure as well. More specifically, such behaviour is achieved via the method of 4 parallel fibre layer with rotation angle different of 45°. This orientation is repeated symmetrically about the symmetry axis. Through this lamination method, symmetrical and balanced reinforcement is achieved eliminating any tendency of the fibres to bend of wrap and via the +45° -45° equal number of plies the shear coupling is also reduced.[W.01]

To sum up, the new sandwich FRP has a sectional thickness of 106mm, meaning 90mm of foam core and 8mm of plies on each upper and lower side. Also, the new density of the material is 112kg/m^3, its young modulus(E) is 15.58GPa, its yield strength fy -equivalent to the one of the plies- 574MPa and its Shear modulus(G) 6.95GPa (Appendix 3). For the corresponding calculations the following formulas were used:

Second moment of inertia(I)

$$I_i = \left(\frac{1}{12}\right) \times \left(\omega_i \times \left(h_i^3\right)\right) + \left(A_i \times {d_i}^2\right)$$

Bending stiffness

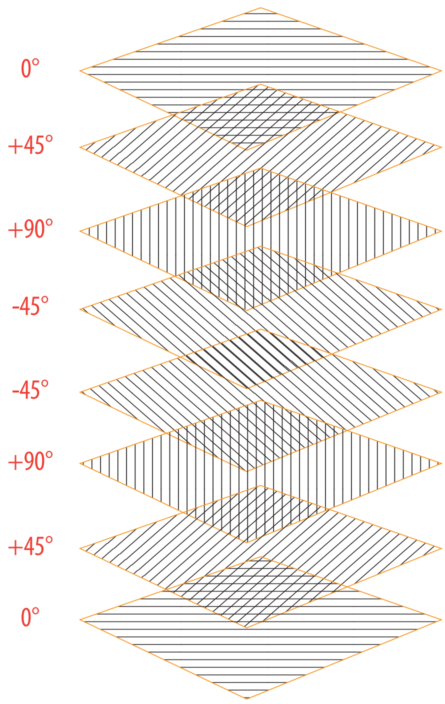
$$E_0 * I_0 = E * I$$

Young modulus(E)

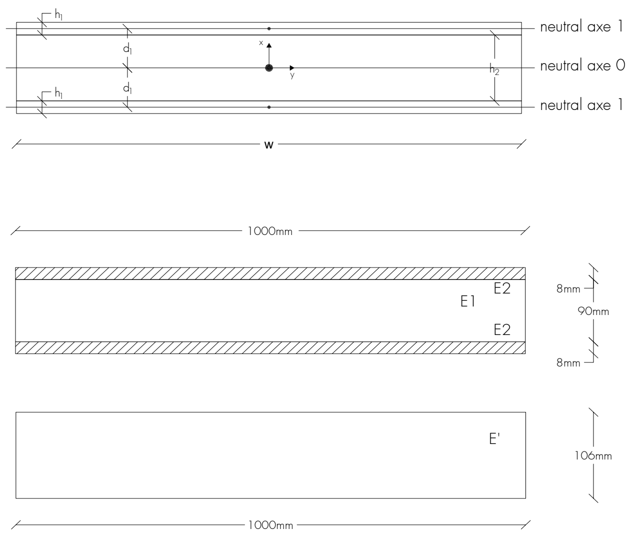
$$E_0 = E * \frac{I}{I_0}$$

Shear modulus(G)

$$G_0 = \frac{E_0}{2 \times (1 + v_0)}$$



F.5.2



F.5.3

F.5.1 Material properties of sandwich FRP
F.5.2 Fibre stacking sequence arrangement
F.5.3 Material cross-section

F.5.2 Boat-shell structure

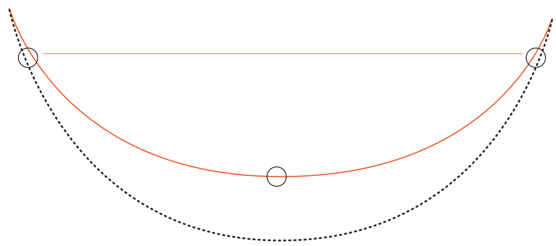
From the prior preliminary structural analysis it was concluded that the boat-shell structure is the more suitable bridge structure which provides the structure with the structural stiffness and non-structural railing at the same time. Thus on this geometry the final design will be based on.

F5.2.1 Analysis of geometry

The boat-shell structure shape as already mentioned is based on the design principle that the structural height will be found below the walking plane. Of course the walking area(deck) will also be part of the design, but it is considered as a different element that will be explained after the final shape of the bridge will be designed.

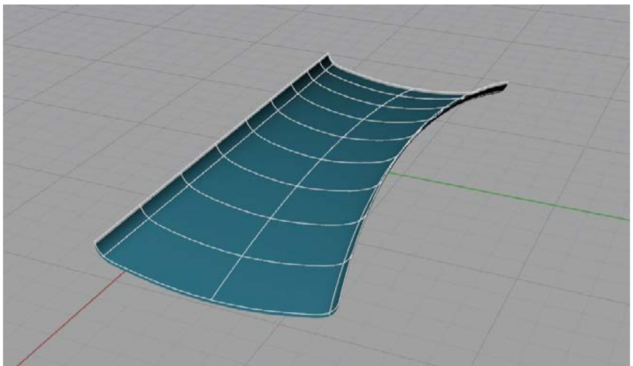
This structure maintains the design principles of the preliminary structural analysis process conclusions. More specifically the length of this model is 16m and its width 5-7m based on a negative curvature plan shape. Also, the parapet height is 0,5m with 30° positive rotation angle and the side height is 1m. Finally the thickness is 0,106m (106mm) homogeneous of sandwich FRP and the "deck" gets shallow 0.5m.

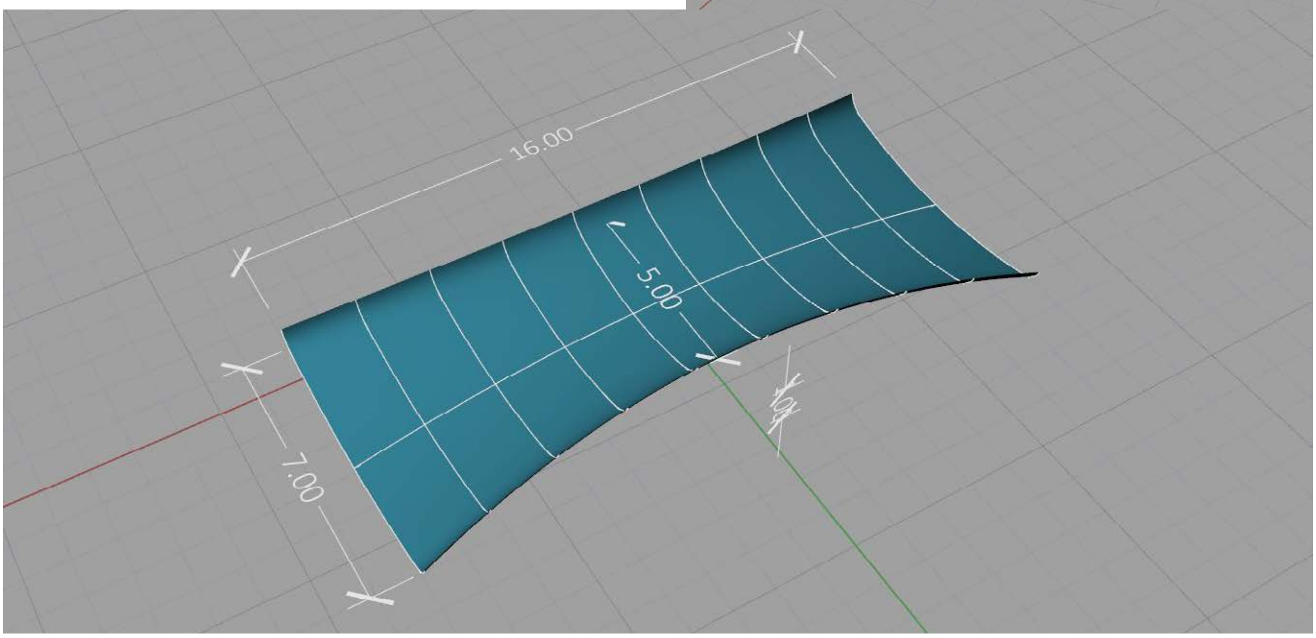
In principle this geometry is based on curved poly-line with the control points the genesis points of the parapet and the middle of the curve. In that way a smooth curved geometry was able to be created that full-fills the free-form shape demands of the project.



F.5.4

F.5.5





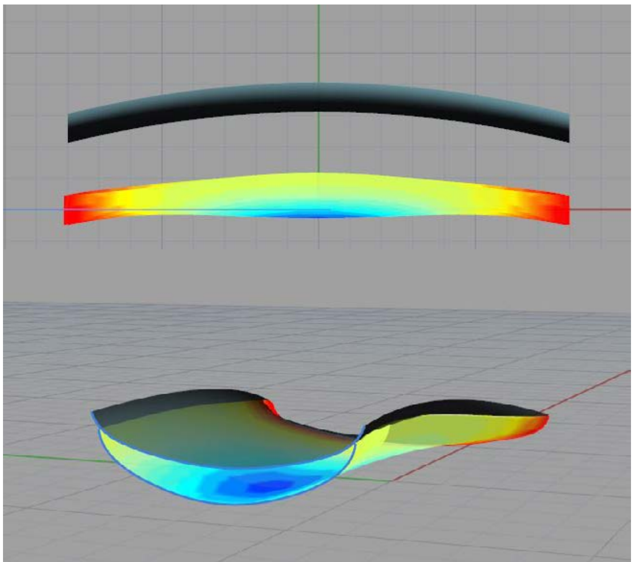
F.5.2.2 Structural behaviour

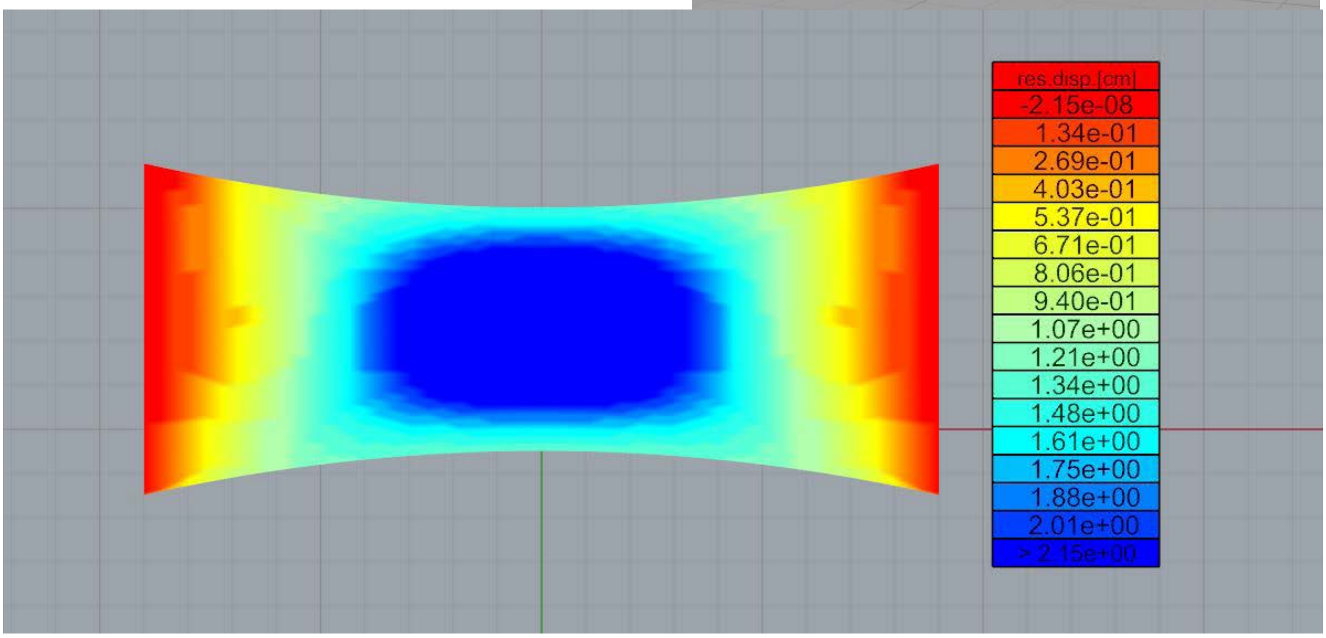
The Boat-shell structure bridge was simulated in Karamba, in order to extract its structural behaviour. The results were pretty satisfactory which indicates that the geometrical modifications suggested from the preliminary analysis were beneficial to its behaviour.
More specifically, the maximum deformation of the model was only 7mm, while the permitted deformation based on the rule of thumb is 53mm (d=l/30). Of course it is assumed that the rest of the bridges from the series will deform even less.

Furthermore, since the maximum deformations is not significant also no important alterations on the geometry is noticed when the shape deforms. Nonetheless, the concentration of the deformation of the centre of the structure indicates that the lower part could be reinforced. The optimisation tool of this project is based on geometry and thus a second version of this shape will try to cope with the structurally weakened bottom parts of the structure.

F.5.4 Geometry of cross-section
F.5.5 Illustration of boat-shell bridge geometry
F.5.6 Illustration of boat-shell bridge deformation

F.5.6





F.5.3 Leaf-shell structure

The Boat-shell structure might perform well enough from structural point of view, but lucks in dynamic appearance. For that reason the shape is modified further in order to provide with a shape that provides both aesthetic and structural qualities.

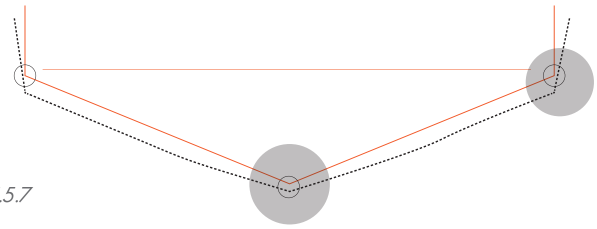
F.5.3.1 Optimisation of geometry

Since the geometry behaves structurally as a curved beam with different cross-sectional shapes in every variation, the structure deforms more on the centre of the geometry. As already mentioned, the deformation is only 7mm, but yet an extra stiffening of the cross-section geometry could benefit the final deformation and genera structural behaviour of the structure even more. This time, the geometrical solution was given by the FRP sheet stiffeners example. Hence through implementing "edges" on the control points of the curve of the cross-section extra reinforcement on the general shape was provided.

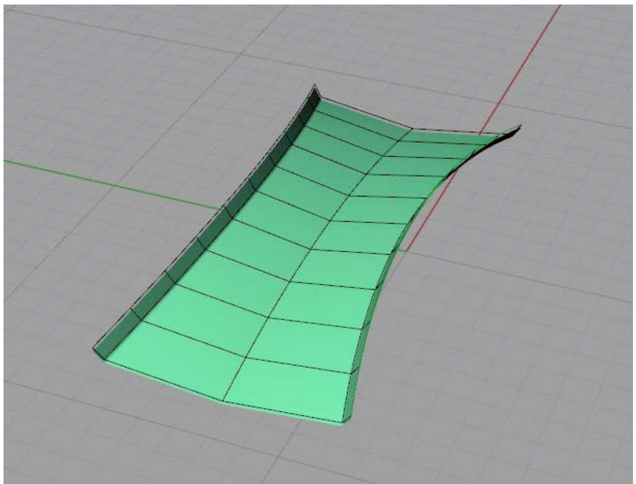
Moreover, this geometrical alteration made the bridge appearance resemble more a natural element like a leaf and it thus adds bigger value to the aesthetic result of the bridge series.

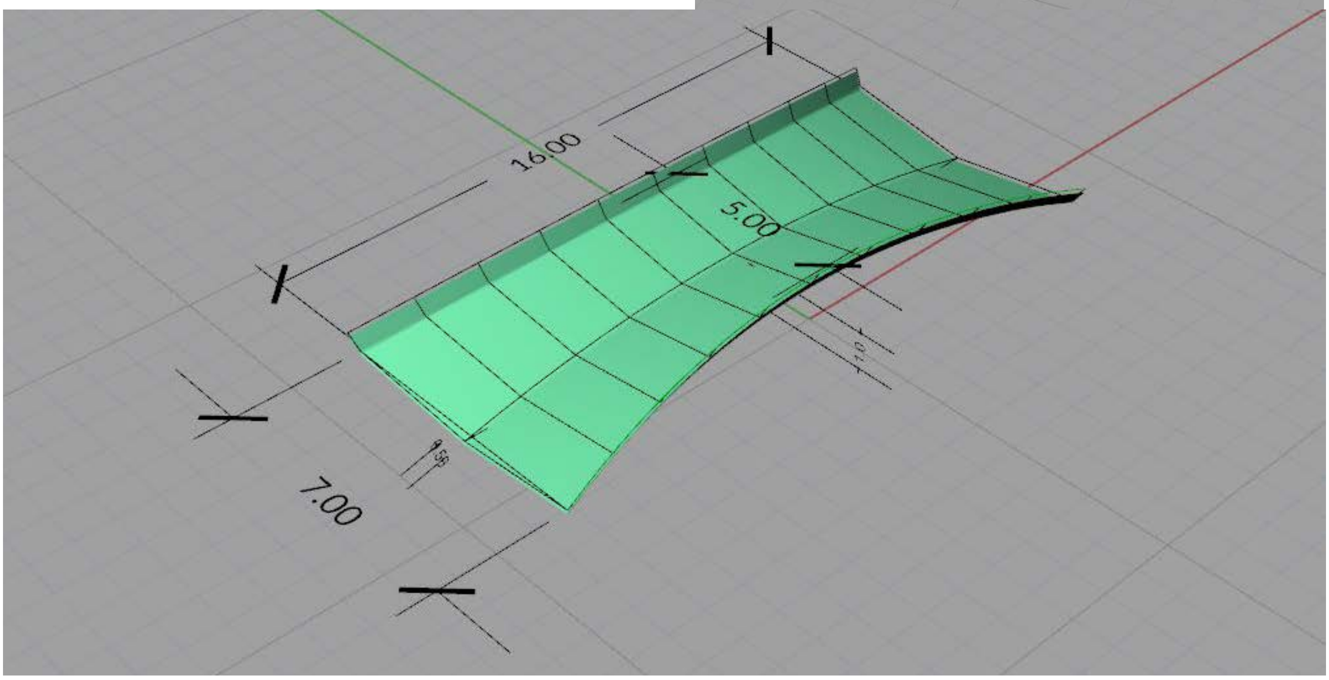
F.5.7 Geometry of cross-section
F.5.8 Illustration of boat-shell bridge geometry
F.5.9 Illustration of boat-shell bridge deformation

F.5.7



F.5.8





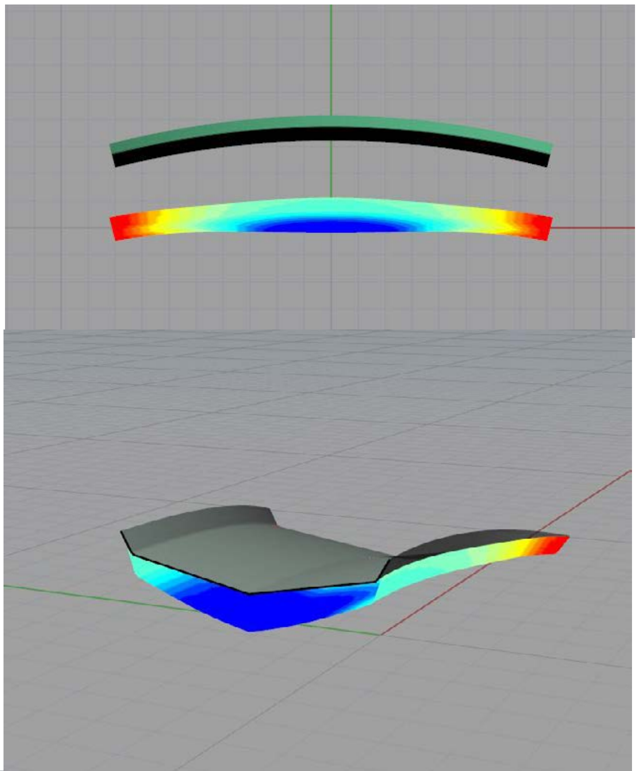
F.5.3.2 Structural behaviour

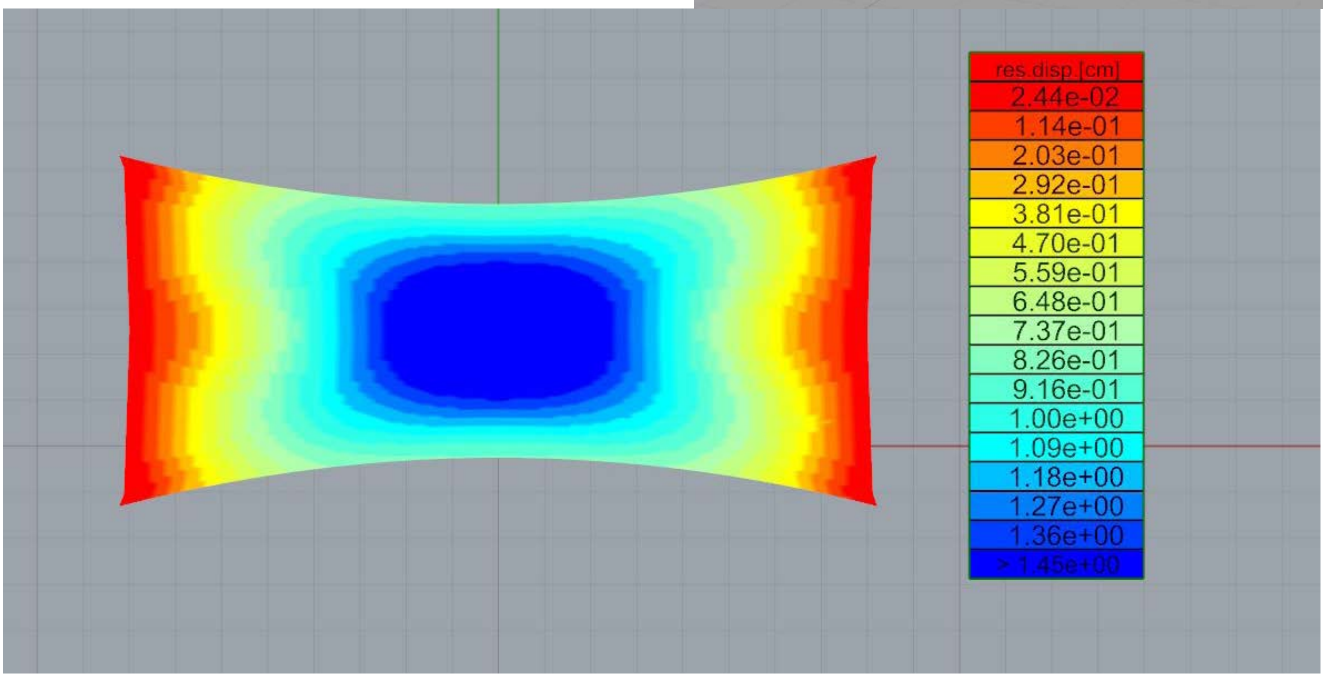
The Leaf-shell geometry is stiffened on the cross-sectional plane trough the flanges, but stays weak on the perpendicular direction. In order to stiffen this direction as well, "sharp" edge stiffeners have been added to the geometry, expecting that the new shape performs better in terms of deformation. Namely, from 7mm deformation on the Boat-shell structure, now the Leaf-shell structure deforms 6mm. A reduction of only 7% on the general deformation of the structure was achieved only be stiffening the geometry in one direction. Of course such a percentage is insignificant, but the aesthetic gains were the reason for further shape research.

Concluding, after study on the parameters of the different bridge shape variations, in terms of deformation performance, a good comprehension of the optimisation aspects was grasped. Through this process the design managed to be narrow down to a satisfactory stiff structure. This shape consisted of the primitive shape upon the final design would be based on. Via further assessment of the boat-shell shape both structural and architectural, the final shape of Leaf-shell shape was designed.

This shape combined both good structural performance and architectural appearance, which could evolve to an urban integrated infrastructure. For such outcome the necessary railing design should be taken care of as will be seen in following chapter.

F.5.9





F.6 Bridge series structural analysis

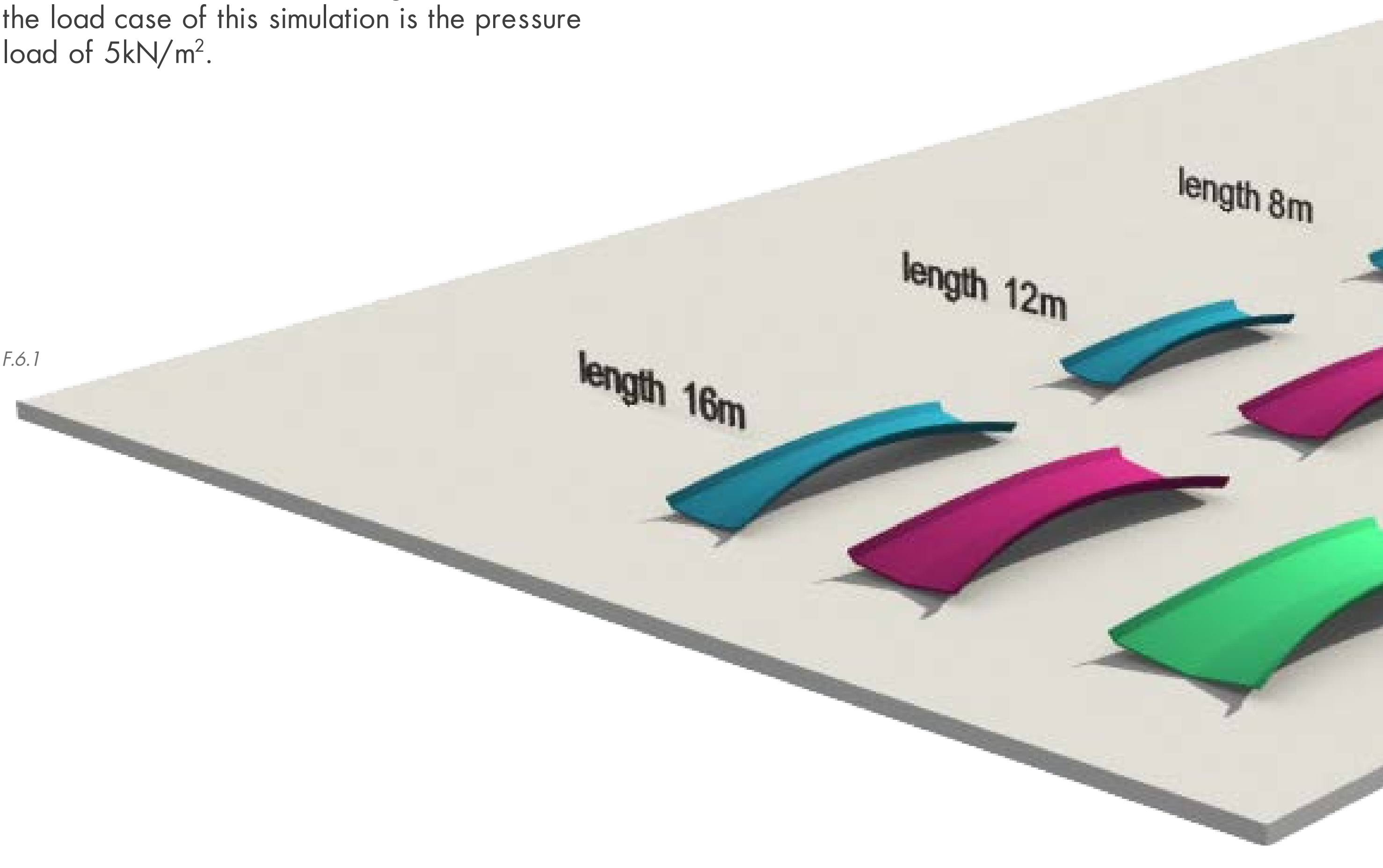
F.6.1 Simulation model

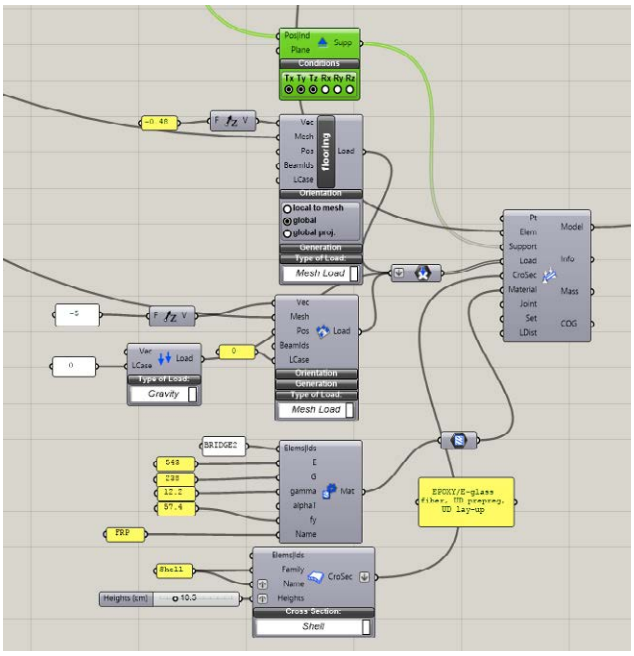
After deciding for the structure of the parent bridge the rest of the series where designed respectively to the decided length and width groups.

This simulation model resembles the philosophy of the previous ones. More specifically, every model-bridge is pinned supported on the edge of the geometry, while keeping the parapet free of supports. Also the material properties used are the calculated ones from the sandwich FRP.

Furthermore, the final cross-section indicates an additional piece of PVC foam for the deck, were resin and gravel are mixed and be placed on top as non-slippery flooring. Since the deck consists of PVC, it adds insignificant weight to the structure an thus will be neglected. Hence, the load case of this simulation is the pressure load of 5kN/m^2.

F.6.1





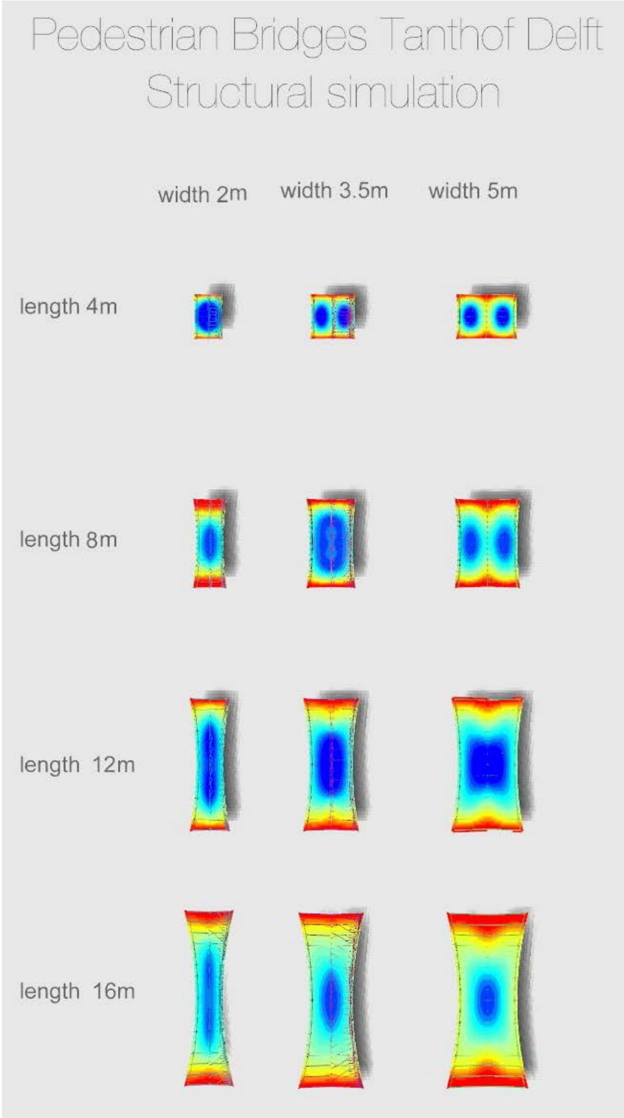
F.6.2

F.6.1 Illustration of the bridge series structure
F.6.2 Karamba work-flow

F.6.2 Structural behaviour

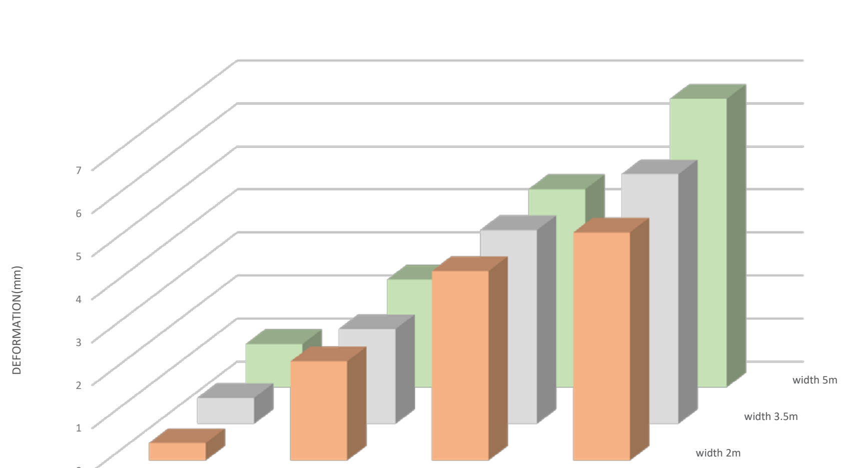
As assumed in the beginning of the research the bridge with the largest dimensions would deforms the most. Hence, that bridge was also the most representative item of the series to be used as parent bridge for the entire series. More specifically the deformations of the bridges vary from 0.4mm to 7mm and the rise of the deformation follows the length rise. Also, the wider the bridge set the more the bridges deform.

Furthermore, the bridges deform in the centre of their structure and their deformation patterns resemble the one of the parent Leaf-shell bridge that has been already explained. A differentiation on the pattern can be observed on the items of the smaller length and 3,5m and 5m width and the bridge of 5m width and 8m length. The general analogy of the bridge structure is based on a rectangular shape but the analogies of the 3 aforementioned bridges resembles more a square geometry and thus the "edge" stiffener functions so well that it permits no deformation on that area. Thus the deformation looks divided on the two sides on the shell.



F.6.3

F.64



	length 4m	length 8m	length 12m	length 16m
width 2m	0.4	2.3	4.4	5.3
width 3.5m	0.6	2.2	4.5	5.8
width 5m	1	2.5	4.6	6.7

F.6.3 Karamba deformation diagrams of bridge series
F.6.4 Chart of bridge series deformation

F.7 Railing design

The appearance of the bridge series is determined by the railing and thus extra attention was given to its design. As has already been mentioned, the railing should be easily replaceable in order for the appearance-based life-time of the bridge series to extend. Also, since it is not part of the structure, it is thinner than the actual 106mm sandwich FRP bridge structure

Moreover through the railing design it is meant to highlight the modularity of the design and the manufacturing technique of moulding production.

Also in order to ensure a coherent project the railing design should not imitate a steel one but discover the architectural language of plastics, which the main structure was trying to use as well. Lastly, in order to use the structural benefits of FRP the railing resemble again an FRP shell, but since it is not structurally demanding, the shell is made out of FRP sheet and not sandwich FRP this time.

F.7.1 Design Principles

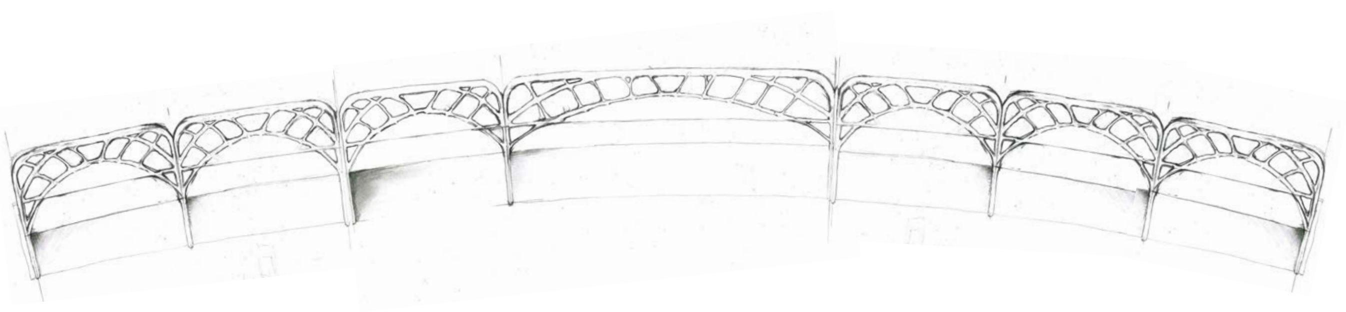
The requirements for the such type of bridges that the series produces are not demanding and thus big freedom is given to the designer.

According to Dutch requirements[W.10] the final height of the railing should be at least at +1.00m with relevant 0m at the deck walking level. Also, concerning the openings on the parapet area, the instructions indicate that a spherical ball of 50cm diameter should not be able to penetrate the railing.

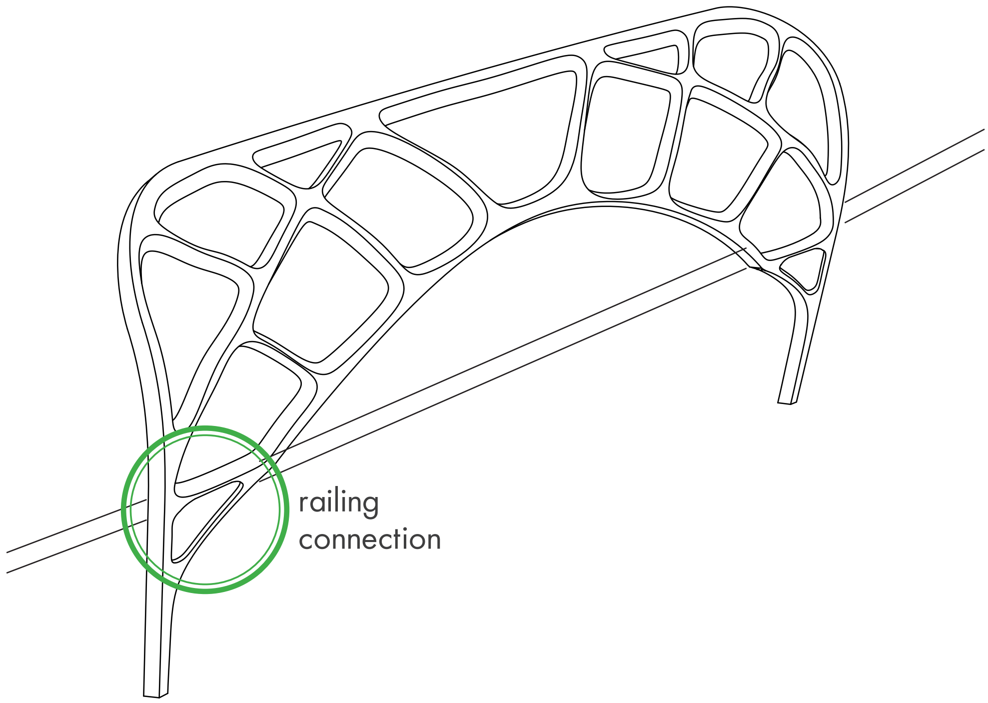
Following the above safety instructions, the natural pattern shown on Figure F.7.1 was created. This pattern tries to imitate the leaf vanes of a leaf that concur with the mould seams. In such a way the modularity of the project is highlighted.

Furthermore the railing consists of the multiplication of the same element and thus the railing is manufactured via Light RTM with one mould set of female and male mould (and an extra one for the middle piece that is double the side of the normal element, as in the module matrix of the project). In order to facilitate the demoulding the cross-section of the railing is tapered and the thickness is 3mm of FRP.

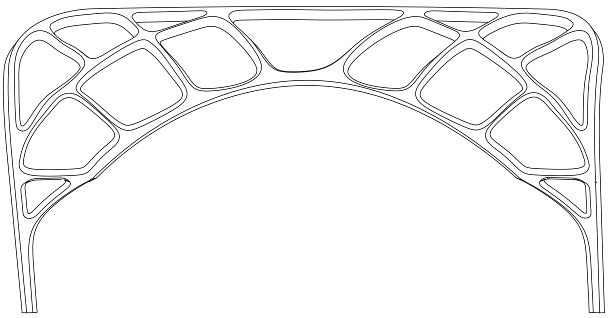
Finally, the railing is placed on the outer side of the bridge structure and every railing element has integrated bolts through which the railing connects to the bridges parapets. For the connection design of the railing, stainless steel elements were used. Important aspect of this detail is the installation of the railing on the main structure. As will be explained in a later chapter as well, first the main bridge structure will be installed on site and then the railing elements will slide on the outer side of the main bridge structure and fastened manually from the inner side of the bridge.



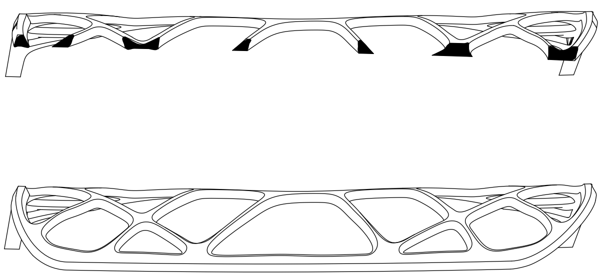
F.7.1 Draft design of bridge railing



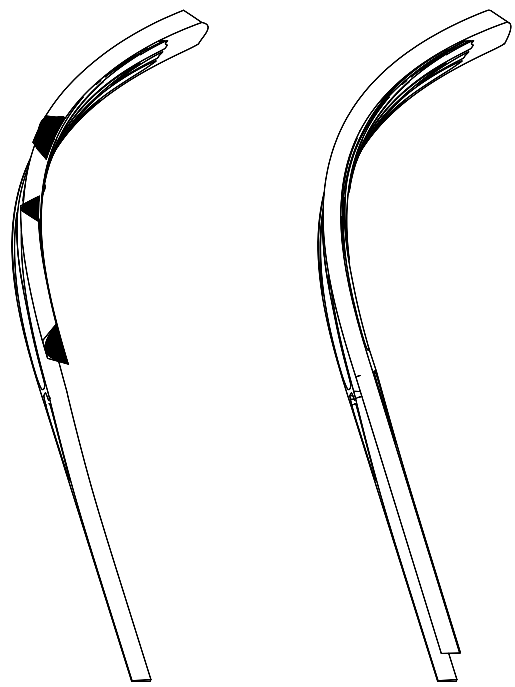
F.7.2



F.7.3



F.7.4



F.7.5

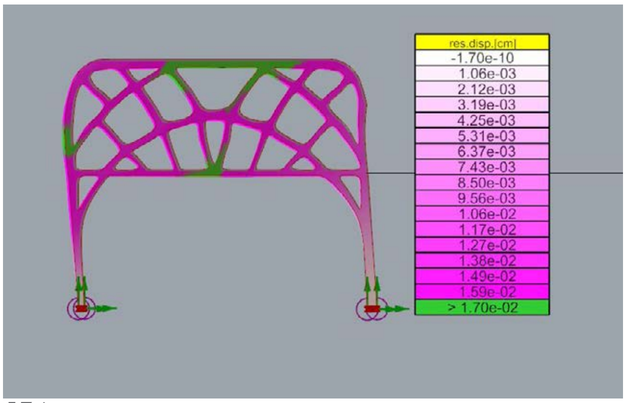
F.7.2 Structural simulation

Due to the irregular shape and pattern of the railing simple hand calculations were insufficient,thus a FEM model was used to determine the thickness of the railing.

For this simulation Karamba program was used with pin supports and epoxy-e-glass FRP material for the bridge structure. The load of this simulation was the self-weight and the extreme load of 3kN/m^2 that was applied on the structure the z direction. Lastly for the simulation a simplification of the cross-section was done from tapered to rectangular cross-section and thus the thickness was set to 2cm instead of the final 3cm.

As the simulation showed the railing element deforms less than a millimetre, hence it is practically rigid. Nontheless, for practical (connection integration) and aesthetic reasons the railing was designed at 3cm.

Finally, the thickness of 3cm could be achieved by the use of foam as well as sandwich FRP, but due to the small general thickness and the tapered cross-section it was considered that such decision would use extra means when not necessary, thus the use of only FRP was decided, which might be more expensive in terms of material cost, but used less means (use and CNC milling of foam).



F.7.6

F.8 Foundation system

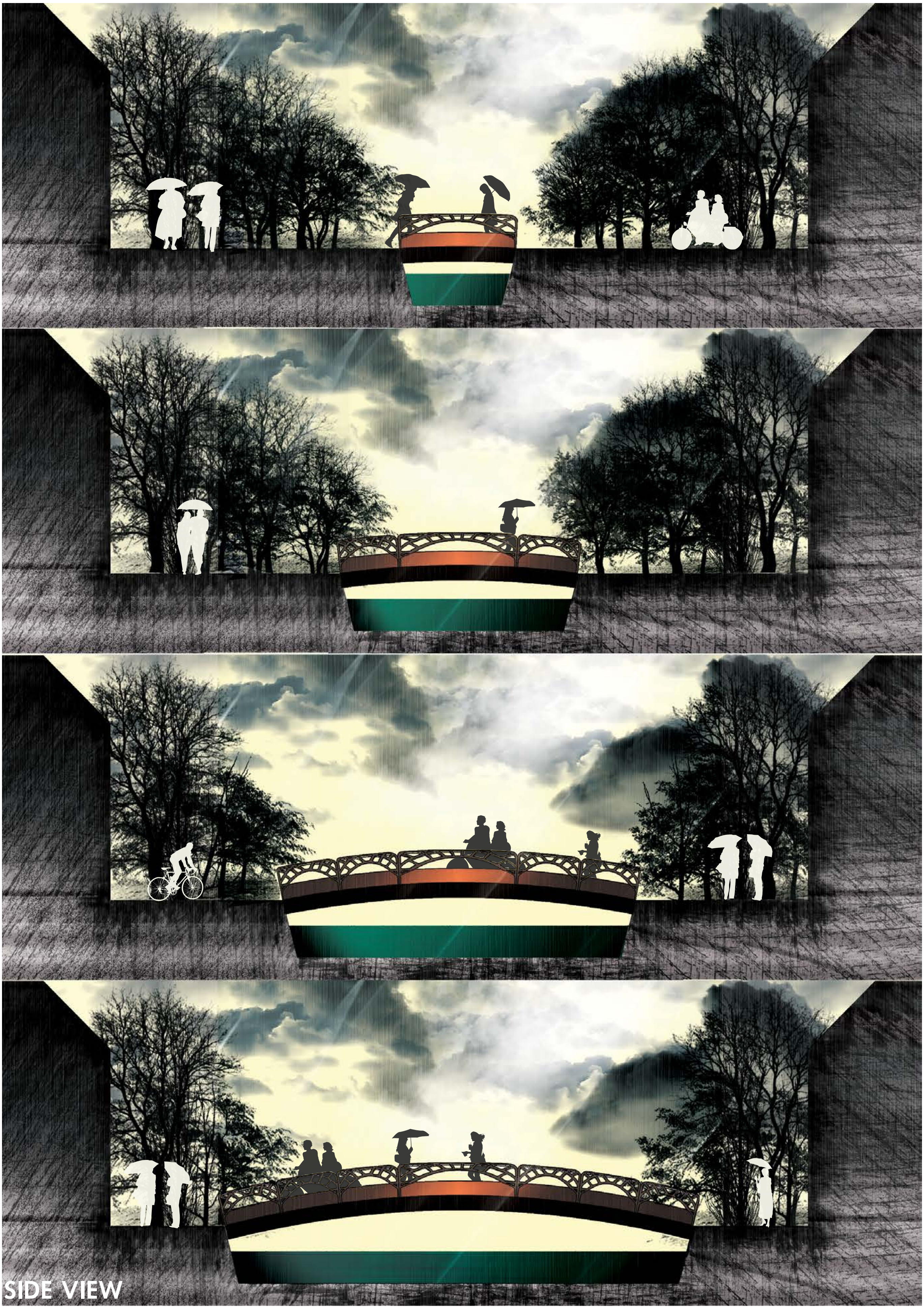
Concerning the foundation system the plate solution that is broadly used as connection to the structure and the concrete foundation block will be used. Important aspect of the foundation design is the fact that the light weight structure will need less piling than usually. Since the soil condition of Tanthof and of the Netherlands generally is relatively week comparing to other countries, a lightweight solution is of vital importance to be proposed. Hence FRP solution is a proper material proposal in terms of foundation loading.

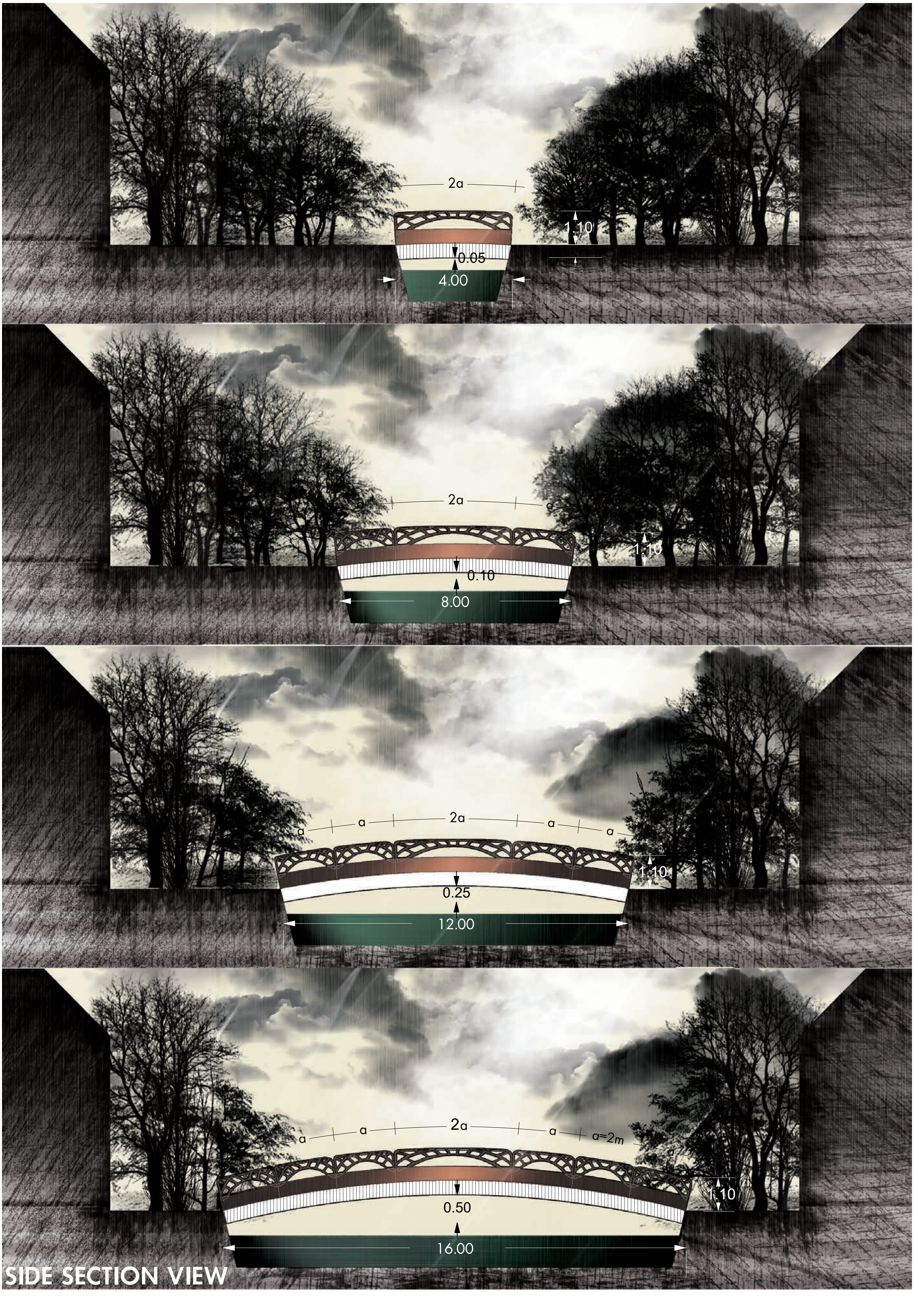
Moreover the connecting L-shape FRP plate that connects the bridge structure to the foundation is not integrated on the mould but consists of an extra piece that is connected to the main bridge after moulding process. In such a way no extra geometries are added to the mould design that would rise its complexity.

Furthermore, the extra L-shape connection can be removed in order to allow for a different connection to be bolted in its place.

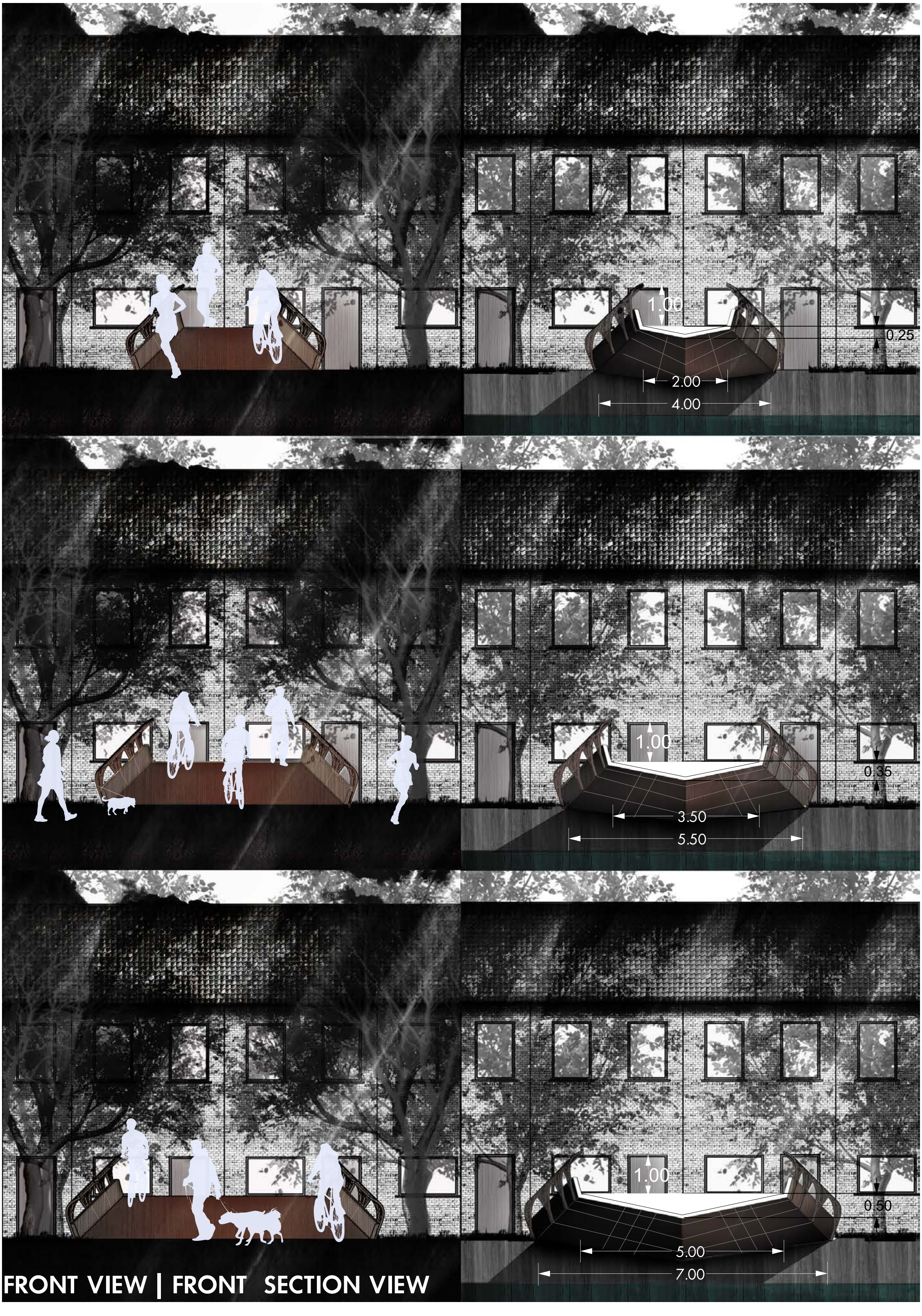
F.7.2 Perspective drawing of railing
F.7.3 Front view drawing of railing
F.7.4 Plan view and plan section drawing of railing
F.7.5 Side view and side section drawing of railing
F.7.6 Karamba deformation diagram of railing

F.9 Final design

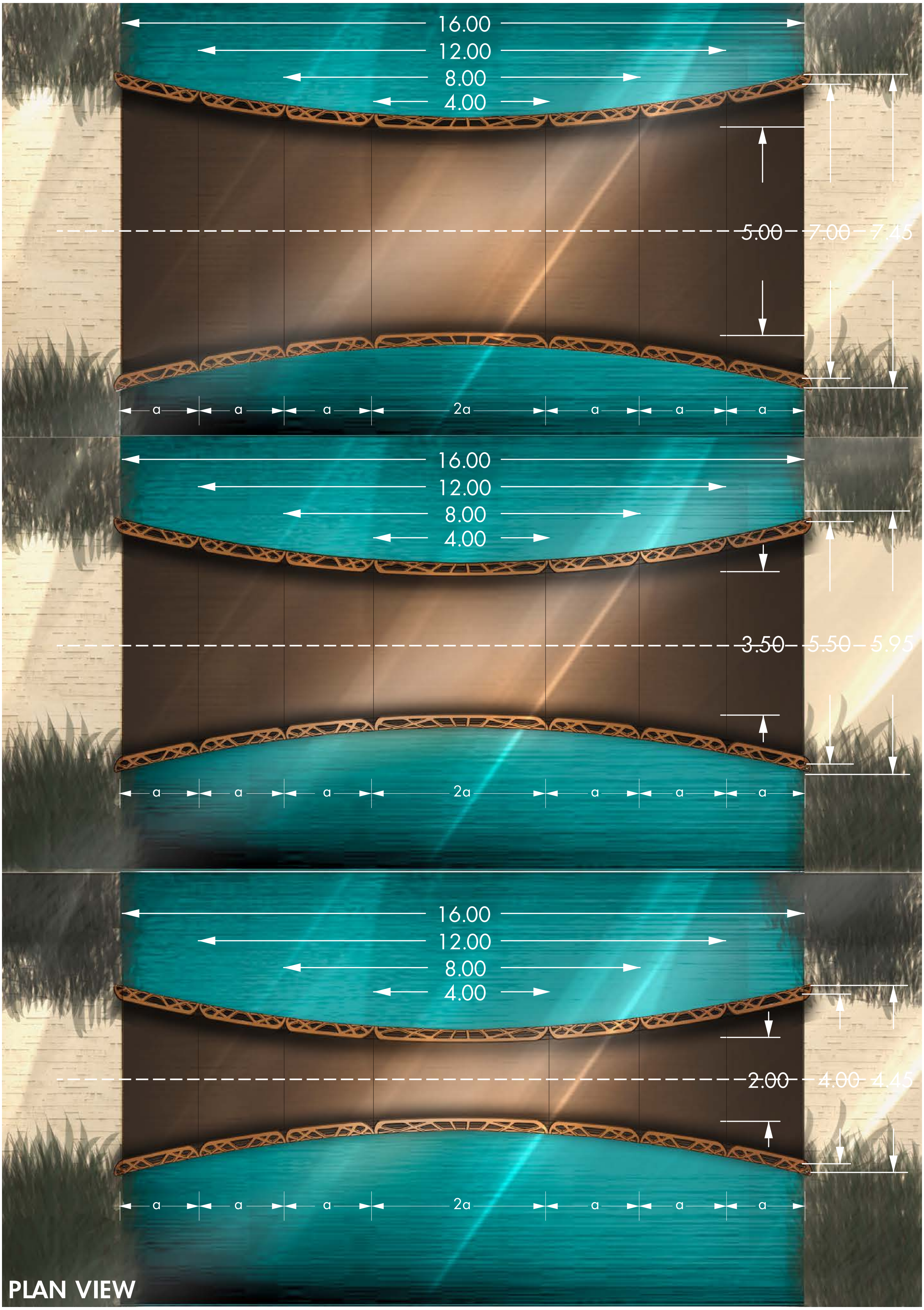




SIDE SECTION VIEW



FRONT VIEW | FRONT SECTION VIEW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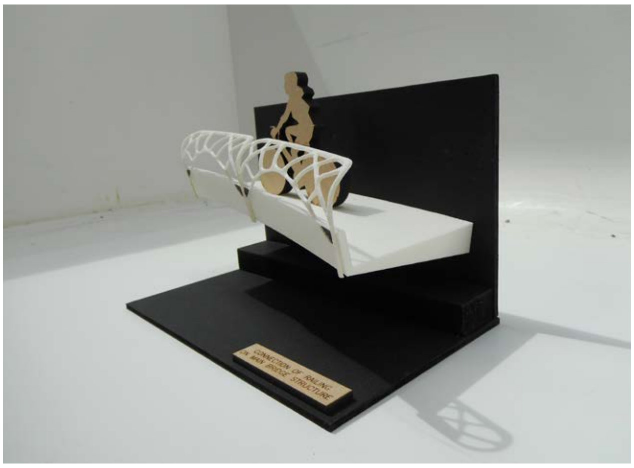
PLAN VIEW

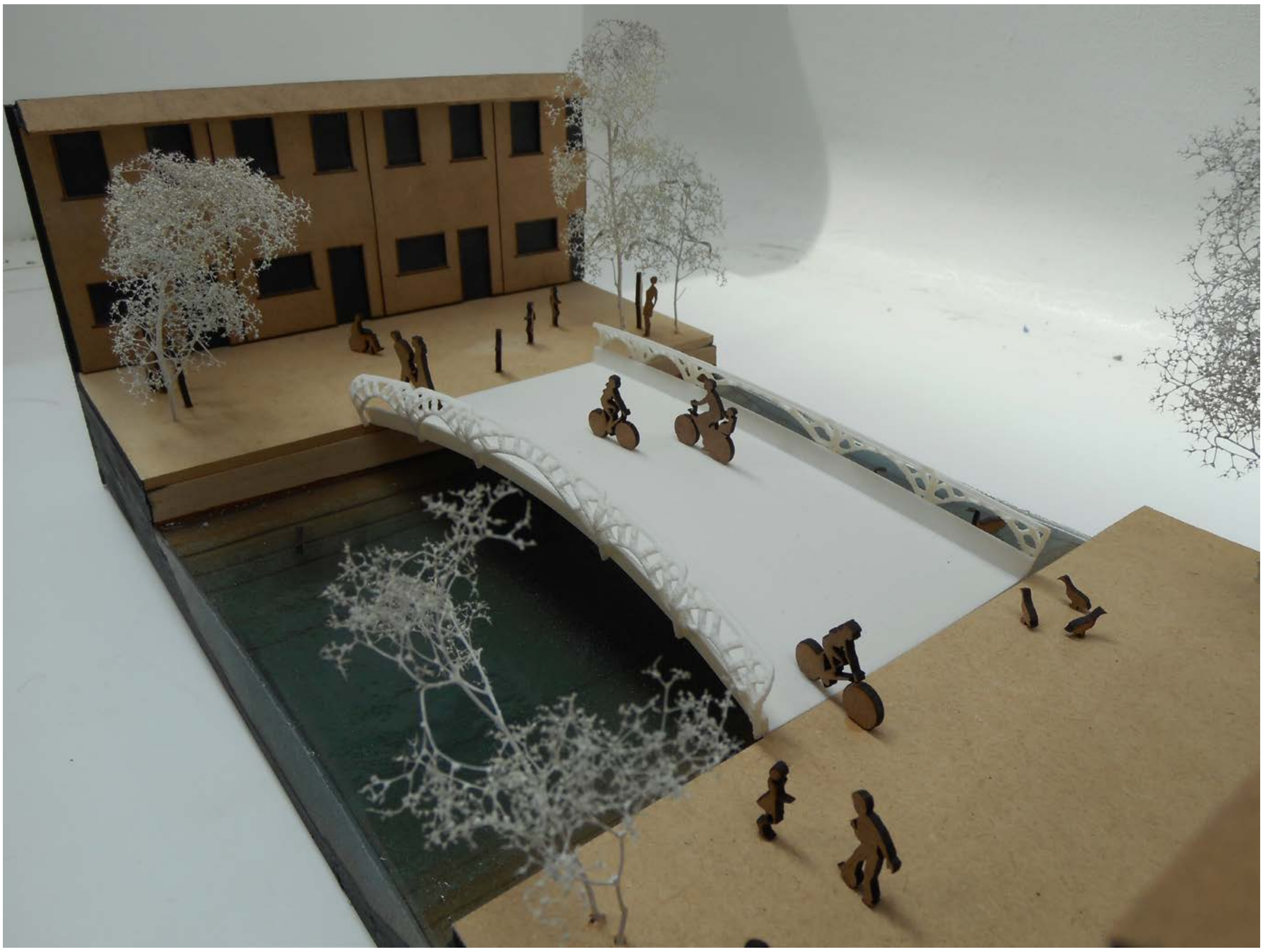
F.10 Physical model

Model of Tanthof environment

Model of Tanthof environment

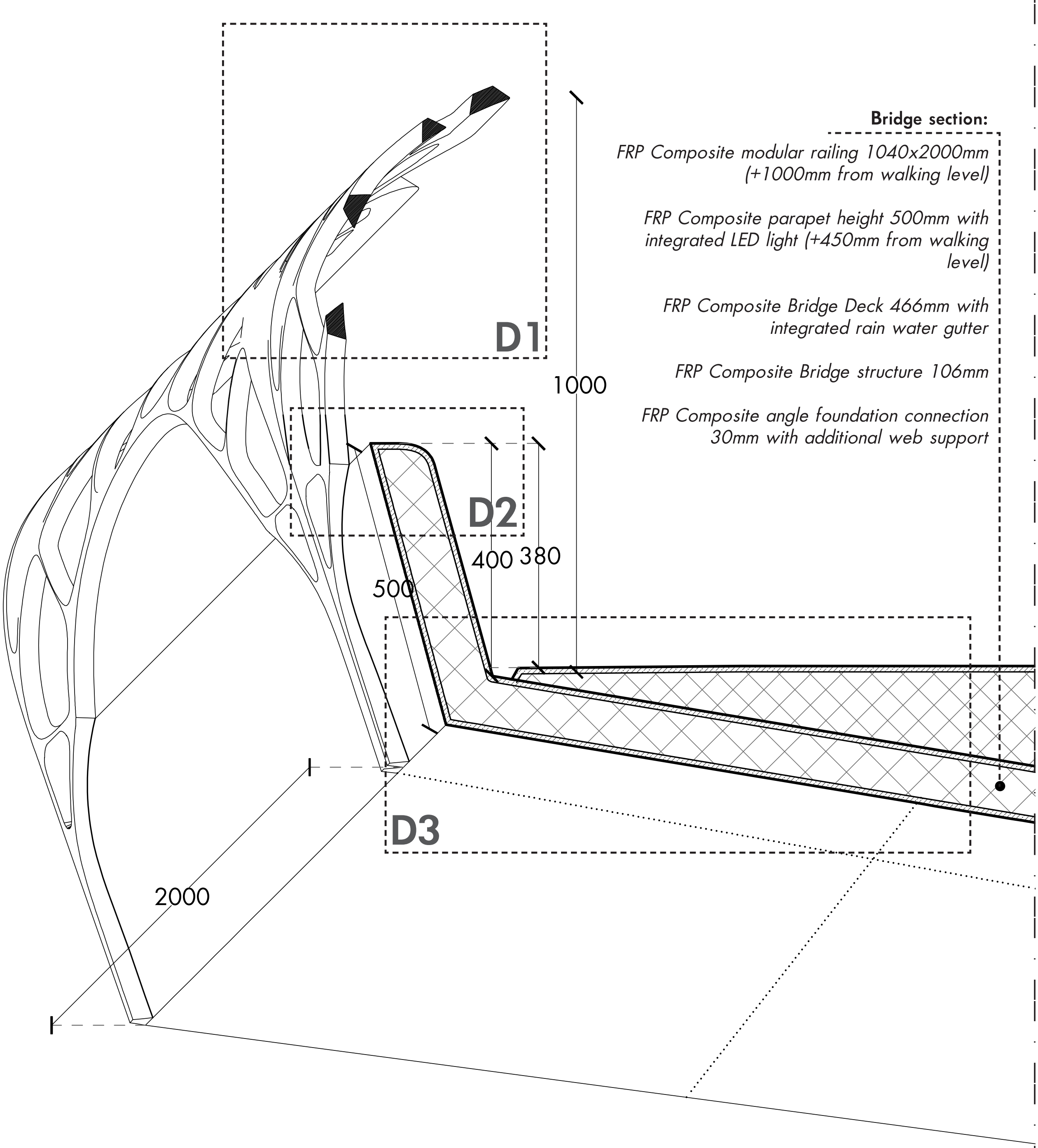


Model of bridge detail

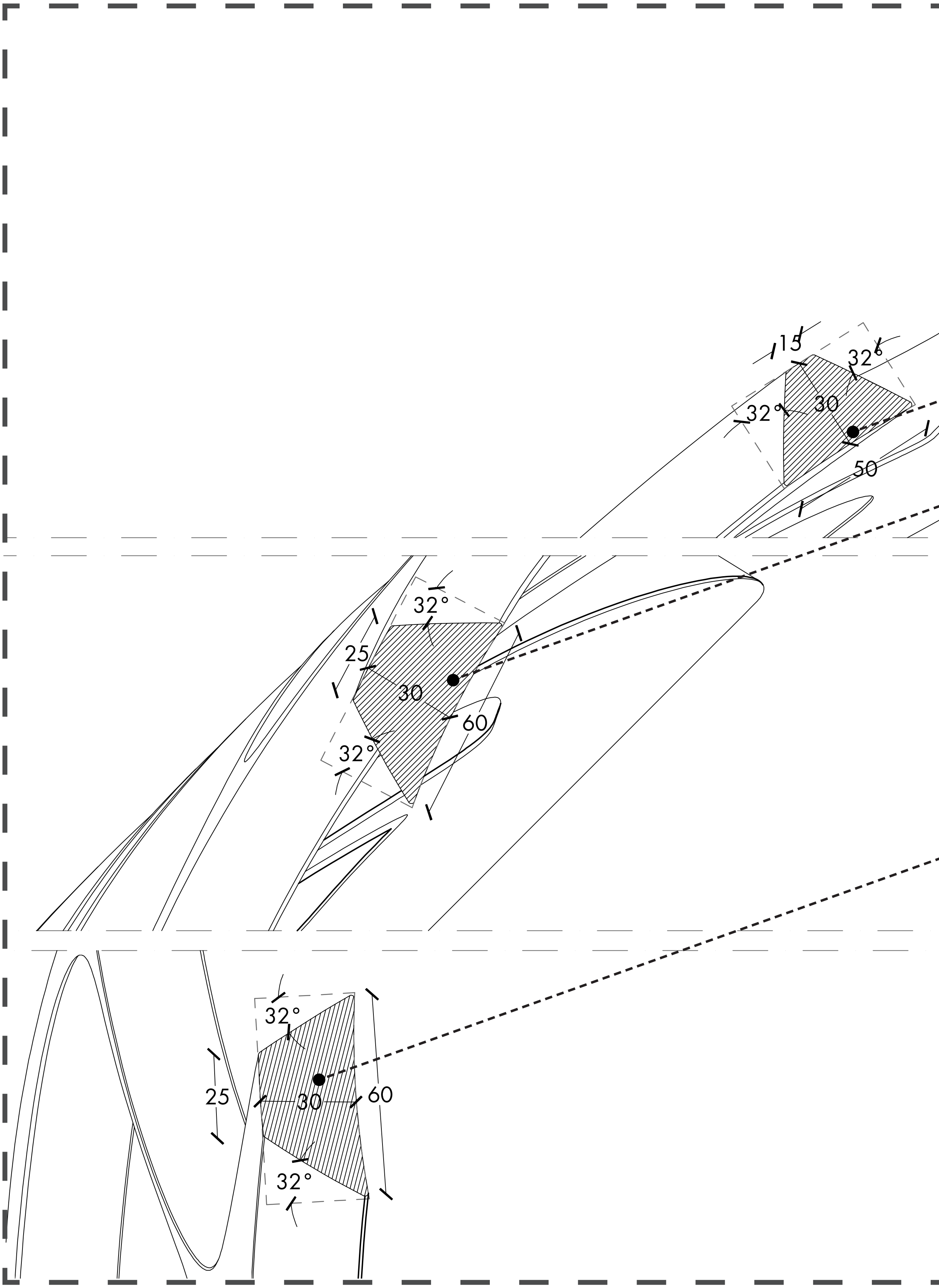


Model of Tanthof environment

F.11 Details



Final cross-section with railing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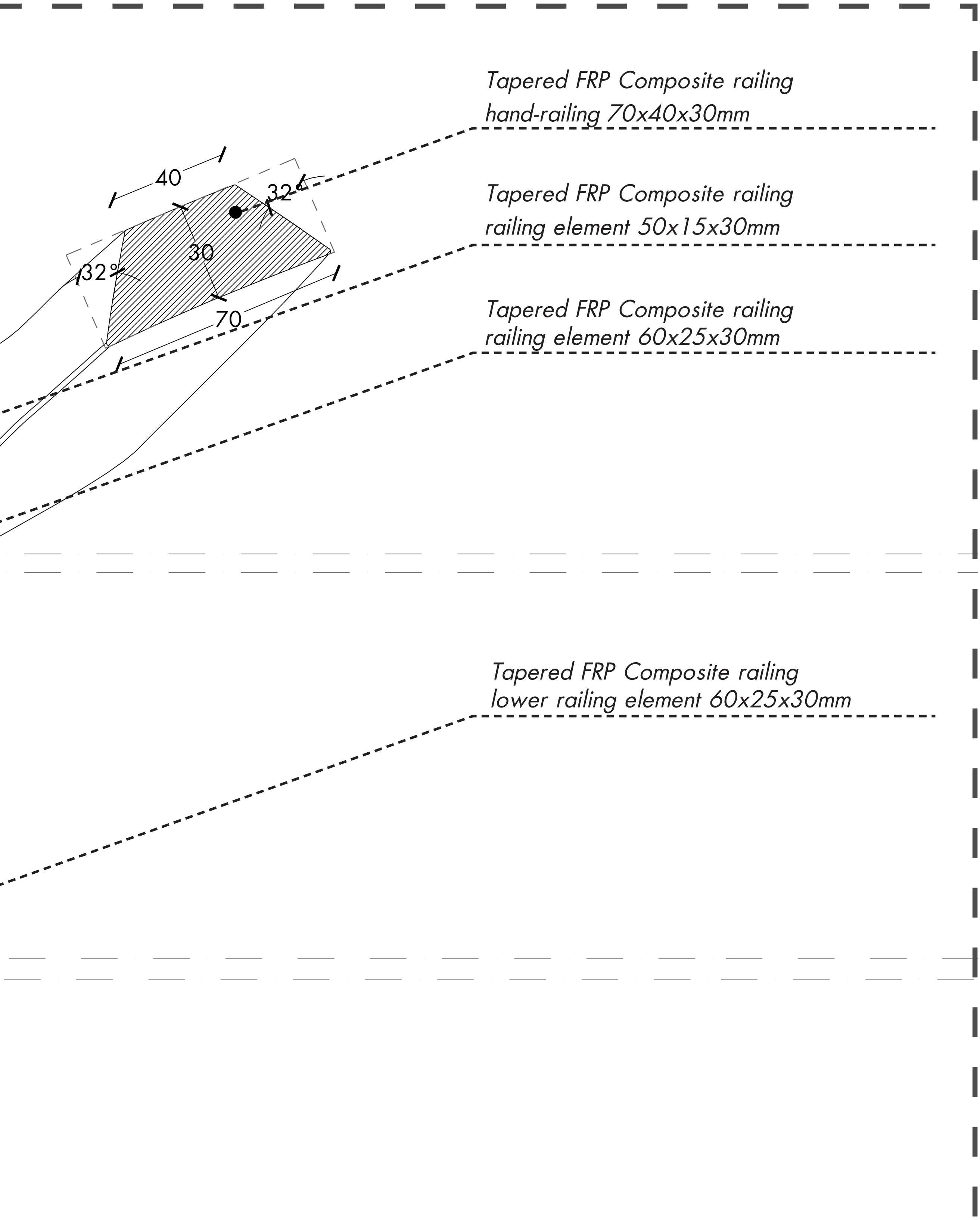
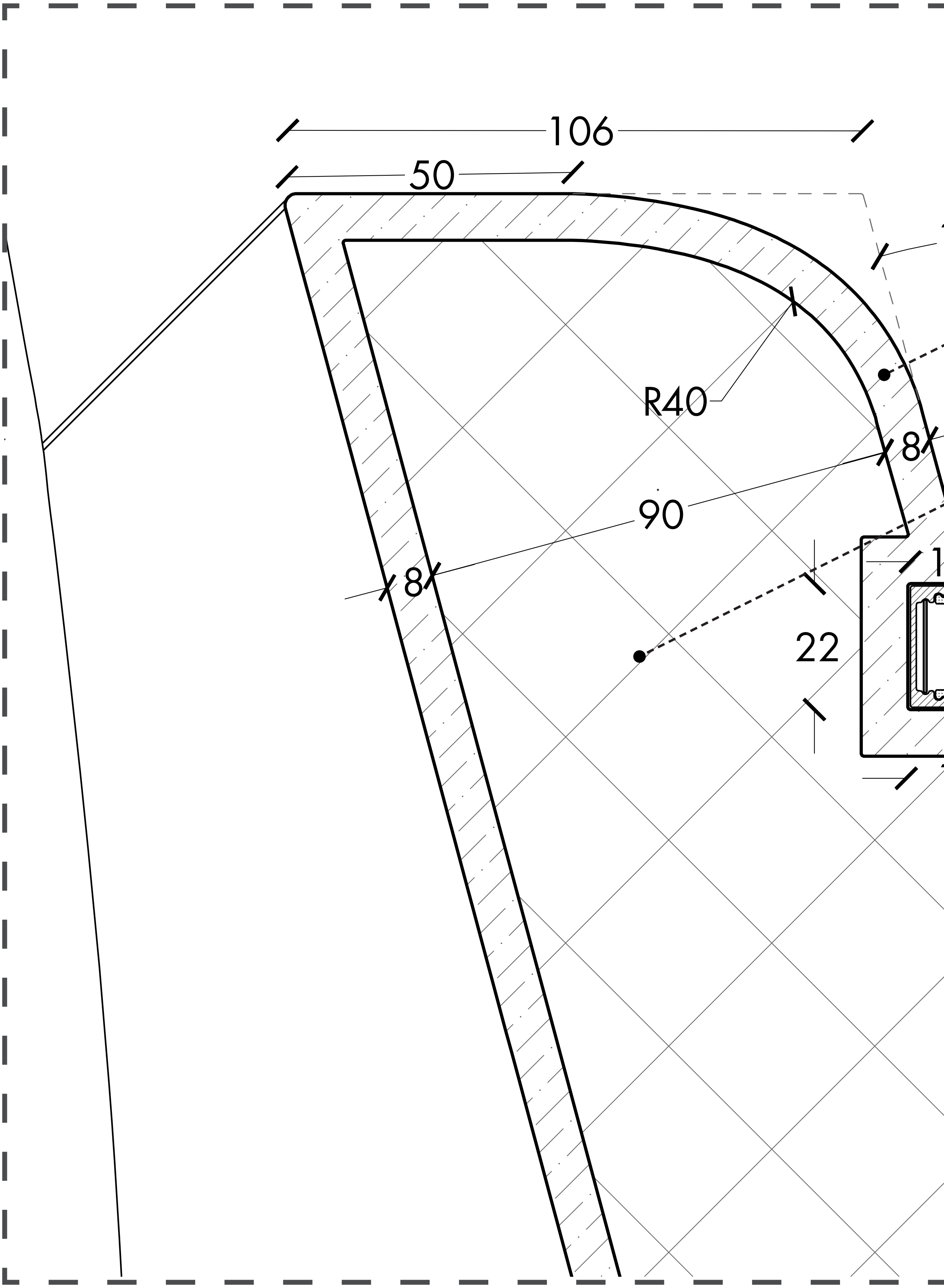


Detail 1 (all dimensions in mm)



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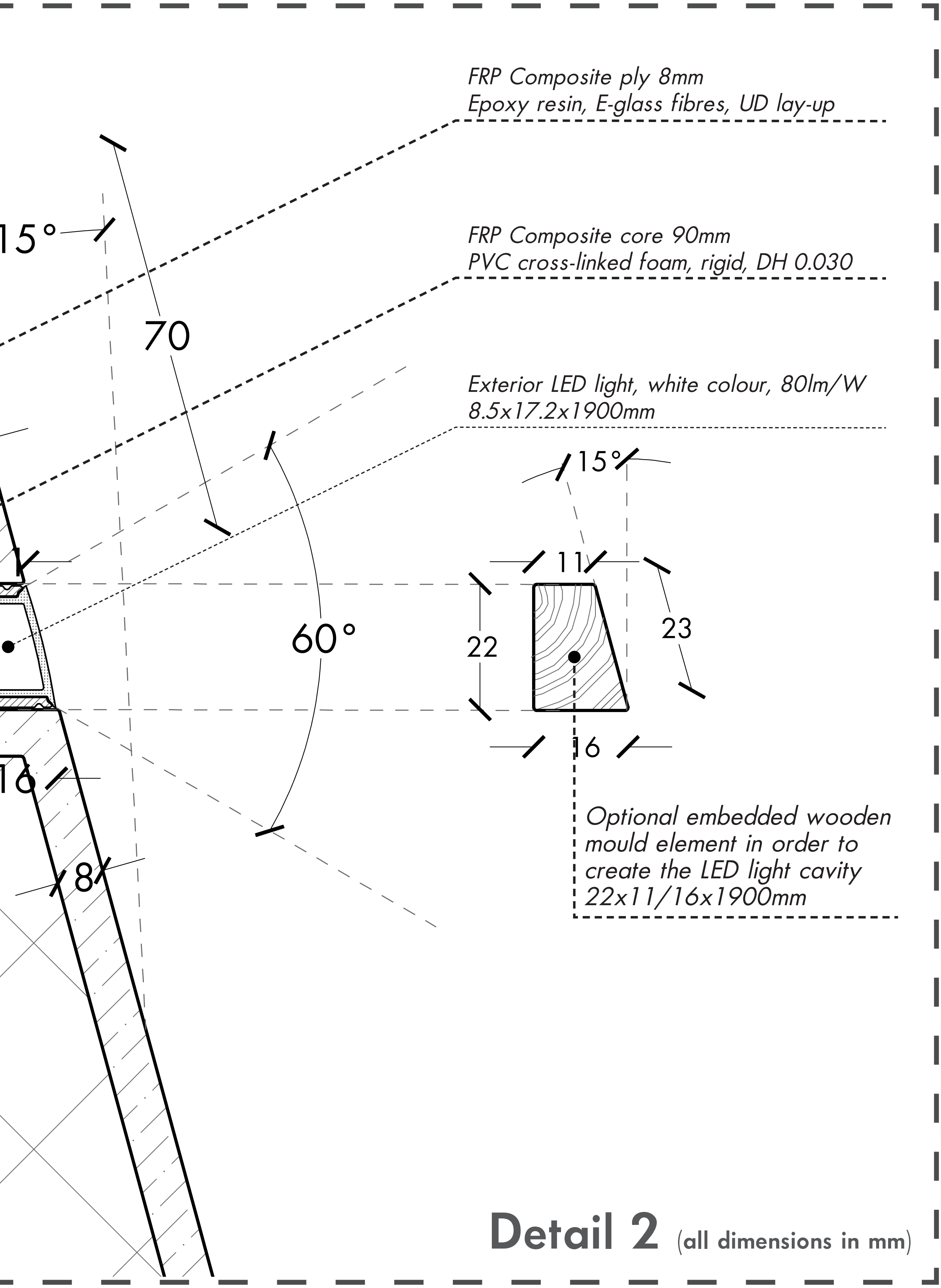
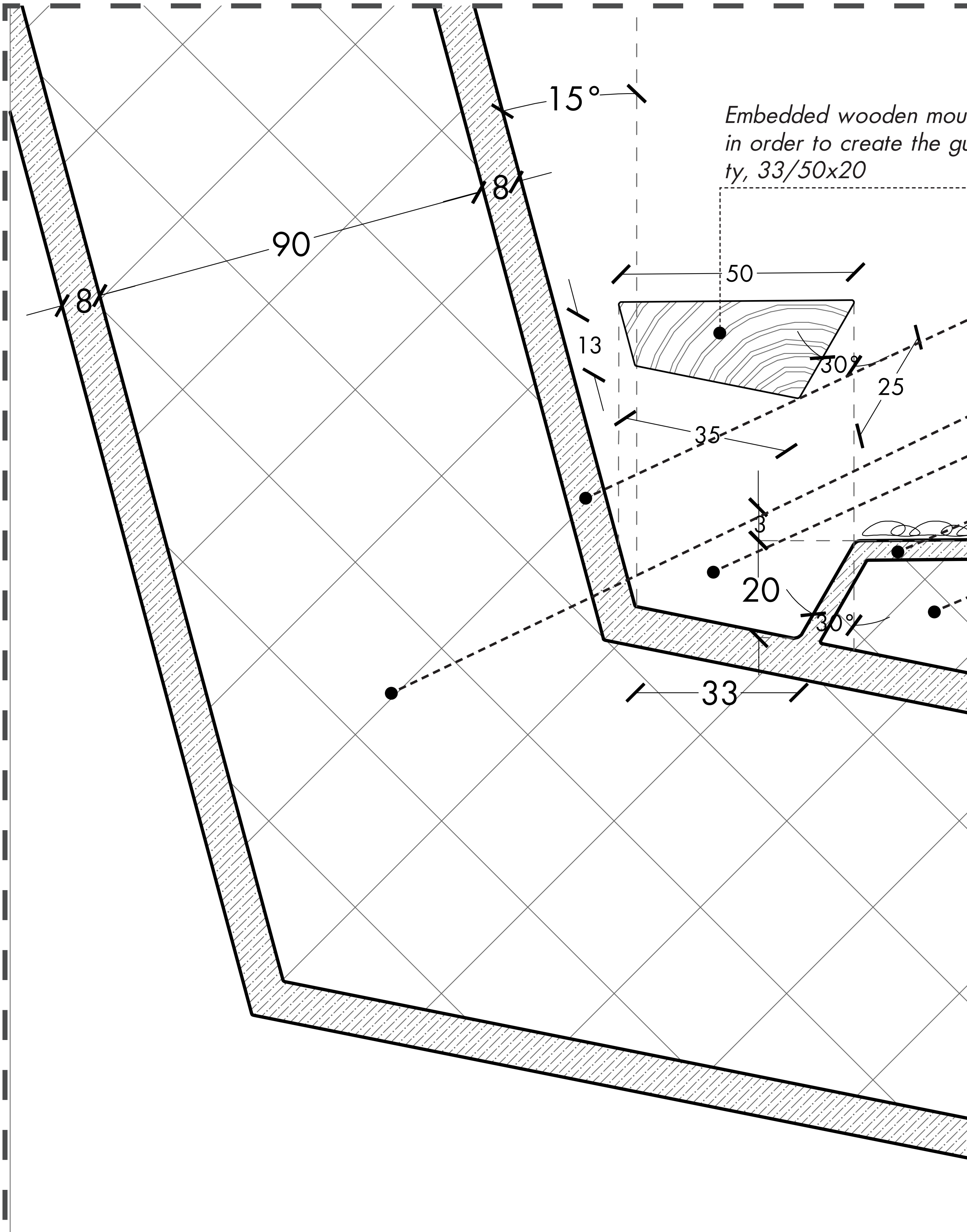
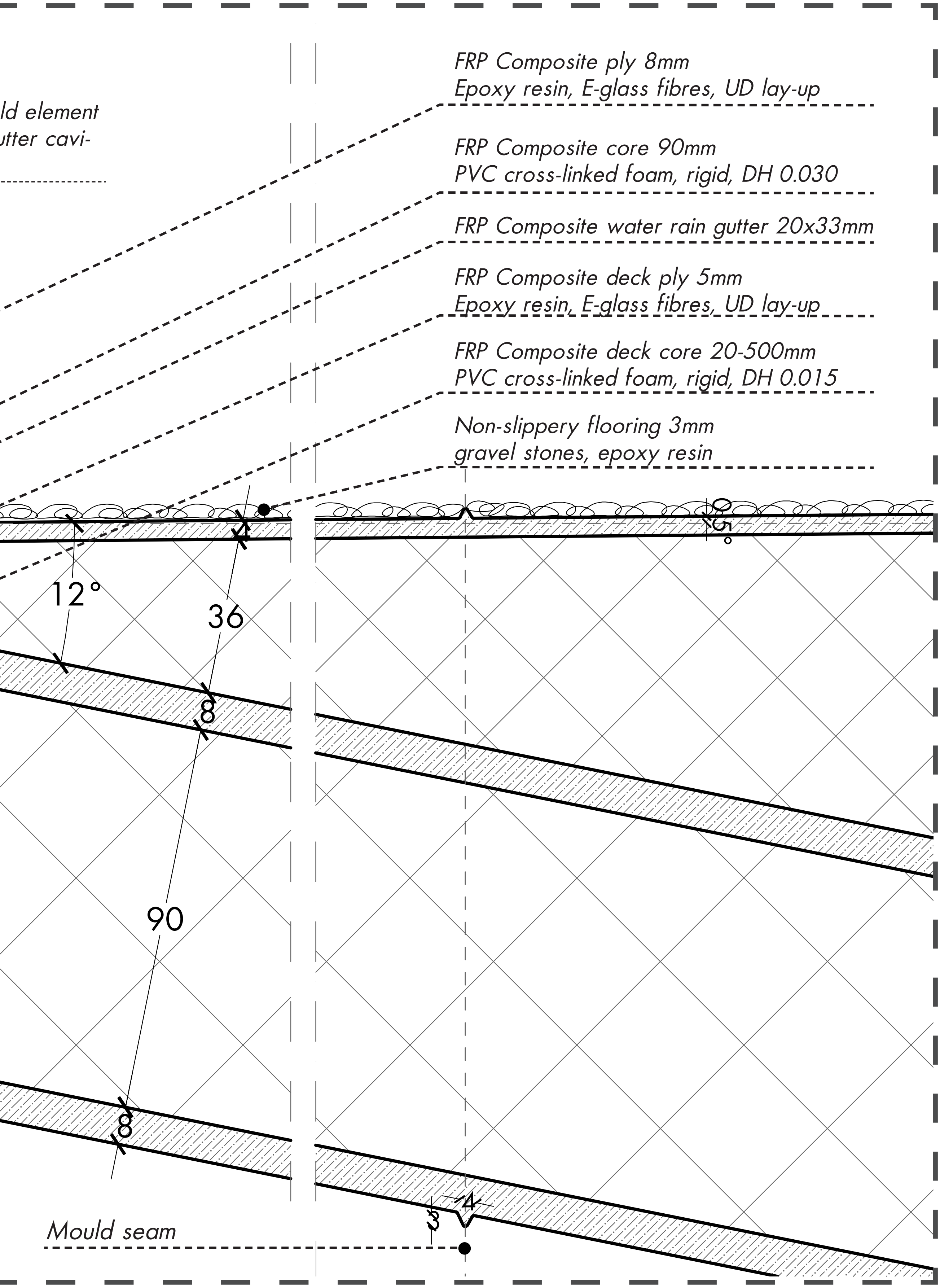
22



Detail 2 (all dimensions in mm)



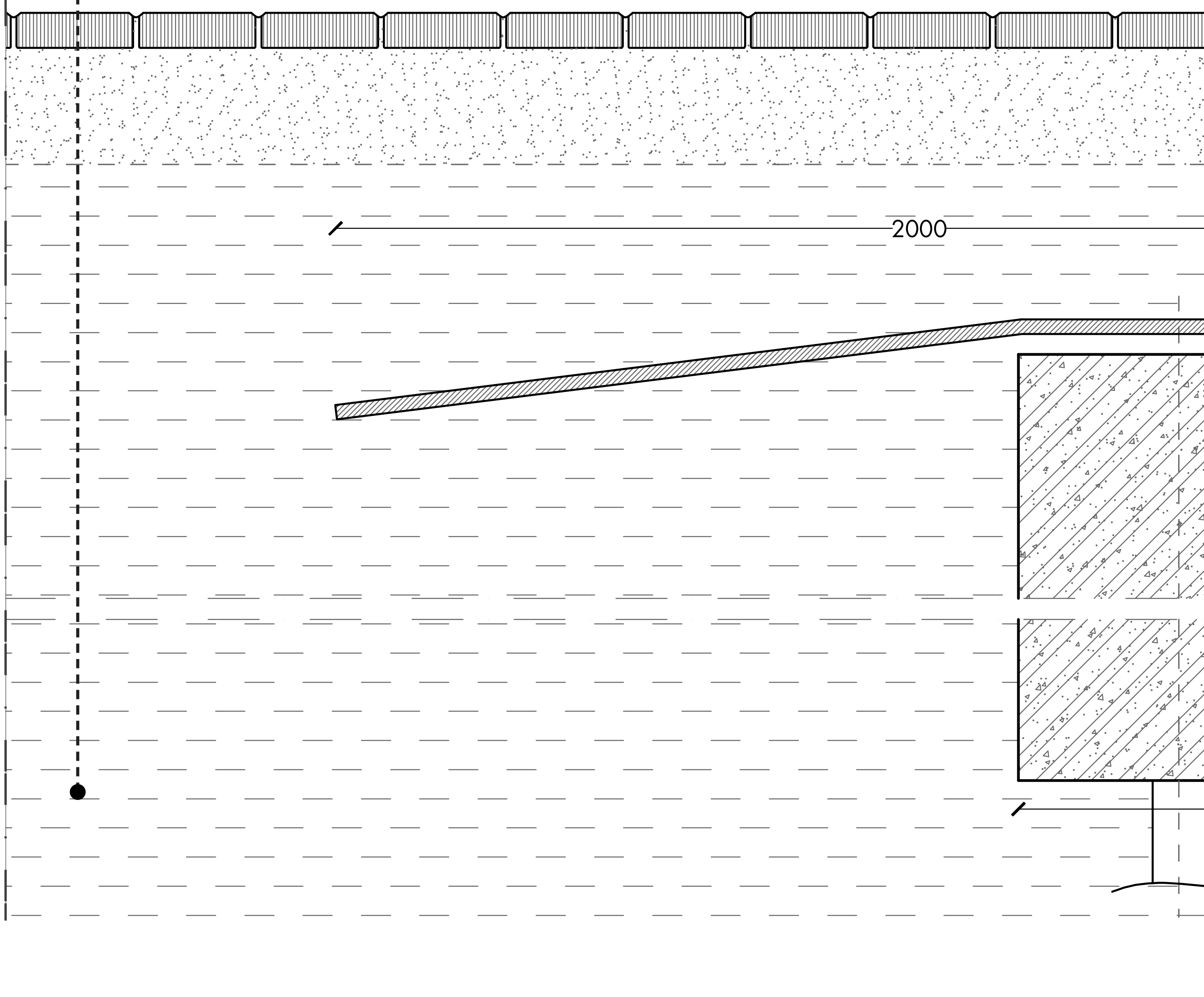
Detail 3 (all dimensions in mm)

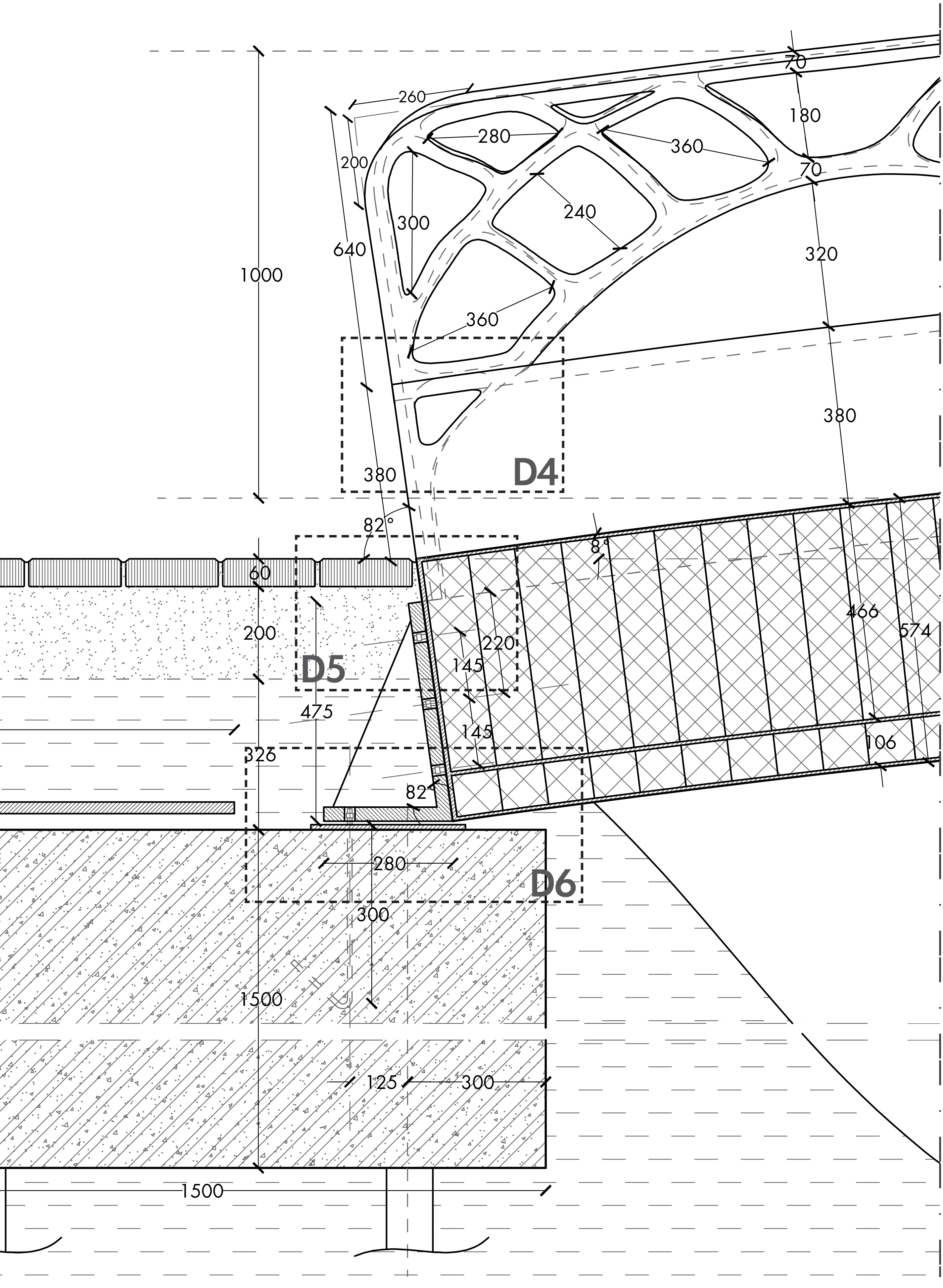

ld element
utter cavi-
FRP Composite ply 8mm
Epoxy resin, E-glass fibres, UD lay-up
FRP Composite core 90mm
PVC cross-linked foam, rigid, DH 0.030
FRP Composite water rain gutter 20x33mm
FRP Composite deck ply 5mm
Epoxy resin, E-glass fibres, UD lay-up
FRP Composite deck core 20-500mm
PVC cross-linked foam, rigid, DH 0.015
Non-slippery flooring 3mm
gravel stones, epoxy resin
0.5°
4
12°
36
8
90
8
4
3
Mould seam

Foundation system

Ground section:

Concrete pavers with sand filled joints 60x200x75mm
Bedding sand nominal 200mm
Compacted soil sub-grade min.300mm
Steel "kick-pate" -protection from uneven ground settlement- 25x2000x800
Reinforced concrete foundation 1500x1500mm

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82°
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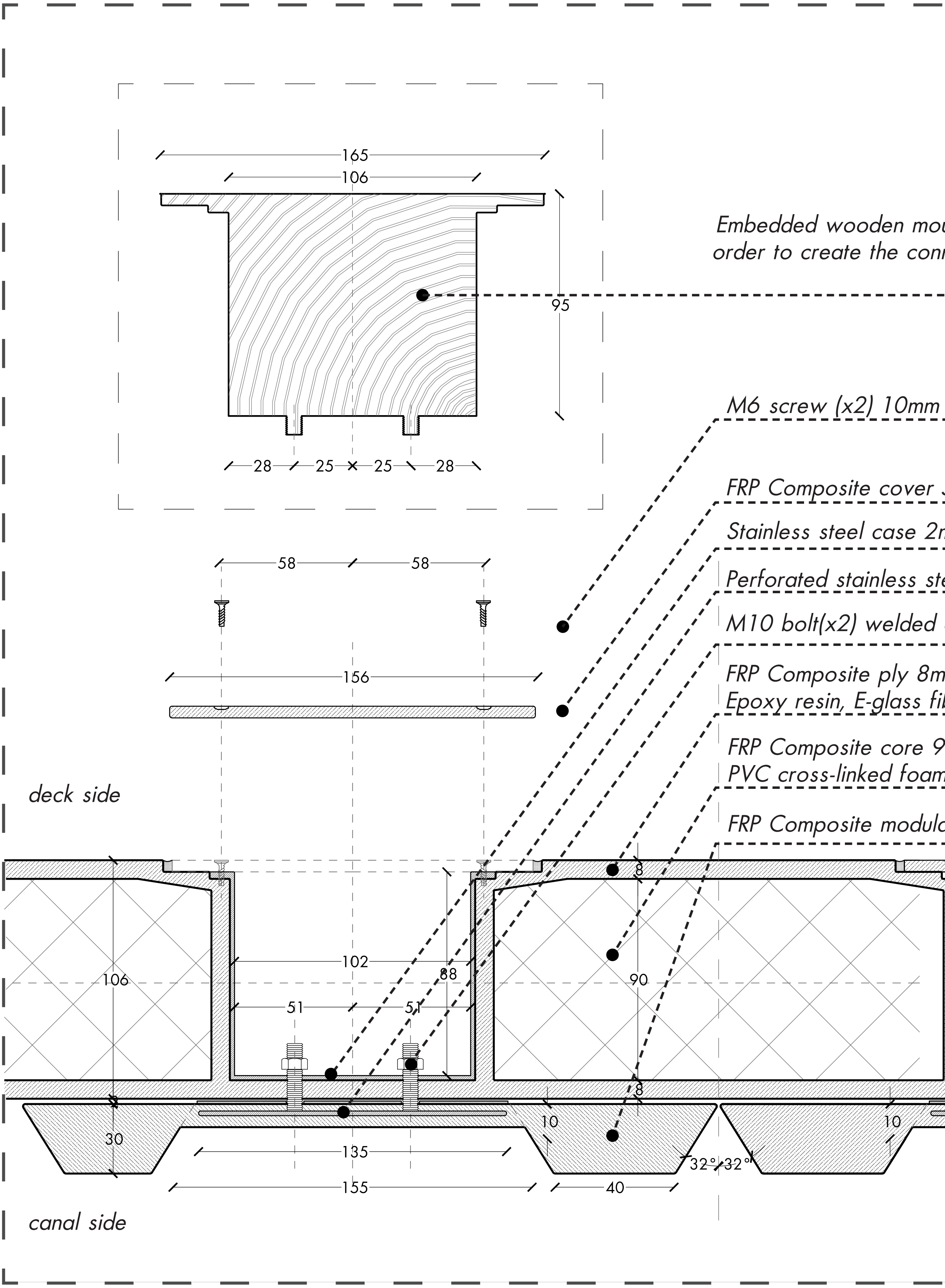
125
300
1500



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25
25
28
Embedded wooden mou
order to create the con
M6 screw (x2) 10mm
FRP Composite cover
Stainless steel case 2
Perforated stainless st
M10 bolt(x2) welded
FRP Composite ply 8m
Epoxy resin, E-glass fi
FRP Composite core 9
PVC cross-linked foam
FRP Composite modul
58
58
156
deck side
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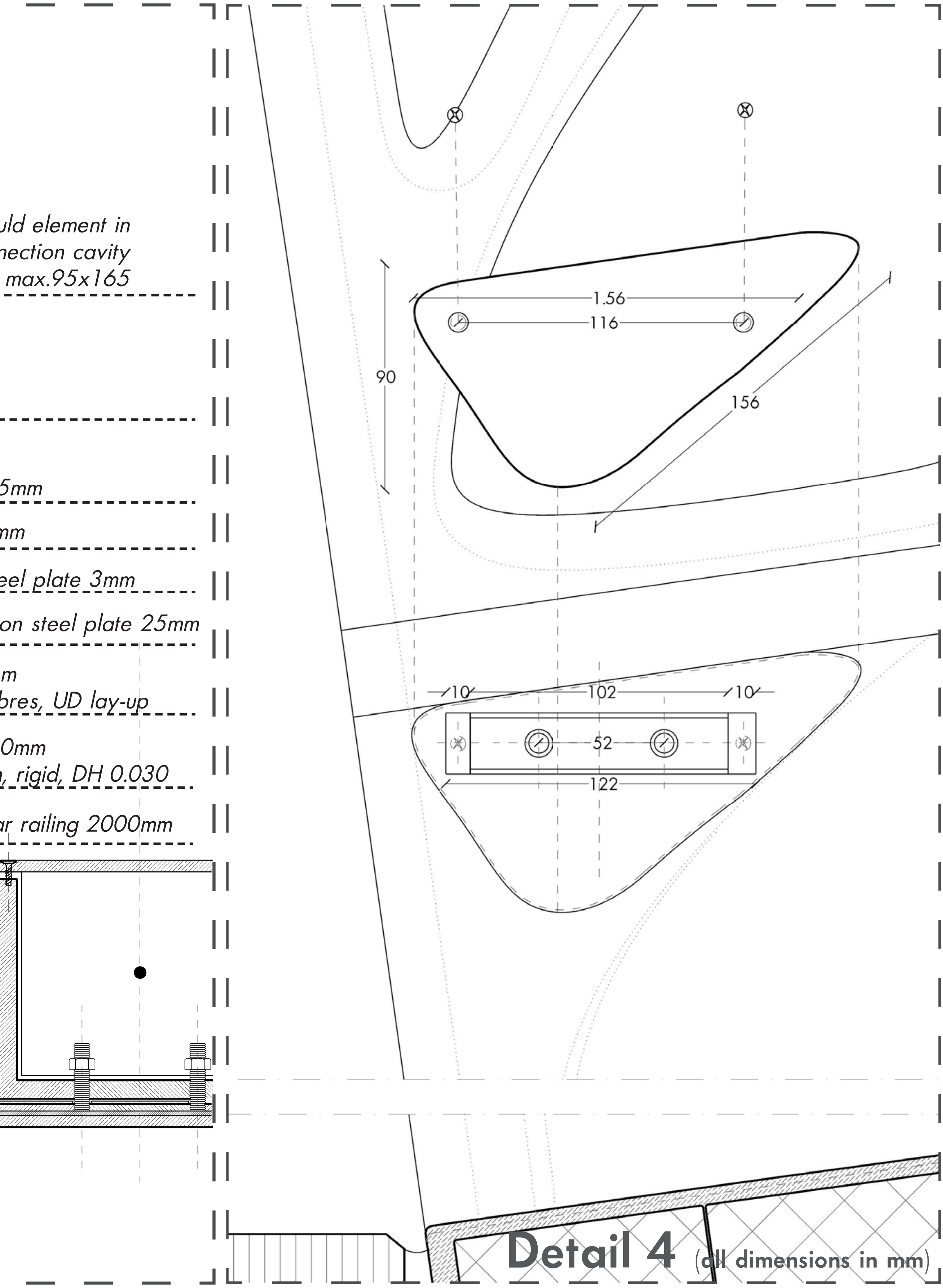
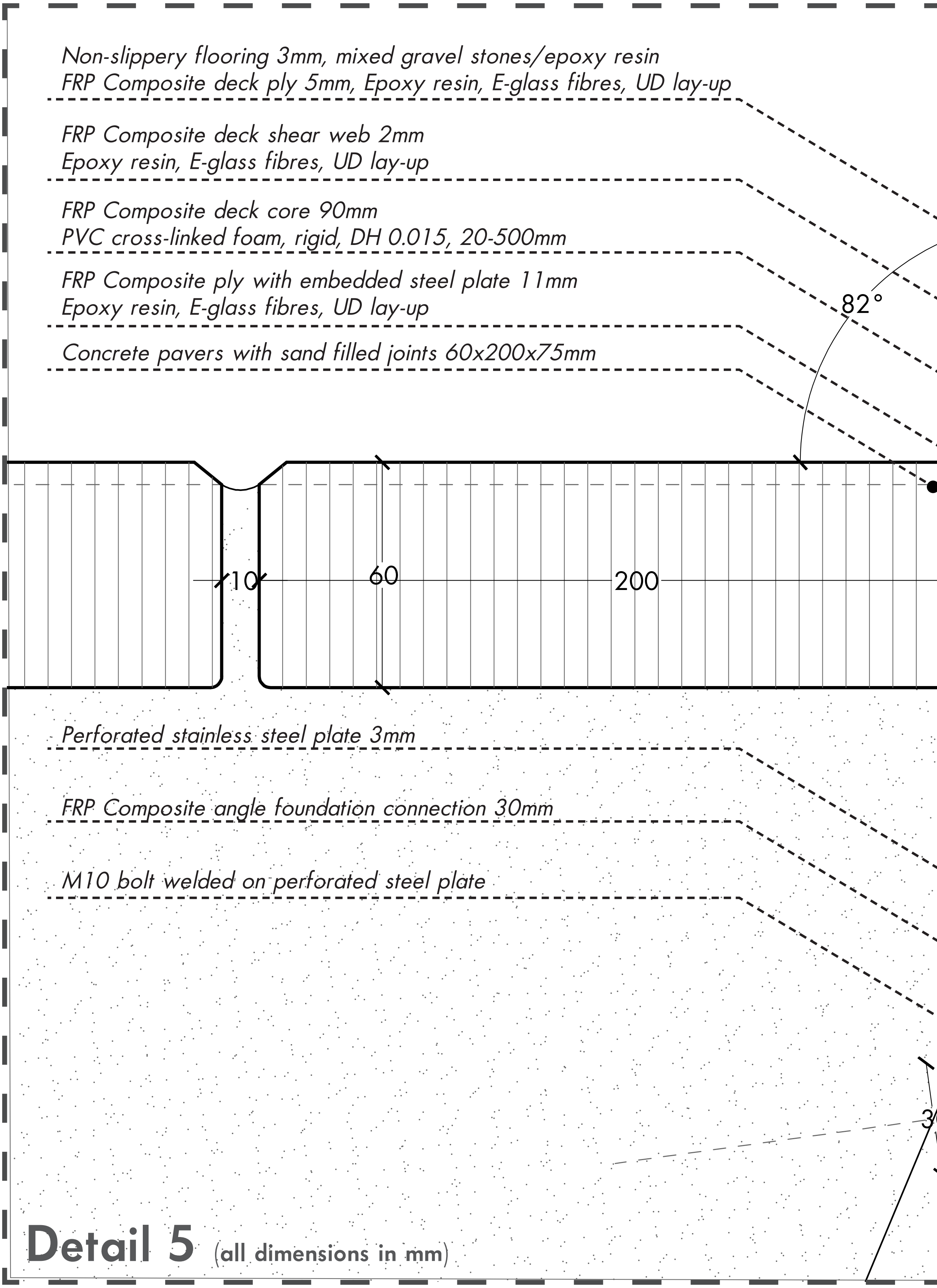
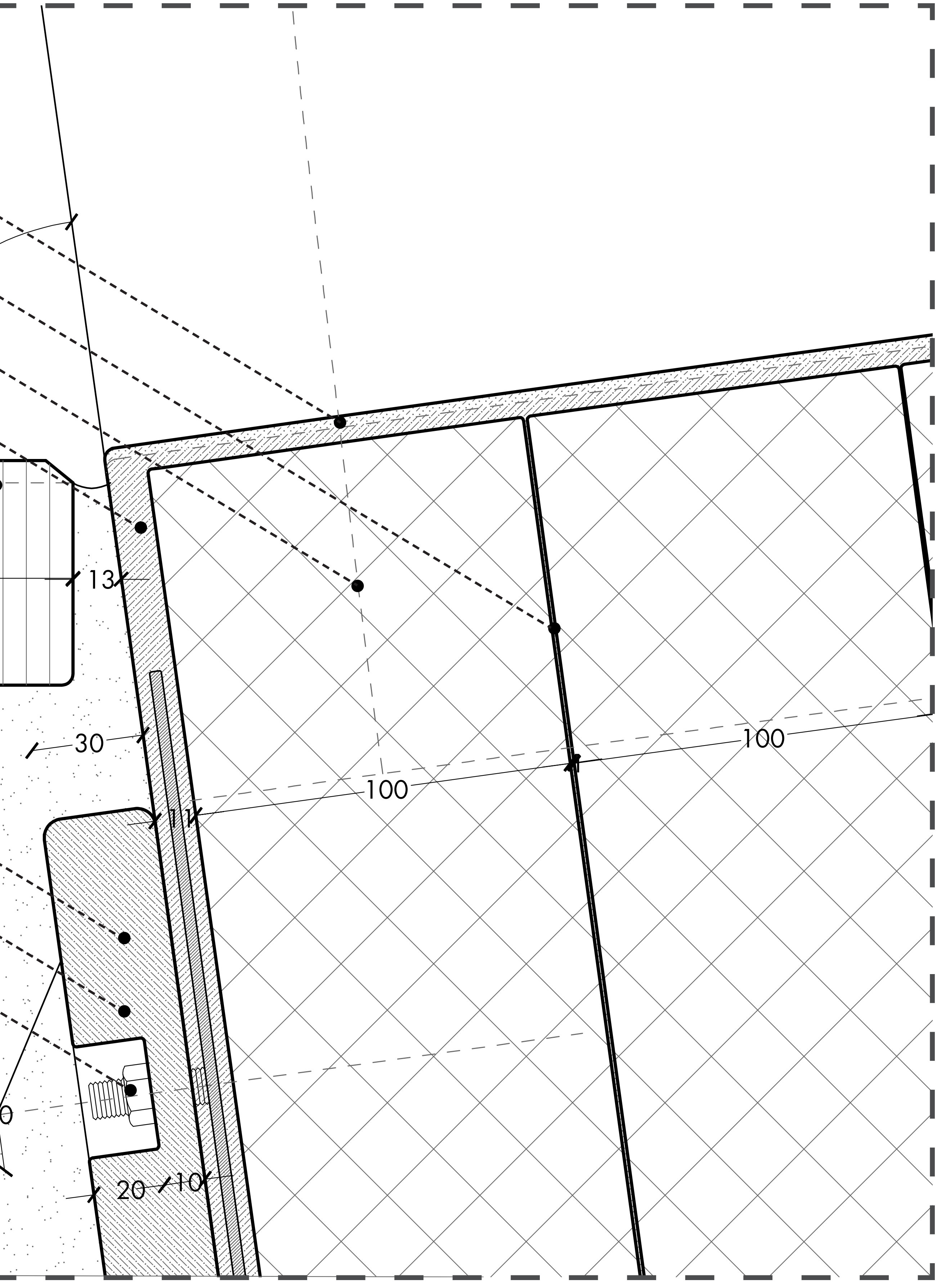
canal side



Detail 4 (all dimensions in mm)



Detail 5 (all dimensions in mm)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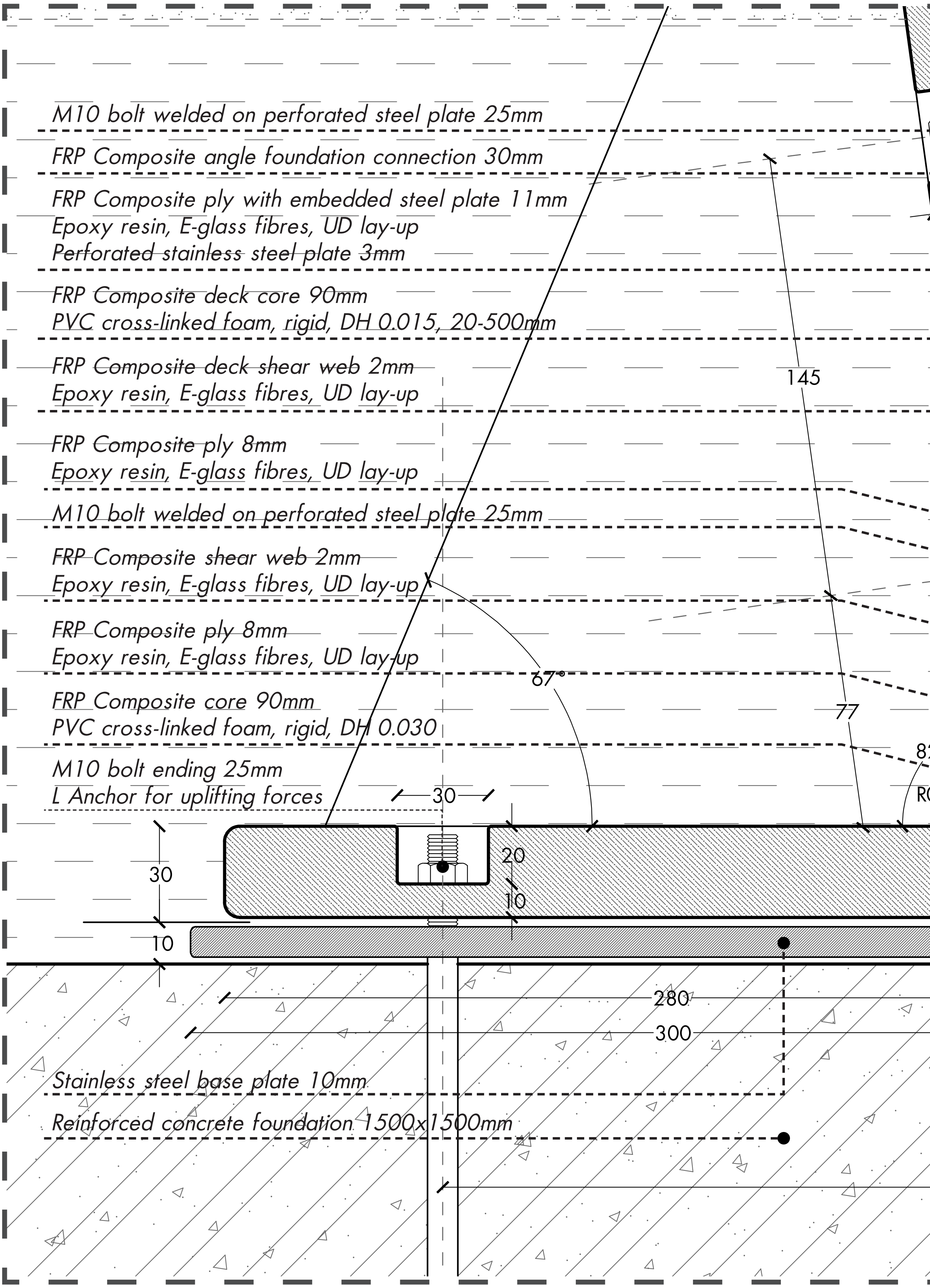
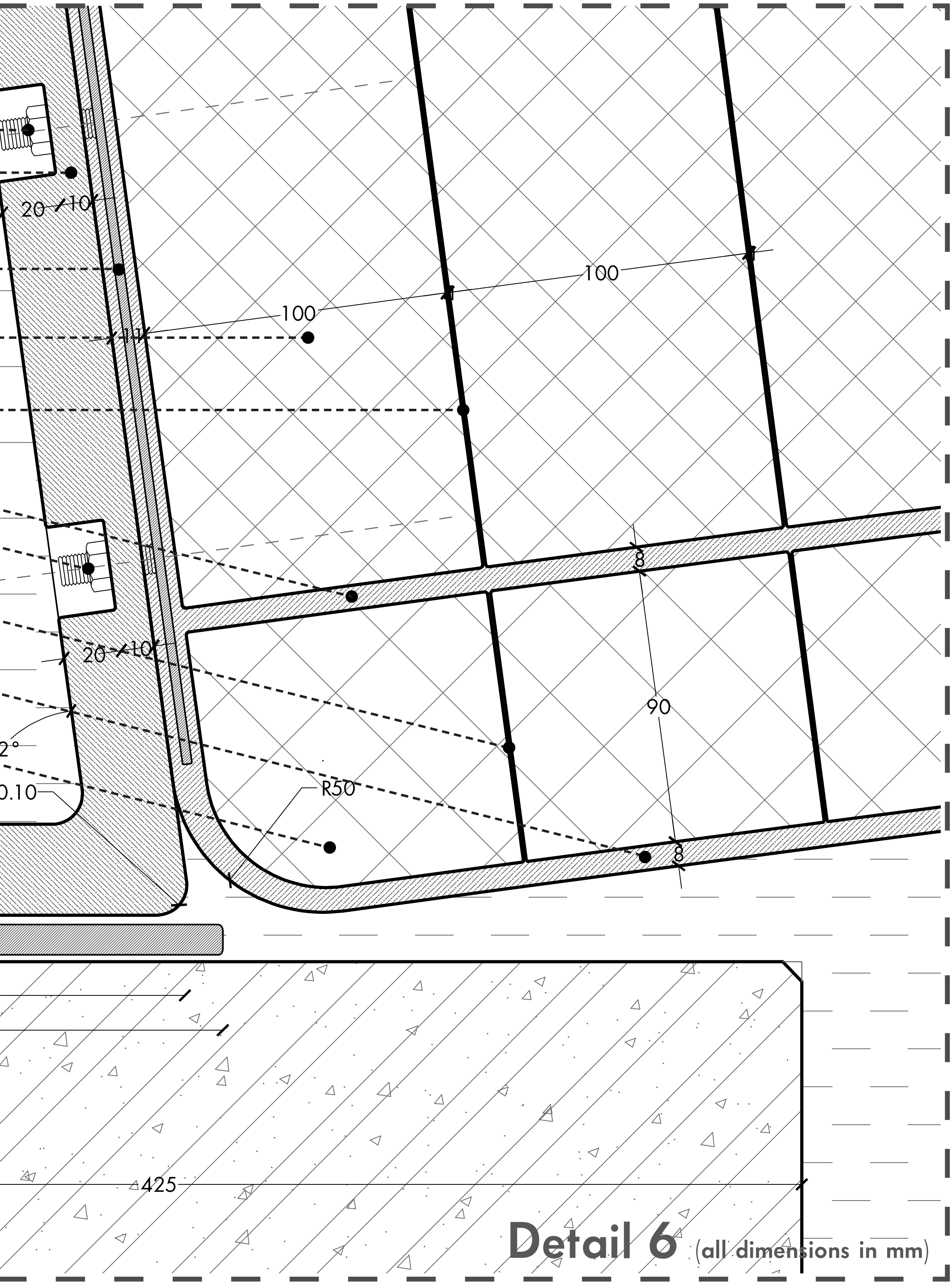

M10 bolt welded on perforated steel plate 25mm
FRP Composite angle foundation connection 30mm
FRP Composite ply with embedded steel plate 11mm
Epoxy resin, E-glass fibres, UD lay-up
Perforated stainless steel plate 3mm
FRP Composite deck core 90mm
PVC cross-linked foam, rigid, DH 0.015, 20-500mm
FRP Composite deck shear web 2mm
Epoxy resin, E-glass fibres, UD lay-up
FRP Composite ply 8mm
Epoxy resin, E-glass fibres, UD lay-up
M10 bolt welded on perforated steel plate 25mm
FRP Composite shear web 2mm
Epoxy resin, E-glass fibres, UD lay-up
FRP Composite ply 8mm
Epoxy resin, E-glass fibres, UD lay-up
FRP Composite core 90mm
PVC cross-linked foam, rigid, DH 0.030
M10 bolt ending 25mm
L Anchor for uplifting forces
Stainless steel base plate 10mm
Reinforced concrete foundation 1500x1500mm
145
67°
77
30
20
10
30
10
280
300


20
10
100
100
11
8
20
10
2°
90
0.10
R50
8
425
Detail 6 (all dimensions in mm)

F.12 Integration of the design in different neighbourhoods

This project is based on Tanthof as a case study area, but its philosophy and design could be expand to more areas of Delft. More specifically, according to municipality data apart from Tanthof there are 140 wooden, hybrid wooden and steel footbridges in Delft area excluding the historic centre. From those, 125 bridges have length and width dimensions that can be produced by the Tanthof bridge manufacturing technique.

On this chapter it will be shown how the bridge design for Tanthof can be implemented on that area and different neighbourhoods of Delft as well.

Tanthof area-small housing context


LANG

Tanthof area- urban context

Delftse Hout area- natural context

Voorhof area- Multiplex housing context

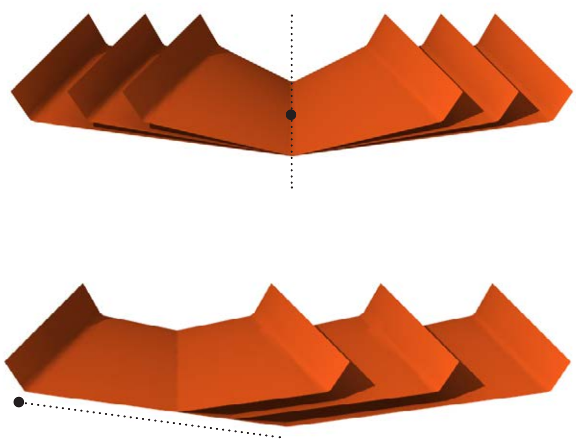
Bridge series manufacturing

G.1 Modular mould

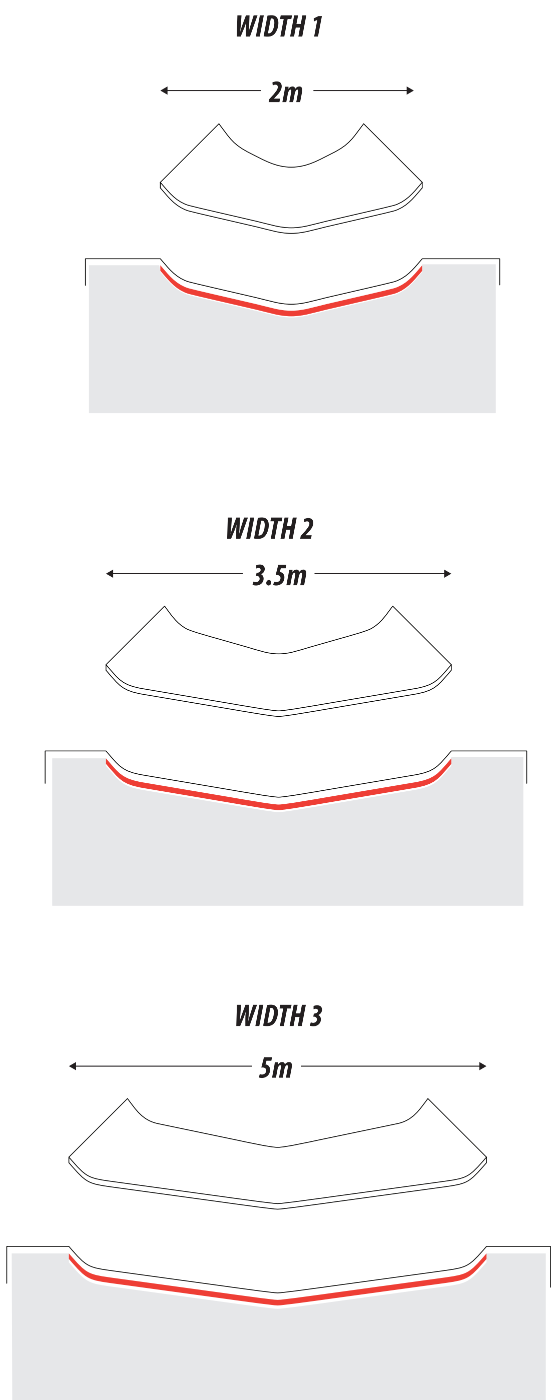
G.1.1 Manufacturing influence

The bridge series would be manufactured with the production method of Light Resin Transfer Moulding technique (LRTM). During RTM method the male and female mould are being reused and so no wastes are being produced and also both sides are smooth and accurate. Especially on LRTM the (female) lower mould is an FRP mould an the (male) upper mould is a light FRP sheet. Thus is much lighter than the original heavy RTM male mould and so it is easier to work with and less energy is needed for moving the parts, while similar if not better accuracy can be achieved.

For the modular design of the bridge series, both the male and the female mould would be divided in smaller mould and be connected according to the bridge dimensions that have to be produced. Initially, the series of bridges would be produced through three (3) different mould sets respectively to the width division. Each set of those sets would be divided in length as was already explained on the module matrix. In such way 23 modules



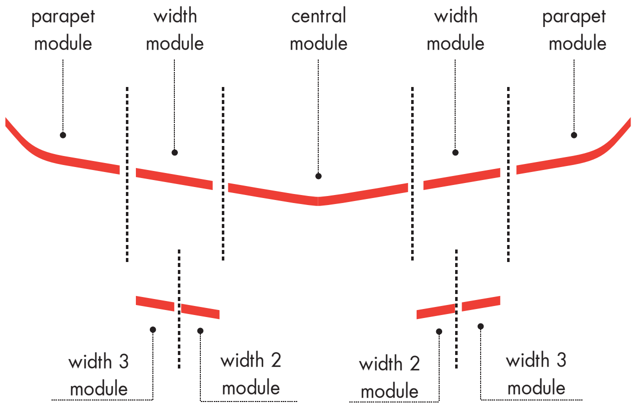
G.1.1



G.1.2

G.1.1 Illustration of the two different modular mould variations
G.1.2 Illustration of mould need for different width bridge variation
G.1.3 Illustration of geometrical relation between the different width variation
G.1.4 Deformation chart of the series on the two different mould variations

(7mould pieces*3 sets + 2side parts) would produce the bridge series. In such a way all the width sets would have the same central symmetry axe and same structural weight, but different deck inclination.



G.1.3

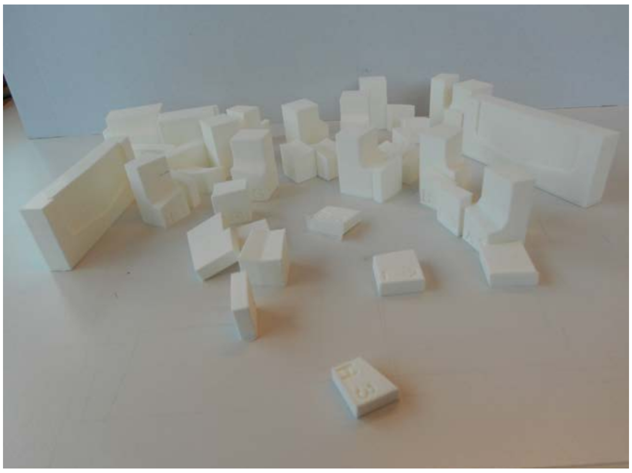
From this first design it was concluded that the length division was well served, but the width division needed to change, in order to optimise the geometrical relation of every bridge group and more mould modules to be reused. More specifically, in the first design attempt the same algorithm in Grasshopper was used to create the different bridge variations and thus every geometry had the same relation of deck height, side height, parapet height and rotation angle, length (16m) but different width respectively to their width group (2m, 3.5m, 5m). The geometrical coherence of the series was the same central symmetry axes. This element was insufficient to transfer a geometrical similarity in the mould. This study indicated that in order to reuse parts of the moulds and produce bridges in different widths, the subdivisions should follow strictly functional principles and not mathematical ones.

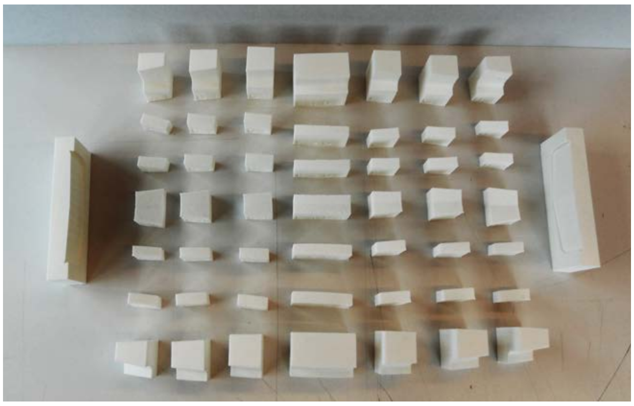
G.1.4

In the second design attempt, the bridges shared the same deck inclination, which was based on the bridge model that was analysed structurally on previous process. Now the different items of the series do not share their coherence on the central symmetry axe, but on the deck inclination and their same starting point is the bridge facade. Also, further division on the width direction was made based on functional parts, namely bridge facade (parapet) and bridge deck. The deck element was subdivided further, based on the different widths variations that the municipality data concluded. Due to connectivity facilitation, seams on critical faces was avoided. Thus the mould part of the facade also includes part of the deck. In that way a more simple module part connection and bridge production can be achieved.

Furthermore, it also needs to be highlighted that shifting of geometry of the series from variation1 to variation 2 also influenced the structural height of the bridge population. Such effect could harm the structural performance of the bridge series. Through performing structural simulation to all bridge variations of the two (2) different mould versions it was proven that no significant differences in the deformations are noticed on each mould version (Figure G.1.4).

Moreover, in this mould design the principle of reusing the same pieces to produce the bridge series is more dominant, but now more pieces are needed. More specifically 52 modules (7length mould pieces*7 width mould pieces + 2 side parts). This version might have more pieces that need to be taken care of and being used, but their area and mass is much less than the first version and thus easier to work with. Also, via the functional division of the mould pieces the deck parts can easily be reused with different facade and also the same facade could be combined with a different deck.





G.1.5

G.1.5 Experimentation of modular mould assembly
G.1.6 Sketches of "edge"mould experimentations

To sum up, in order to design a modular mould that re-uses as many modules as possible a dense subdivision of the length and width variations was necessary. In that way a big number of pieces is made, but those pieces are smaller than the initial ones and thus easier to work with. Also, a functional subdivision of the bridge and its translation into the mould pieces broadens the variation of bridge designs and the reuse of old pieces in new moulds.

G.1.2 Mould seams

Architects field may not extend in solving the manufacturing and assembly engineering of a project, but he/she ought to have an insight of those processes, alternatives and challenges especially when these interfere with the final product that he/she designed initially. In this chapter, some plans will be proposed, but in a real project these solutions should be discussed with the appropriate expert. Nonetheless, an architect having knowledge of the manufacturing and assembly process can only benefit the project and the interaction between the different disciplines in order to produce a well integrated project. For this project, the proposed solutions and methods in designing and assembling the mould modules should be seen as design philosophy that the final product aims on. Also, the proposals are based on literature review and scaled modules, so their success or failure cannot be assessed in real conditions.

In principle, when moulding manufacturing technique is chosen, the creation of perimeter seam consists of an ineluctable consequence and thus a designer has to bare this in mind. The seam is formed on the final product, due to the tolerances of the connection of two or more moulds. Normally, the moulding of round or irregular shapes with complex geometries needs to use more than one mould. In general, where these moulds meet an extra seam net is created that interferers with the designed shape. For the specific project, these seams

G.1.6 Mould seams on final products

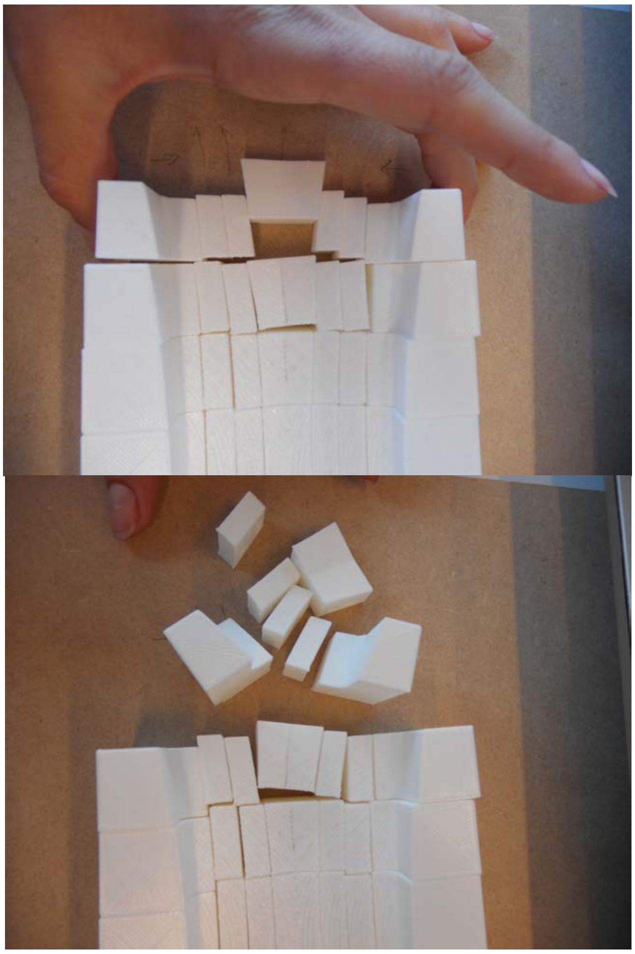
indicate the number of moulds used in order to create the bridge and also function as an indication of which example of the bridge series it is. Especially the seams on the bridge parapet are being highlighted additionally with the railing design.

G.1.3 Module connections

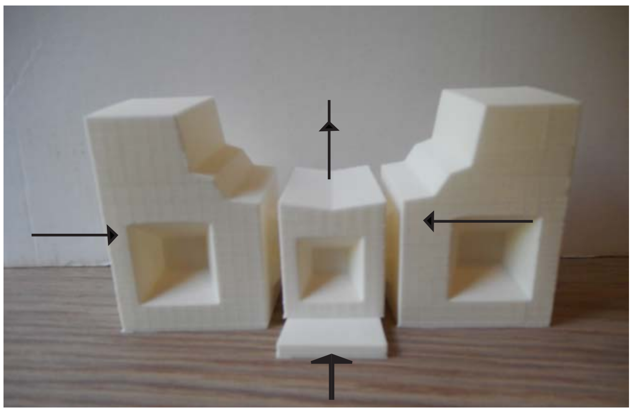
An additional important aspect of the modular mould design is the connections between the modules. A not well served connection between the modules would have an immediate impact on the manufacturing technique and the final product. For that reason extra research was done on the connection of the modules. From the literature review on LRTM it was found that the airtightness of the mould pieces could be covered via the use of sealing strips placed on the perimeter of every module preventing the resin to flow between the module seams and insuring and airtight connection. Also, the moulds are produced from FRP, so they are able to withstand the pressure and temperature loads that are applied on their walls during resin injection. So, no extra reinforcement is needed. The only crucial part of the modular mould design is the successful and accurate module placement.

Moreover, in order for the different mould to be assembled, an assembly sequence is proposed, in order for the connections between the modules to be defined. This sequence was tested on working models. From the first working model was concluded that the straight transversal mould face was creating a very slippery connection allowing free move between the pieces. Also, due to the section geometry, when side pressure is applied to connect them in row the pieces are sliding forwards. This effect is even greater on the centre piece, where the shape of the module foster such displacement.

After having conducted this experiment it was clear that a connection greater in shear resistance was essential for the design. As



G.1.7



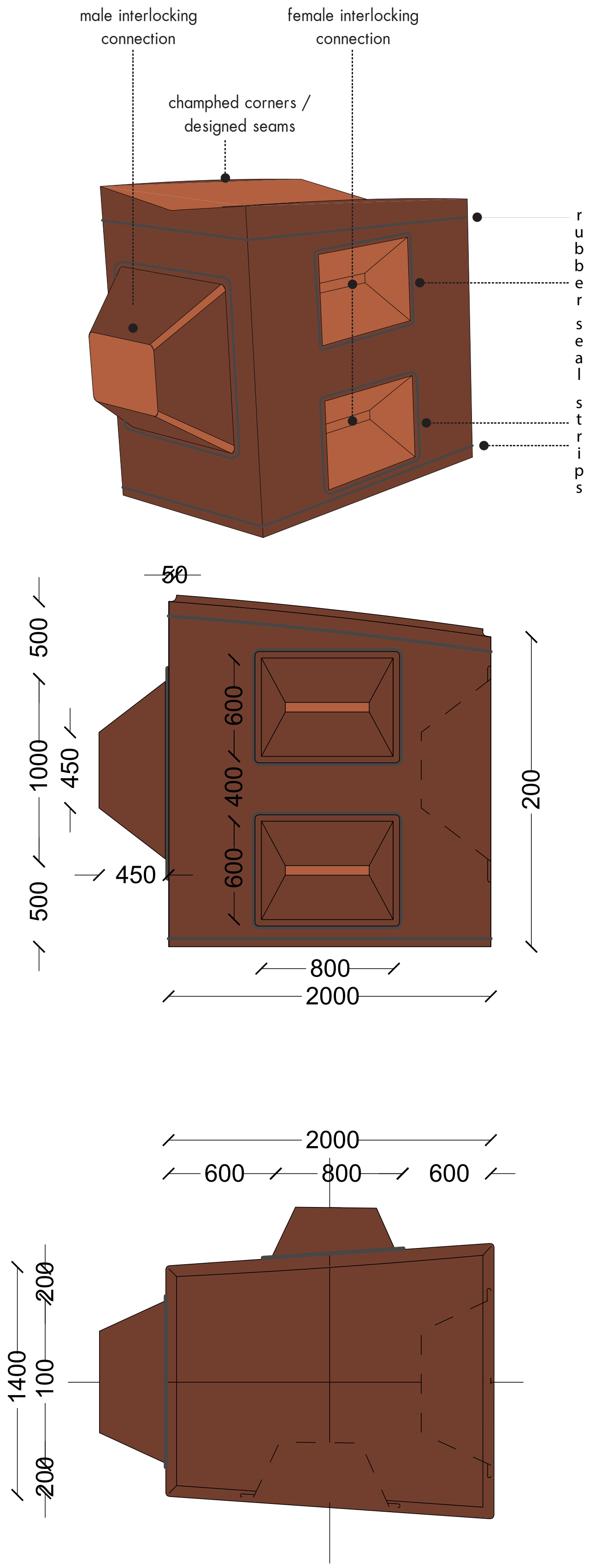
G.1.8

G.1.7 Experimentation with working model in order to determine the module connections
G.1.8 Heigh difference of width modules and proposed solution
G.1.9 Module principal connections and airtightness architecture

it is known interlocking connections provide sufficient shear resistance due to geometry. Such a connection would leave its seam on the final product. In order to secure linear seam and shear resistance a combination of straight face and interlocking connection is proposed.

Moreover, as can be seen from Figure G.1.8 due to the height difference of the width modules, when combining modules in order to create the narrow width a height difference is being created. In order to prevent such heigh difference, the connections on the female mould is placed on the same height measuring from the upper face. In such a way when sliding the different modules to the central one they slowly rise. On the other hand, this heigh difference is being transferred from the upper face to the lower face, where the surface is straight so if necessary for extra stability an extra plate can fill in the gap.

Finally, the male mould consists of an FRP sheet that substitutes the injection bag in simple resin injection manufacturing process. During Light RTM this piece of the manufacturing mould set is responsible for the airtight connection with the female mould via the flange connection and also for the airtight injection of the resin on the fibres. During the process, the female mould is rigid and is subjected to thermal and pressure loads of injections and resin curing while the male mould part should be slightly flexible in order to shape the FRP, but at the same time to take over the small deformations that occur from the stresses inside the manufacturing process. For that reason, the connection of the male mould modules has to be airtight but not rigid. Thus, a flange is introduced around the sheet modules and bolds are used to connect them. Also, extra rubber is used that allows for the pieces to slightly deform, but not for air to penetrate the process. Also the rubber piece is surrounded by FRP in order to protect it from melting due to direct contact with the thermosetting resin. On the intersection of 4 modules extra cross-shaped flanges are used



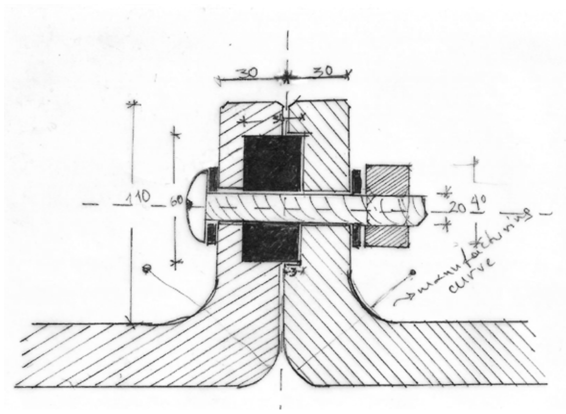
G.1.9

in order to connect the pieces from the correct directions. Finally,all of these connections will leave a seam on the final product that most of them will be covered from the non-slippery flooring on the deck.

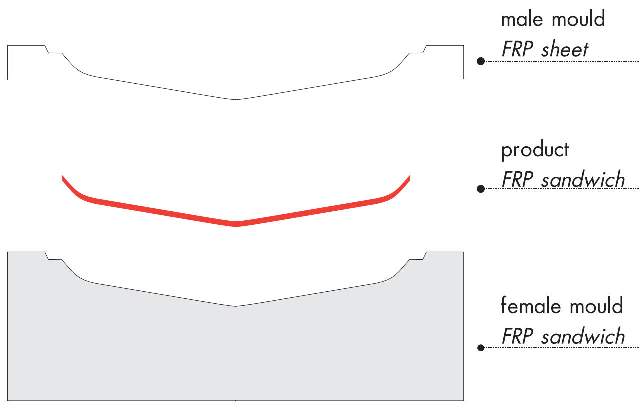
G.2 Mould design

The division and the connection of the modules of both the female and male mould have been explained. On this chapter the general mould design will be explained. More specifically as can be seen on the next page apart from the male and female mould also a side flange is needed to ensure the successful vacuum connection of the two moulds. Also, according to literature, for shapes as in this project it is more efficient to inject the resin via a central feed gate and from there to lead them outwards. In the same illustration this arrangement can also be found.

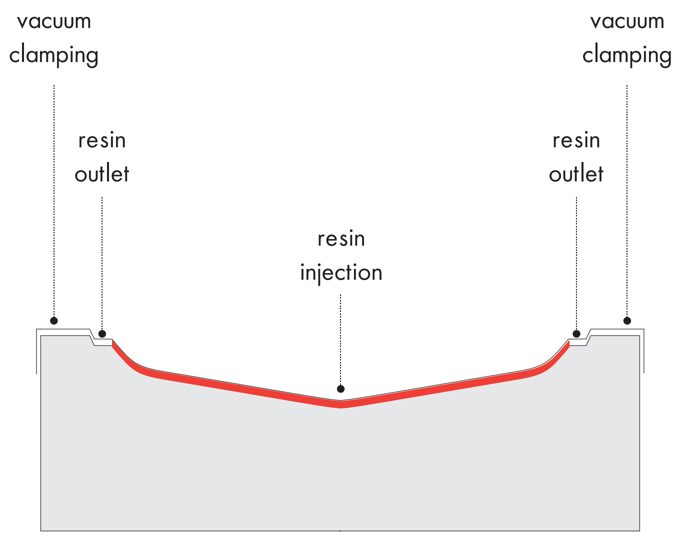
G.2.1 Proposed connection for the male mould
G.2.2 Illustration of light RTM production mould requirements
G.2.3 Illustration of light RTM resin injection requirements



G.2.1



G.2.2



G.2.3

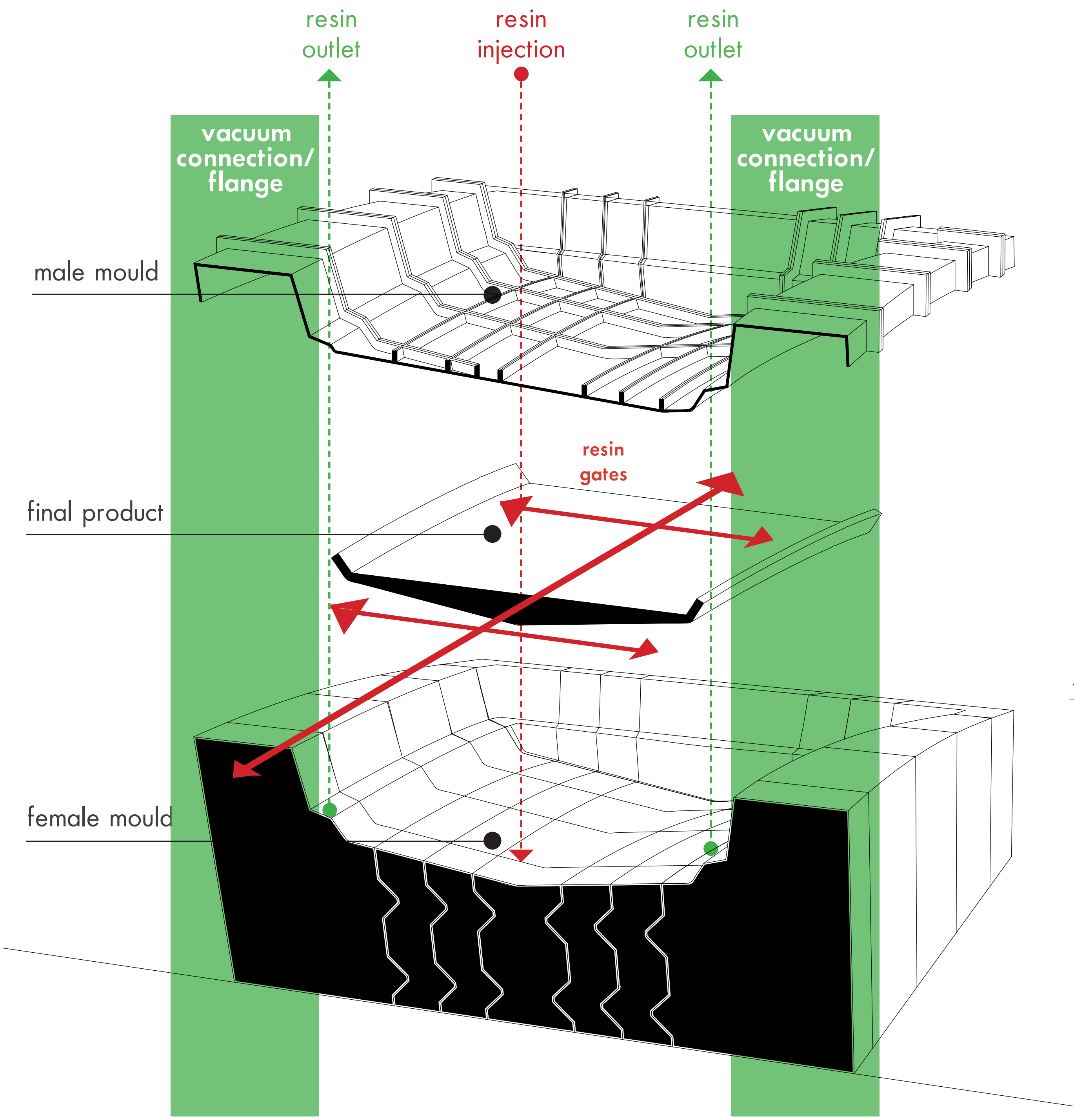


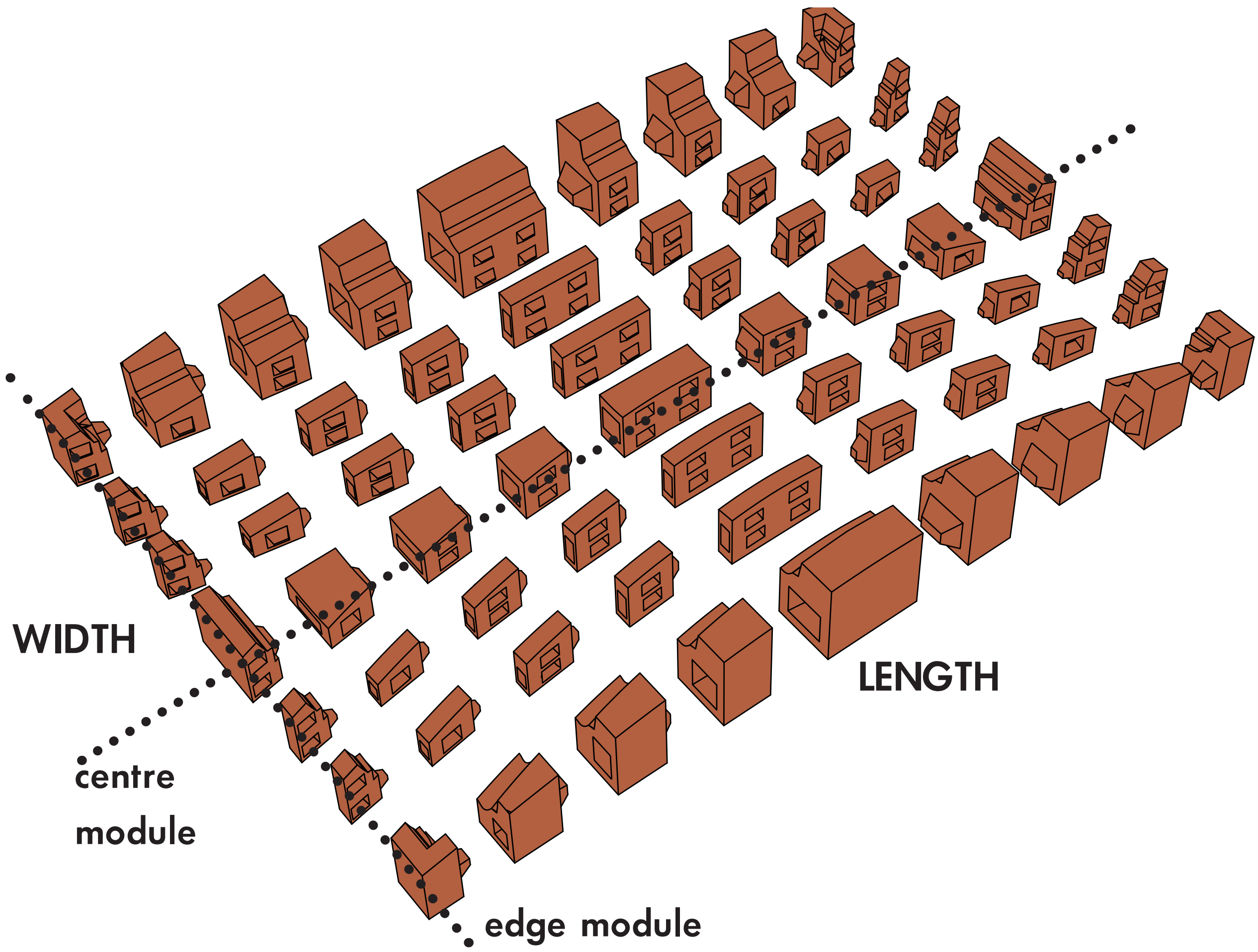
Illustration of Light RTM manufacturing technical requirements (flange, resin gates, resin injection and outlets, clamping areas and vacuum options)

G.3 Manufacturing process

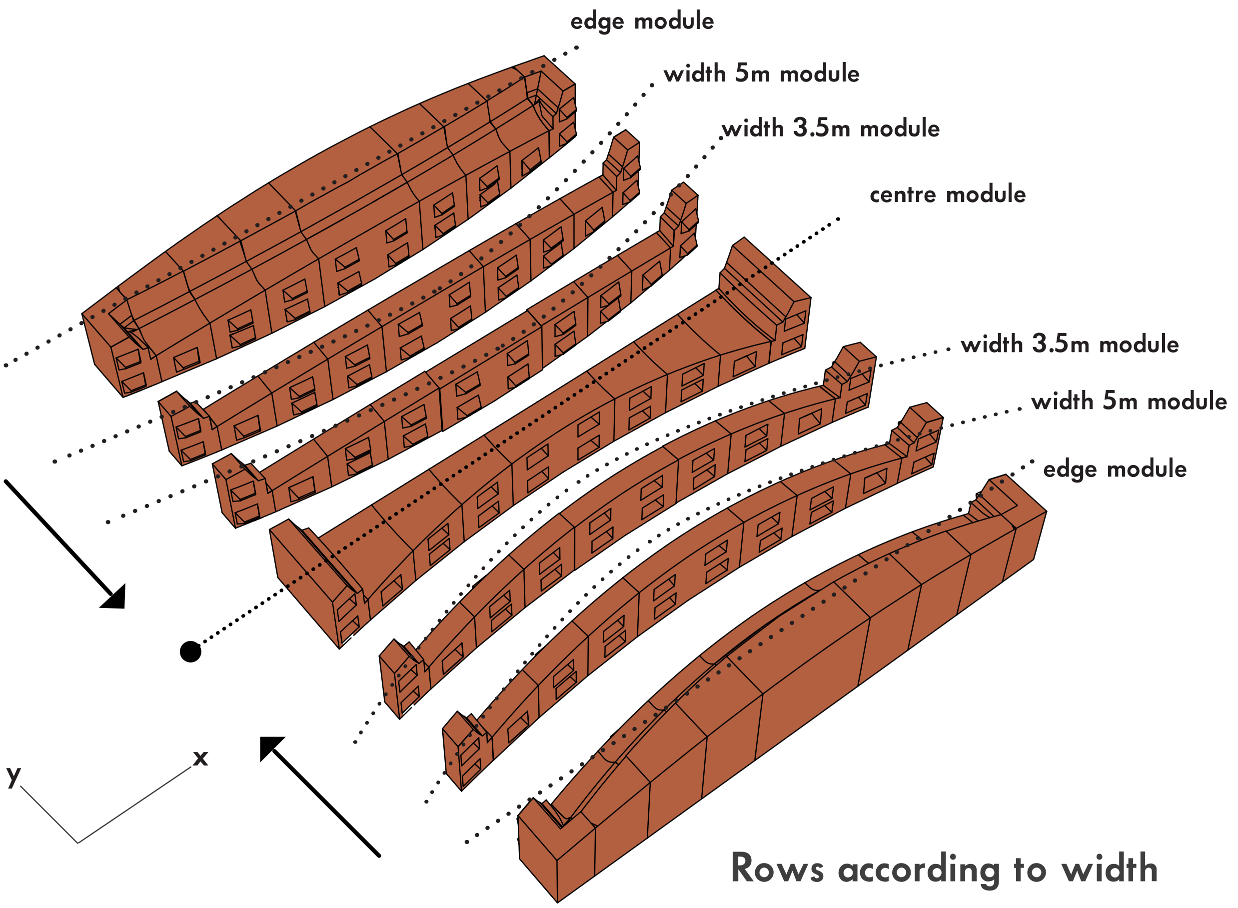
G.3.1 Mould assembly

In order to start the manufacturing process the suitable pieces will be gathered in terms of width and length. After that the right modules of length are combined together in order to create rows and later these rows are slide towards the central raw and interlock with each other providing a rigid female mould.

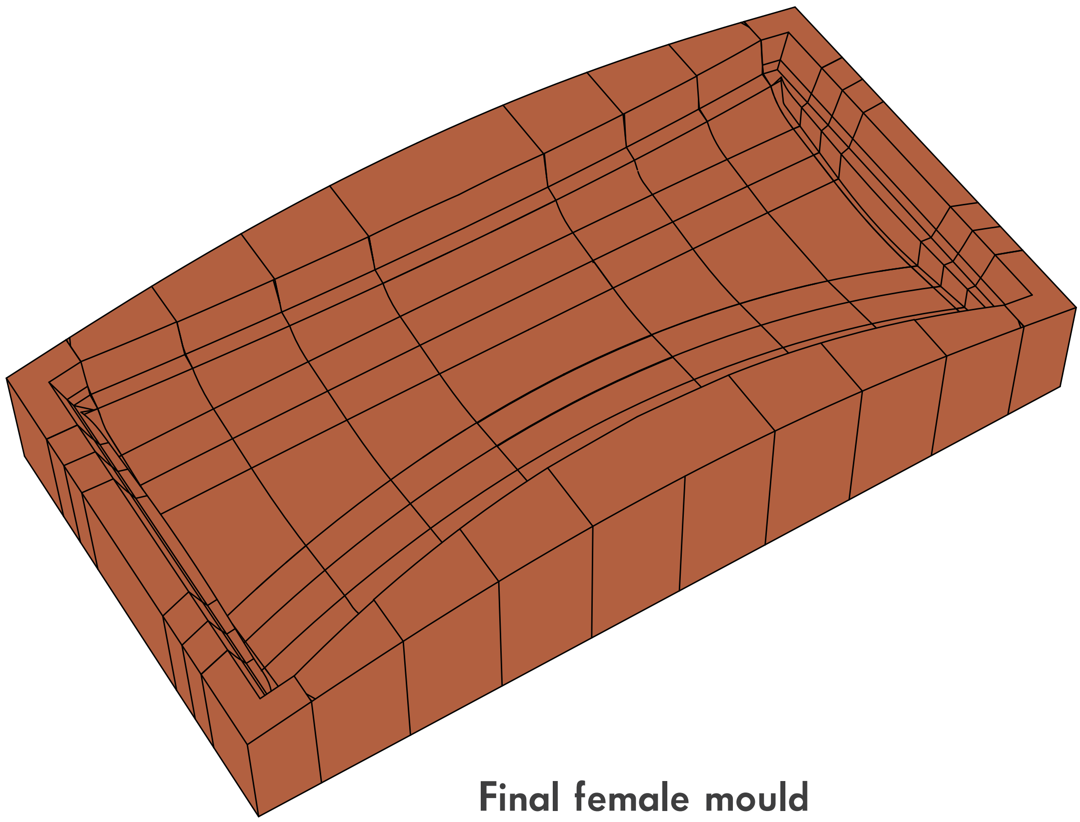
The modules of the male mould also have to follow the same process in order for the mould to be created.



Arrangement of modules



Rows according to width



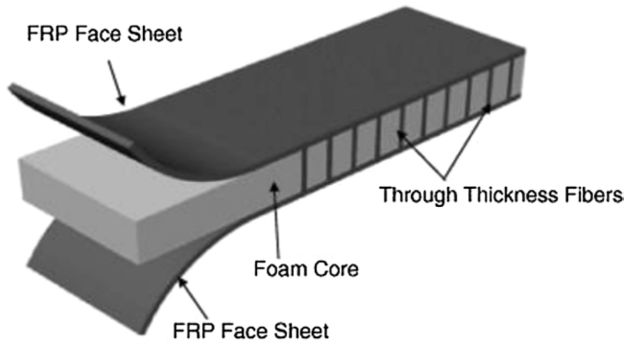
Final female mould

G.3.2 Raw material placement

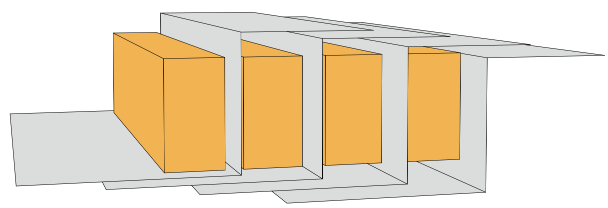
After creating the moulds, the raw material for the structure will be placed on the female. Then the male mould will be added and the resin injection may start.

Concerning the raw materials arrangement order, first comes the coating that will also determine the final colour of the product. Then the foam and the fibres are placed using the technique as shown in FigureG.3.2 where the fibres are "woven" between the foam pieces. By this method a strong web is produced between the two plies and also the suitable ply thickness. Additionally, the core consists of PVC sheets shaped by CNC milling. Every piece is shaped on the cross- section shape.

After the placement of the fibres along with the foam the inner coating follows and finally the railing connections. After that, the male mould encloses all the materials together and the injection begins in order for the final product to be produced.

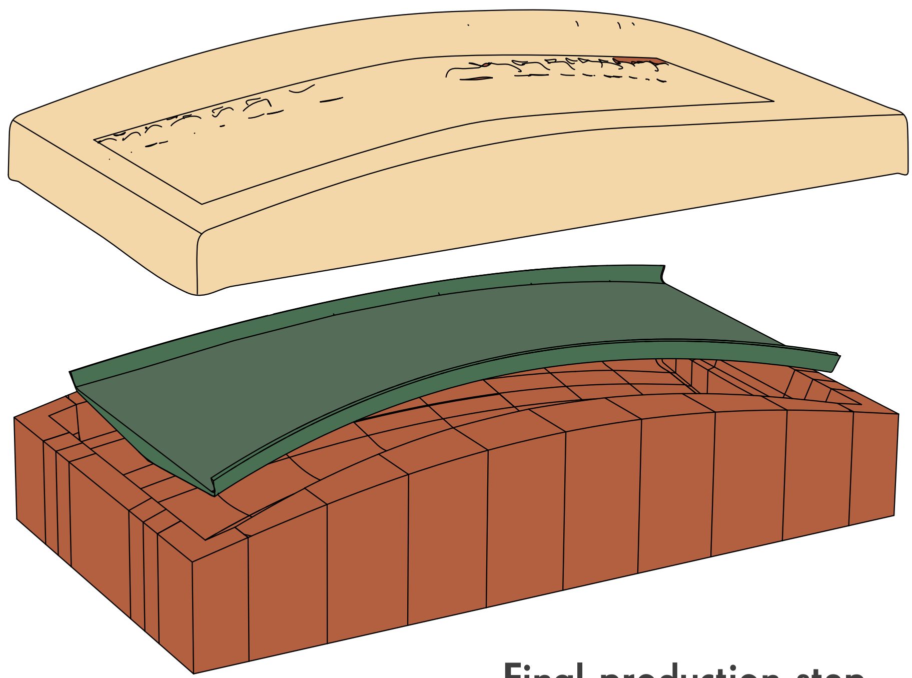


G.3.1

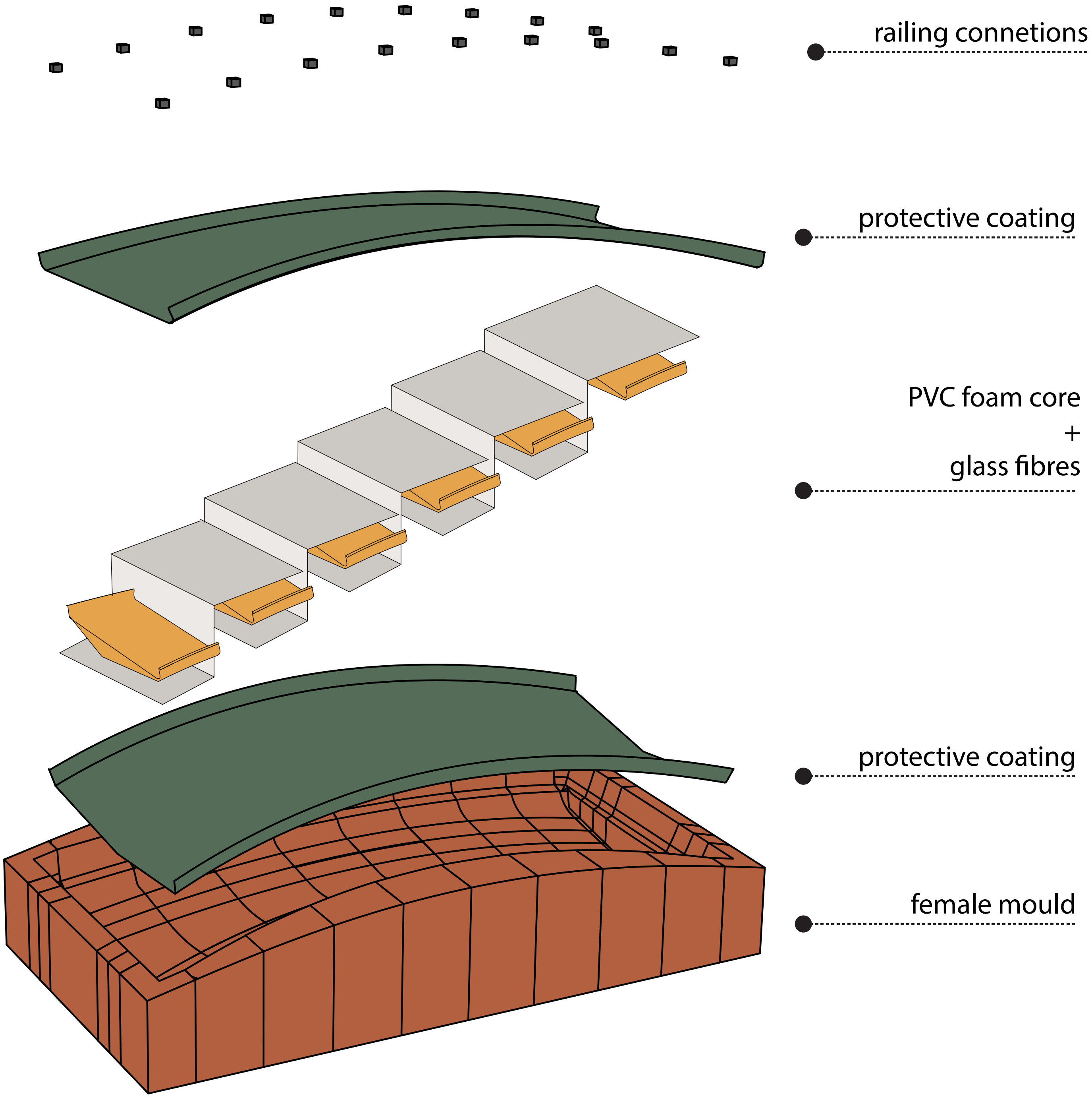


G.3.2

G.3.1 Structural architecture of sandwich FRP
G.3.2 Illustration of structural web creation



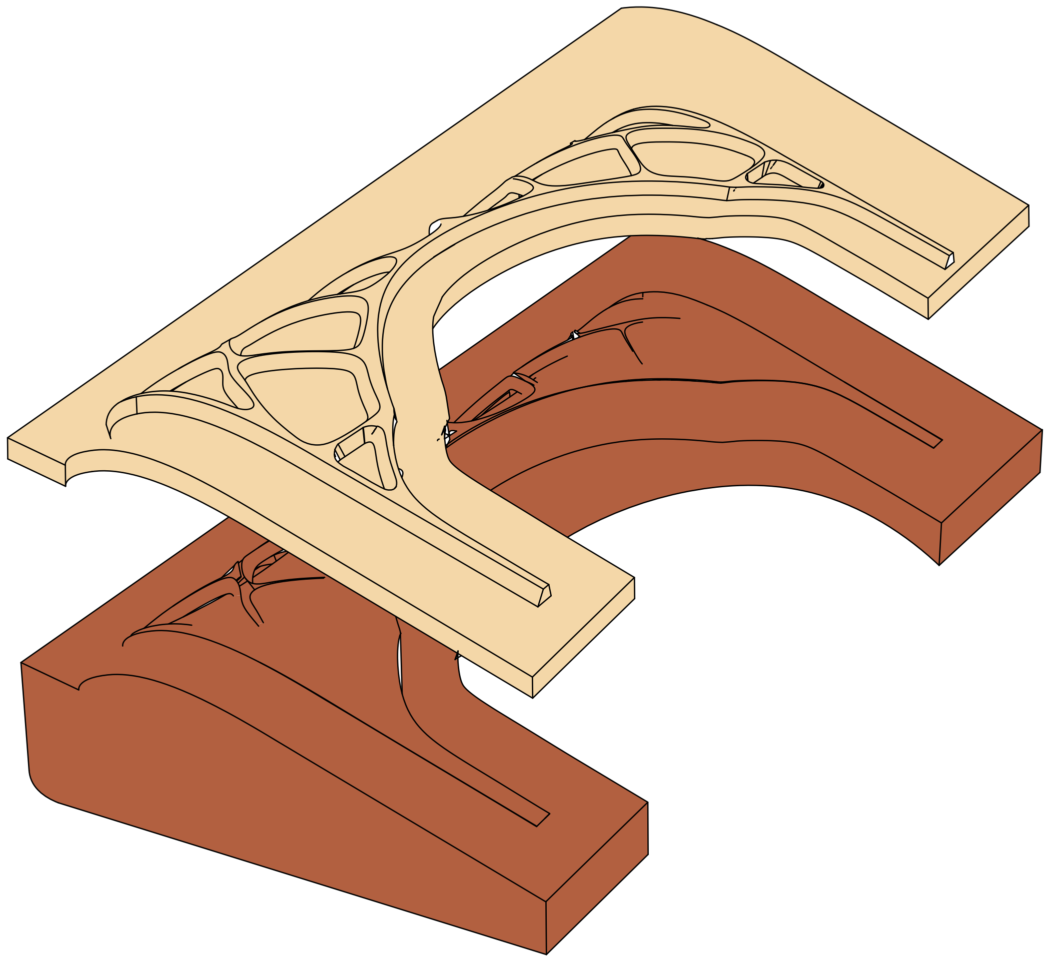
Final production step



Material arrangement for Light RTM production

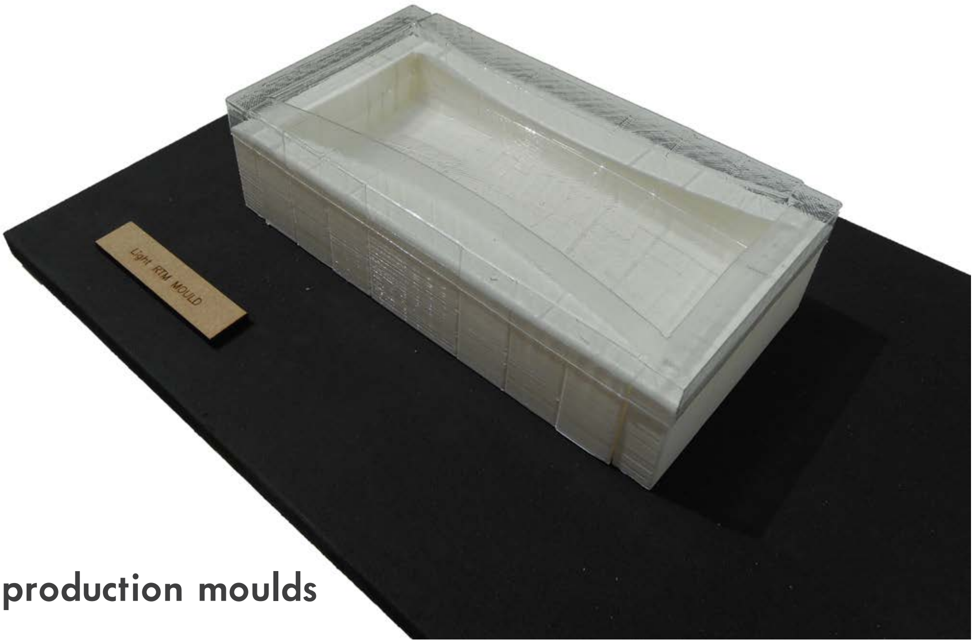
G.3.2 Railing moulding

Similar technique for the railing manufacturing is being used as for the main structure. Again two moulds will be used. This time only fibres and resin is being used. In order for the injection to take place, first the coating is placed, then the fibres and then again the coating and the railing connections. After the placement of all the materials, the upper mould encloses the materials and the injection starts.

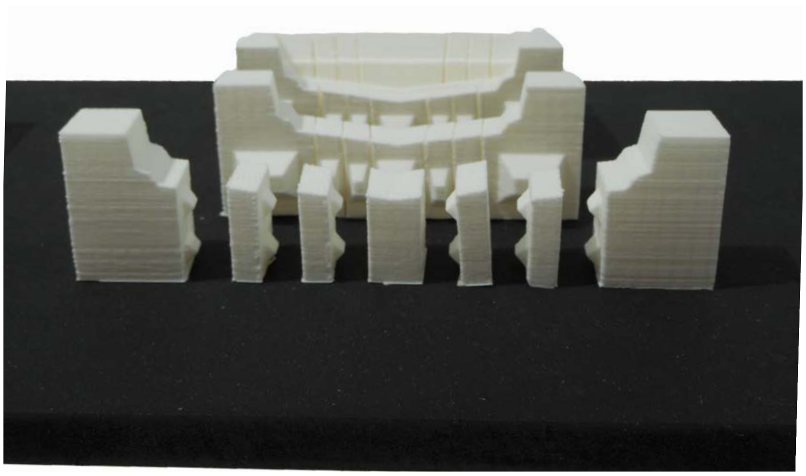


Railing manufacturing

G.4 Physical models



Light RTM production moulds



Light RTM modular moulds

Bridge series transportation and installation

H.1 Bridge series transportation and installation sequence

In this chapter, a proposal of the series transportation and installation on the area will take place. In reality, such programming requires the assistance of an expert in such matters. Nontheless the Architect should have an awareness on the difficulties and demands of installation sequence and transportation on site, in order to provide a viable design of the components of the structure and the connections. For this project, the general principles will be presented, since there was no time to check for the particularities of every installation area.

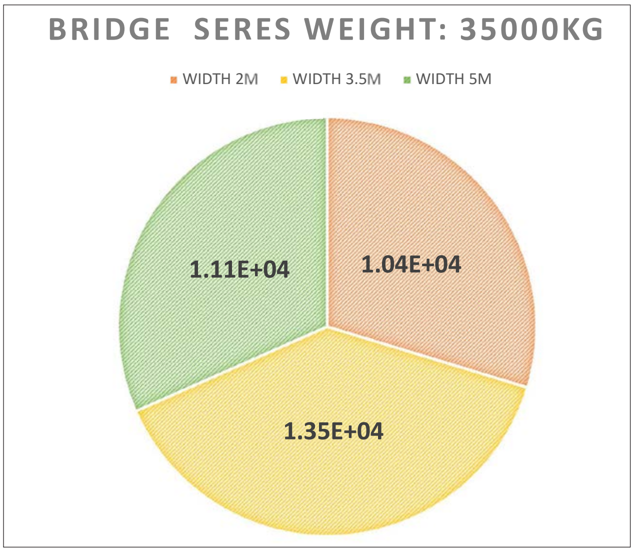
Foremost, the amount of transportation trucks had to be calculated according to Dutch legislations for transporting goods. There, the permissible maximum height is 4m and the minimum permissible weight is 10t. Also for the transportation Flat-bed articulated trucks will be used in order to reach the permissible length of 16.50m that satisfy the needs of the longer bridges of 16m.[W.11]

According to these specifications the bridges will be places facing upward as set of 4 items in order to use the entire 4m permissible height. Also, in order to use less trucks the bridges of 4m and 8m length will be combined in order to create bridges of 12m length. Through that process the initial bridge number of 63 bridges downsizes now per 9 bridges giving. Along with the structures, also their railings are being loaded following their curvature in order to save even more space.

Lastly the weight of the final load had to be estimated and comply with the limit of 10t. For that calculation the worst scenario was taken into account, where all 4 bridges of the truck would consist of the longest and widest bridge of the series (16m length and 5-7m width). The weight of such load would be less than 5t,

BRIDGE SERIES				
	WIDTH 2M	WIDTH 3.5M	WIDTH 5M	
	ITEMS	ITEMS	ITEMS	SUM
LENGTH 4M	7	2	0	9
LENGTH 8M	7	2	0	9
LENGTH 12M	14	14	2	30
LENGTH 16M	3	4	8	15
SUM	31	22	10	63

H.1.1



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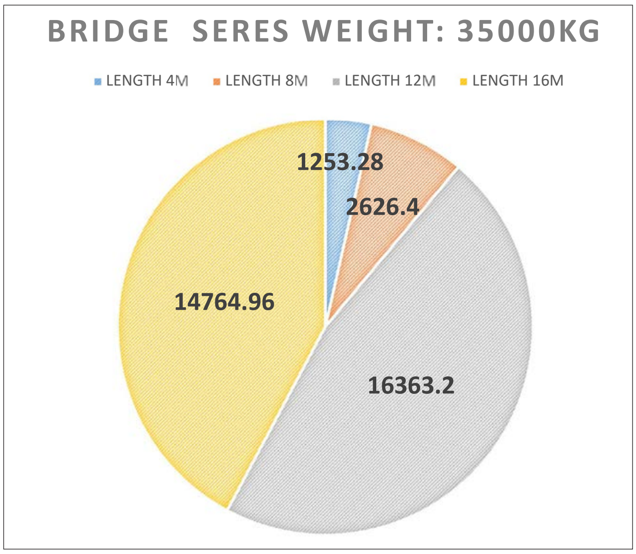


H.1.3

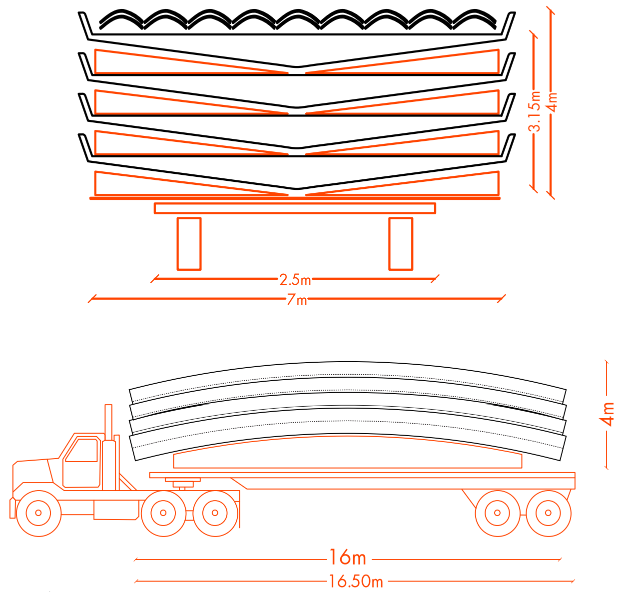
H.1.1 Analytic population of bridge series
H.1.2 Pie chart of bridge series weight according width categories
H.1.3 Pie chart of bridge series weight according length categories
H.1.4 Illustration of bridge series transportation
H.1.5 Illustration of bridge series installation
H.1.6 Map of possible transportation routes to Tanthof Delft

which is only half of the permissible weight. Concluding the entire 63 bridges could fit on 14 trucks (54 [63bridges - 9 combined] / 4 items)

After loading the bridges on the flat-bed trucks the bridges will be transported to Tanthof via the road system. As has already been mentioned, Tanthof Delft is surrounded by main streets and highways, hence it is easy to reach the area via the use of the existing road system.

After reaching the area via the neighbourhood streets the flat-bed trucks can reach the exact location of the bridge installation. In case of inconvenient installation plots the bridges can always be transported in an alternative way by smaller vehicle on the site. Since the bridges are relatively small and the structures lightweight such alternative is possible.

After reaching the installation area the bridges will be placed in place by the assistance of crane trucks. After that, the bridge will be bolted on the foundations. Lastly, through the aid of a lift crane the railing will be lifted and positioned correctly in order to manually be connected on the bridge structure.



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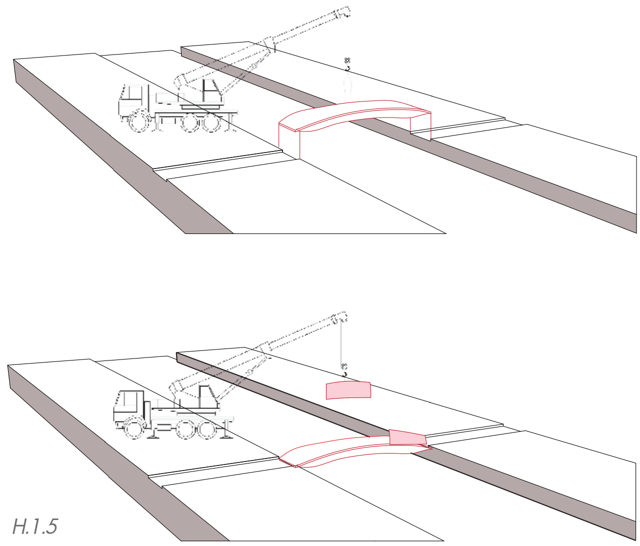

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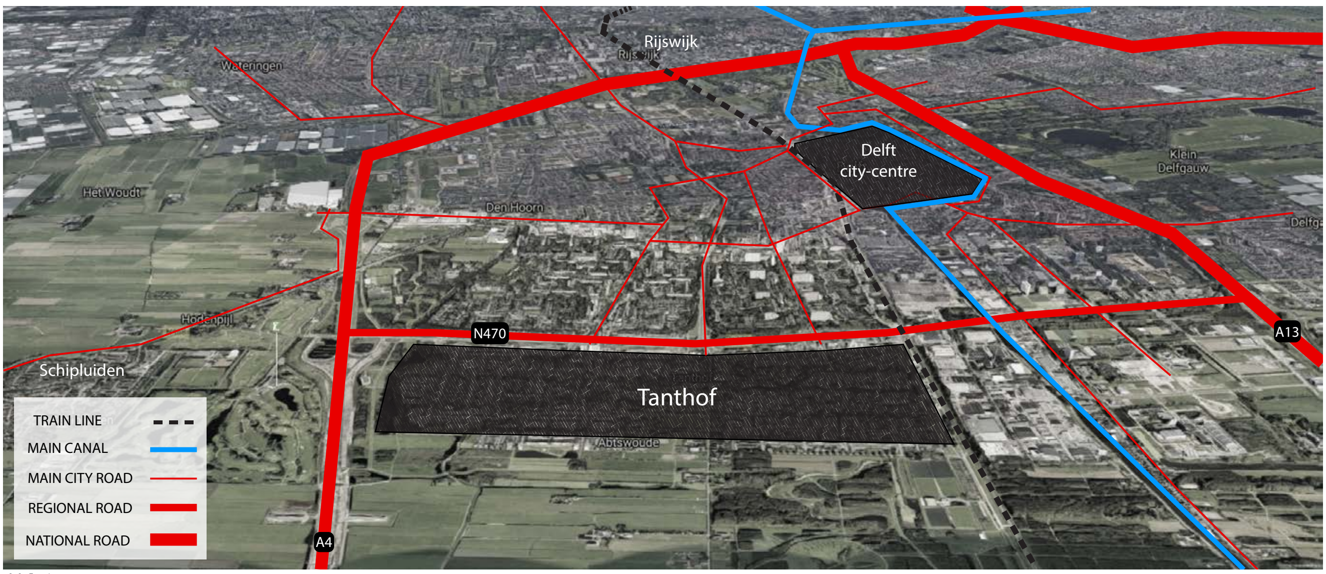
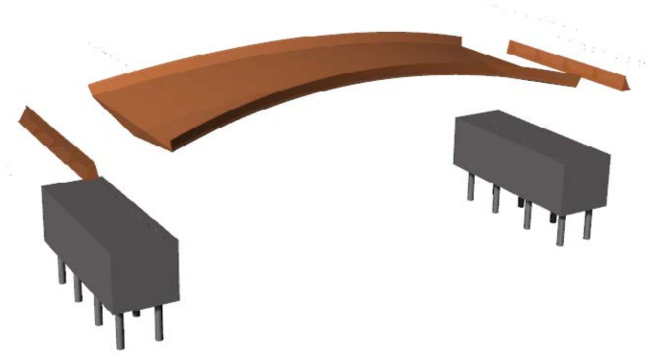


H.1.6

H.1.1 Bridge installation



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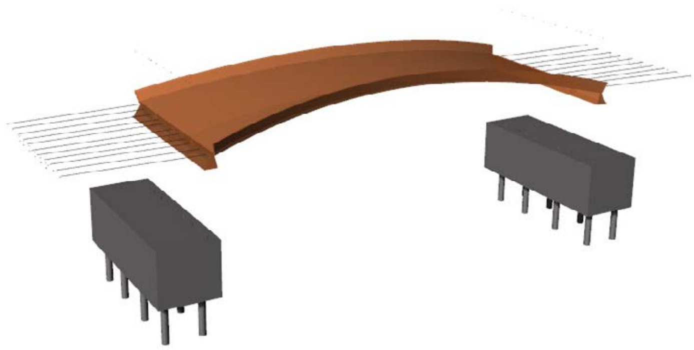

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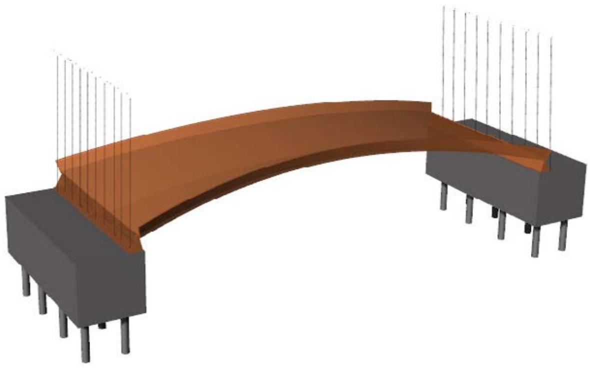

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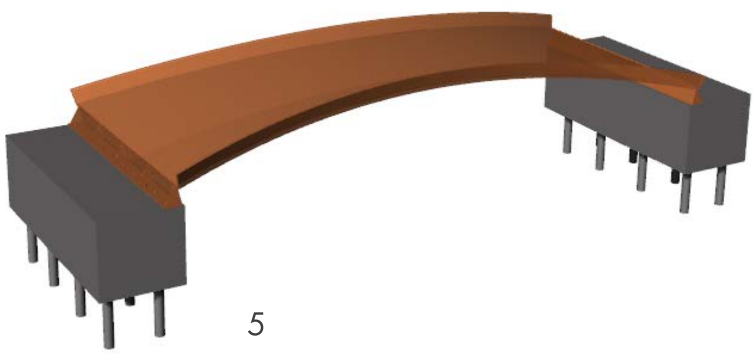

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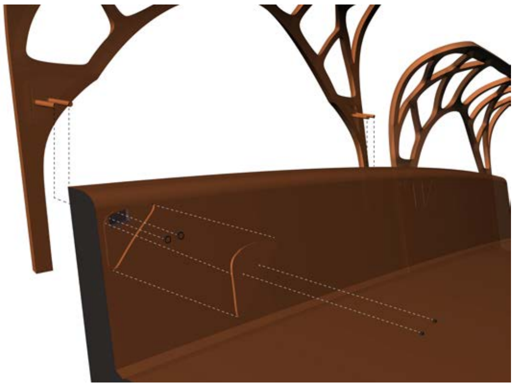
H.1.2 Railing installation



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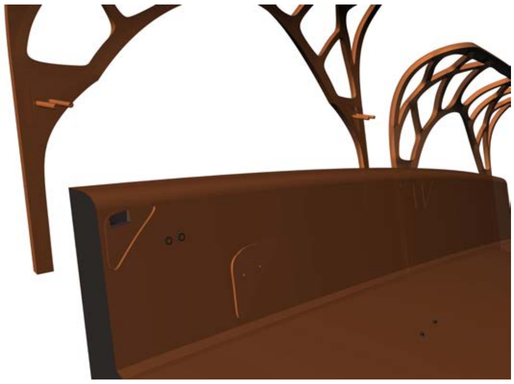

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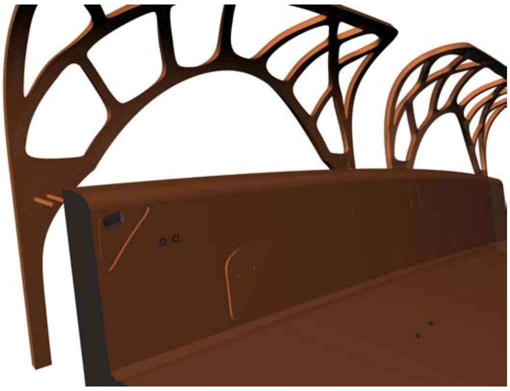

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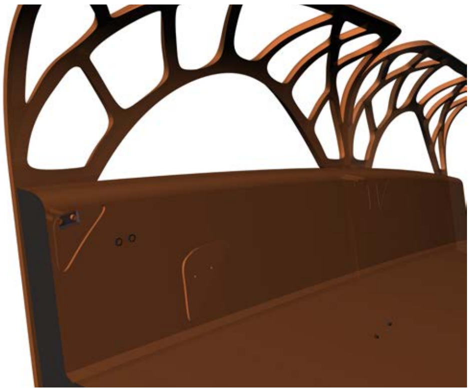

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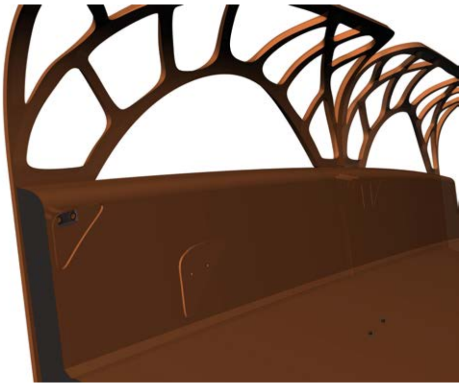

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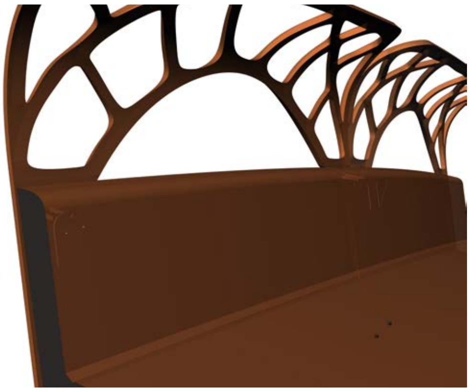

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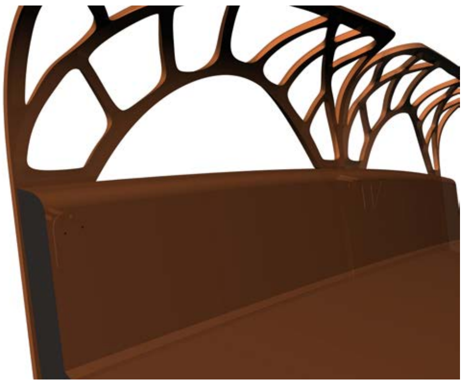


6

Sustainability aspects

I.1 LCA

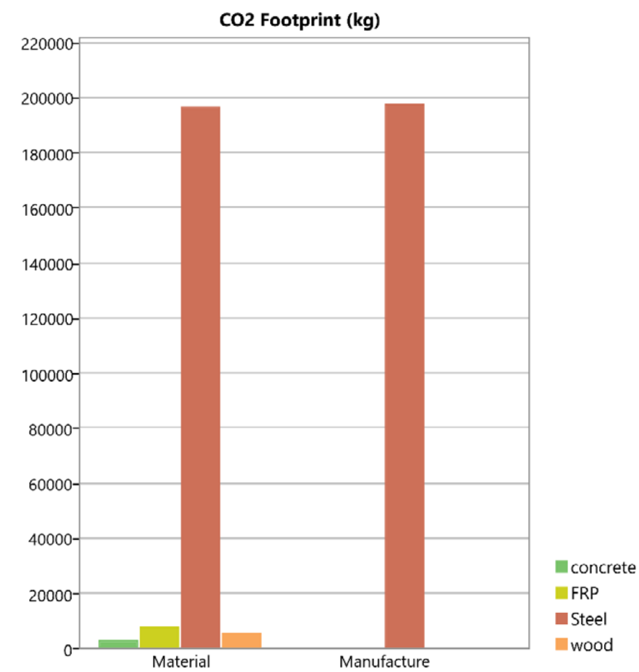
Fibre-reinforced polymer as already mentioned in previous chapters is a material of great strength and durability, but at the same time cannot be recycled and its manufacturing costs are high. Nontheless, its high ratio of strength to weight, especially on the case of sandwich FRP is a strong sustainable asset. Apart from that, also FRP performs better than other structural bridge materials when comparing their manufacturing methods. On this chapter this aspect will be illustrated comparing FRP with other usual bridge materials, as steel, concrete and wood. From this purpose, the existing design of the bridge series will be used.

I.1.1 Comparison of FRP and other materials

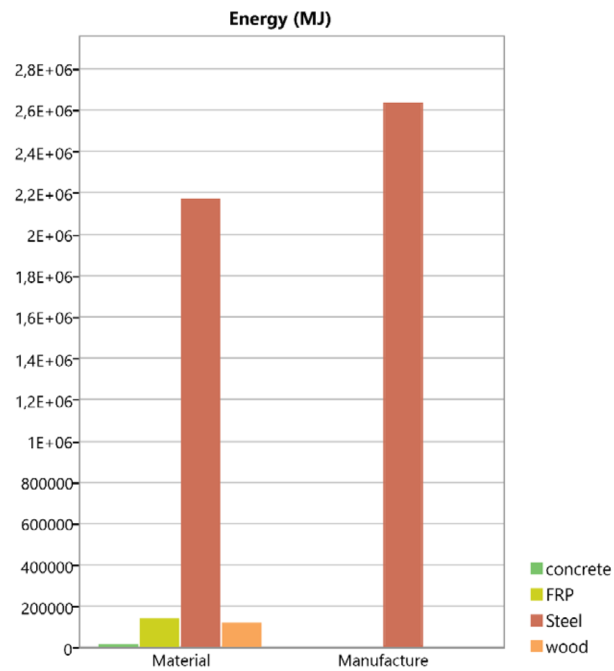
In order to compare this material with alternative ones, specific structural materials where selected form CES. More specifically the materials to be compared are wood, steel and concrete. For this comparison the following materials were used:

- Wood: Density: 955 kg/m^3, Price: 2.13 EUR/kg, Young modulus: 16.8GPa, Shear modulus: 1.24GPa, Yield strength: 50.2MPa
- Steel: Density: 7850 kg/m^3, Price: 0.536 EUR/kg, Young modulus: 210GPa, Shear modulus: 80.5GPa, Yield strength: 50.2MPa
- Concrete: Density: 2390 kg/m^3, Price: 0.045 EUR/kg, Young modulus: 25.2GPa, Shear modulus: 11GPa, Yield strength: 2.16MPa
- Sandwich FRP: Density: 112 kg/m^3, Price: 23.5 EUR/kg, Young modulus: 5.431GPa, Shear modulus: 2.38GPa, Yield strength: 574MPa

As can be seen from Figures I.1.1 and I.1.2 steel and its manufacturing needs the most energy and CO2 footprint. The rest of the materials show much better performance. In the case of the concrete it is considered that steel will be used as reinforcement, thus its performance will aggravate. Hence, FRP might not be able to be recycled, but its good energy and CO2 performance is definitely a strong sustainability asset.



I.1.1



I.1.2

I.2 Recycling
I.1.2 Reuse of components

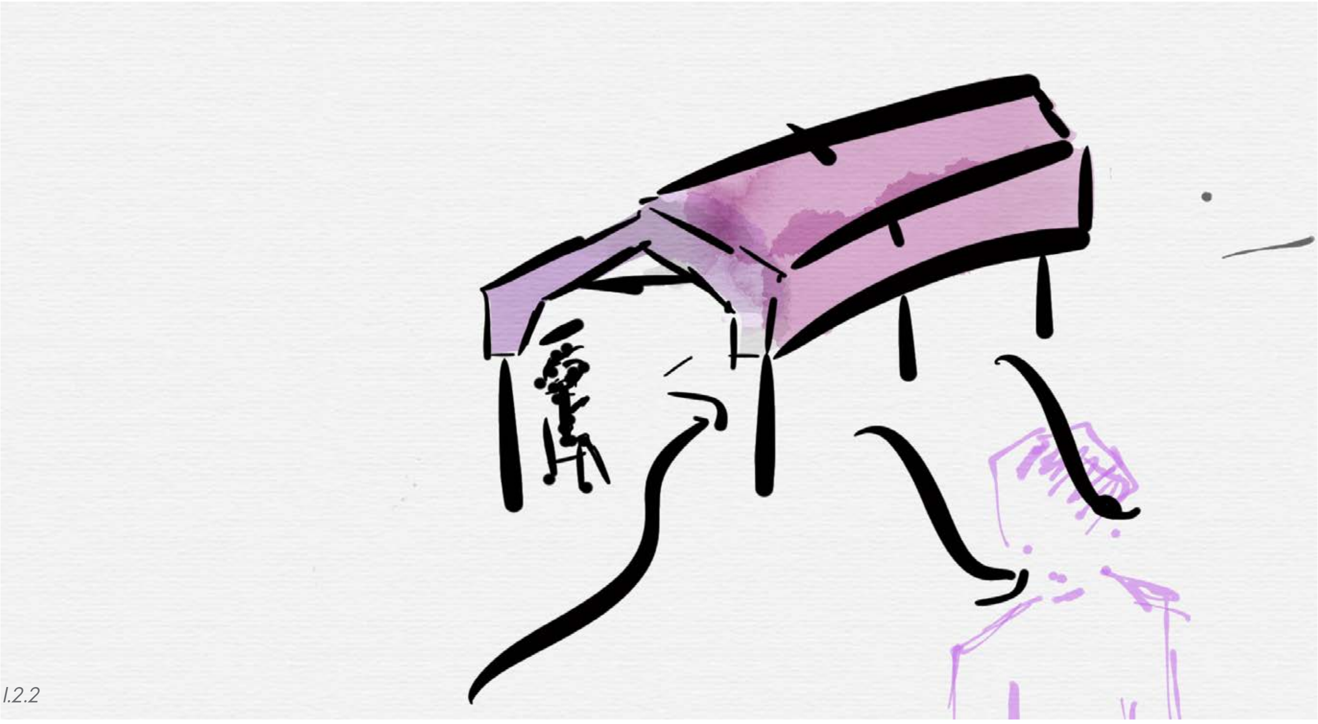
The principle of modularity on the design or on the manufacturing is based on the idea of reusing component. An indicator of such reuse was been already mentioned on the modular design mould. There, the same components are been used in order to produce the bridge series and future designs by replacing the facade member. Also, since the railing component is replaceable, it could be used in different structures, or the same bridge structure could be renovated only by changing the railing. As can be seen, the modular principle of this project enriches the complicity of the project by simple design principles and busts the sustainable value of the project.

Moreover, in case of replacement of the bridges, an alternative solution of reuse is proposed for the bridge structure. Due to the shape and the material the most appropriate re-use of the structure is as roofs. The sandwich FRP bridges are lightweight and water proof ideal to be used as a shelter-roof in the public domain, for example in squares and bus stops.

An extra filter could be applied in order to withstand the direct sunlight in case it is estimated that is needed.

Finally, the existing connections for the railing can be used in order to connect the roof with the columns. Since the roof is lightweight there will not be demanding loads so no extensive material is needed for the columns.

I.1.1 Comparative chart from CES of C02 Footprint levels for different bridge materials
I.1.2 Comparative chart from CES of energy consumption during production for different bridge materials
I.22 Sketch idea of reusing the project as a roof



I.2.2

Conclusions and Recommendations

J.1 Conclusions and recommendations

Stimulus for this project was the extensive need of the Netherlands for public bridge infrastructures, especially on municipality level. Additionally, since FRP is not so broadly being used as structural material there is still room for experimentation concerning its architectural appearance combining structural properties. Hence the aesthetic and structural potentials of FRP were included in the research in order to design the bridge series and its manufacturing method. Finally, in order to cover the different dimensions of bridges needed in real life conditions the manufacturing would be modular. In this way the bridge infrastructures would be manufactured more efficiently via the use of a definite number of modules by re-using them. In addition, a case study was proposed, in order to target the research to existing needs of bridge dimensions. Through this project it was proven that when combining different research topics their individual full potentials can not be explored.

More specifically, the intention of double curved/free-form **bridge design** was restricted and the final design is double curved but does not provide with a fluid appearance that can be found in roof and column designs made out of FRP. The need for modularity (repeatability in different dimensions) and the small dimensions of the bridges of the bridge series did not allow for brave design shapes. Free-form design would be more appropriate in large structures or individual structural elements as columns and roofs.

Moreover, the **moulding manufacturing** allows for curved design and also is an easily applicable manufacturing technique that does not require heavy machinery. Hence moulding based solution can be used broadly even in countries with lower technological level than the Netherlands. Also, it can be used in case of emergency where many bridges need to be produced in big batches in a short time. Moreover, the different modules allow for manufacturing of many different sets with the use of the same pieces. Due to the variation of the length and the width the mould finally consists of numerous pieces and might complicate the assembly process. The use of non modular male moulds could simplify the assembly process by reducing the module's population in half. Also, on the proposed closed mould manufacturing technique the use of bio-based FRP is excluded due to the high temperatures that occur during curing. An alternative open moulding technique would allow the use of such FRP and would endorse the sustainability aspect of the product.

Furthermore, for this project the properties of **modularity** were limited to the design of the manufacturing mould, but its potentials are much greater. Particular interest shows the modular design principles when it comes to connection design for large structures, as bridges and roofs or structures with different components, like the same bridge with different railing, modularity could provide the knowledge of industrial design in structural design.

Concluding, despite the aforementioned contradictions of the different research topics, their combination successfully provided an all FRP bridge series design and its respective modular manufacture moulds. Also, valid indicators about the appearance of FRP bridge design were provided to future designers/ researchers.

To end up, initially it was assumed that the moulding manufacturing technique would set strong boundary conditions which would define the design. After investigating deeply into the technology of this technique this assumption was proven wrong and on the contrary moulding manufacturing technique is flexible and can provide big freedom to the designer. On the other hand, the general appearance of the design is defined by the use this technique Also, this project consists only of a preliminary design phase and still small alterations may be needed. For example, in the case of realization of such project, the structural properties of the proposed sandwich FRP material structure, the railing and the connections should be tested in a laboratory environment.

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Appendix

Appendix 1- Material comparison tables

RESIN COMPARISON											
	Unsaturated polyester resin (UP)	Epoxy resin (EP)				Vinyl ester resin (VE)					Phenol formaldehyde resin (PH)
	rigit cast	high heat	cycloaliphatic	flexibilised	unfilled	flame retarded	flexible	novolac	novolac, flame retarded	standard	casting resin
GENERAL INFO											
Density (kg/m^3)	1210	1210	1180	1140	1250	1170	1060	1110	1160	1040	1280
Price (EUR/kg)	3,77	2,36	2,36	2,36	2,36	6,4	5,91	5,91	6,4	5,91	1,61
*PRICE*DENSITY*	4561,7	2855,6	2784,8	2690,4	2950	7488	6264,6	6560,1	7424	6146,4	2060,8
Transparency	Transparent	Transparent	Opaque	Transparent	Transparent	Transparent	Transparent	Translucent	Translucent	Translucent	Opaque
MECHANICAL PROPERTIES											
Young's modulus (GPa)	3,02	2,64	3	1	2,41	3,44	3,14	3,54	3,6	3,44	3,65
Tensile strength (MPa)	60,9	60	67,7	52,5	63,5	85,3	77,5	85,3	86,7	83,9	46,3
Compressive modulus (GPa)	3,02	2,64	3,4	2,41	2,41	3,44	3,14	3,54	3,6	3,44	3,65
Compressive strength (MPa)	170	120	119	69,5	133	94,6	85,2	94,6	95,6	92,8	92,3
Shear modulus (GPa)	1,09	1	1,08	0,352	0,861	1,27	1,16	1,3	1,33	1,3	1,32
MECHANICAL PROPERTIES	48,21	188,92	197,58	128,172	204,591	191,49	173,28	191,82	194,43	188,32	150,87
THERMAL PROPERTIES											
Maximum service temperature (°C)	120	170	140	130	130	160	153	200	160	180	149
Minimum service temperature (°C)	-18	-18	-18	-18	-18	-18	-18	-18	-18	-18	-18
Thermal expansion coefficient (µstrain/°C)	133	72,2	103	80,5	97,3	55,3	55,3	62,5	62,5	55,3	122
DURABILITY											
Water absorption at 24hrs (%)	0,3	0,212	0,141	0,27	0,11	0,391	0,391	0,391	0,391	0,391	0,19
Water (fresh/salt) resitance	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Alkalis resistance	Unacceptable	Limited use	Acceptable	Acceptable	Acceptable	Excellent	Excellent	Excellent	Excellent	Excellent	Unacceptable
Acids resistance	Acceptable	Acceptable	Limited use	Limited use	Limited use	Excellent	Excellent	Excellent	Excellent	Excellent	Acceptable
UV radiation	Good	Fair	Good	Fair	Fair	Fair	Fair	Fair	Fair	Fair	Good
Flammability	High flammable	Self-extinguishing	Self-extinguishing	Self-extinguishing	Slow burning	Self-extinguishing	High flammable	High flammable	Self-extinguishing	High flammable	Self-extinguishing
RESISTANCE	1	2	3	2	2	5	4	4	5	4	3
RECYCLING											
Recycle	no	no	no	no	no	no	no	no	no	no	no
Downcycle	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
PERFORMANCE											
PRICE*DENSITY	2	4	4	4	4	0	1	0	0	1	4
MECHANICAL PROPERTIES	0	4	4	2	4	4	3	4	4	4	3
THERMAL PROPERTIES	0	3	1	1,5	2	3	3	4	3	3,5	1
DURABILITY	0,5	2	3	1,5	2,5	2	1,5	1,5	2	1,5	2,5
PERFORMANCE	0,625	3,25	3	2,25	3,125	2,25	2,125	2,375	2,25	2,5	2,625
GENERAL PERFORMANCE	0	4	4	3	4	3	3	3	3	3	4

CORE COMPARISON												
	Polystyrene foam (EPS,XPS)			Polyurethane foam (PUR)			Polyvinyl cloride foam (PVC)			Polymethacrylimide foam (PMI)		
specific gravity	0,02	0,025	0,05	0,062	0,24	0,6	0,04	0,16	0,4	0,051	0,11	0,2
GENERAL INFO												
Density (kg/m^3)	19,9	24,9	49,9	61,6	240	599	39,8	160	400	50,5	111	200
Price (EUR/kg)	2,67	2,67	2,67	9,59	9,59	9,59	14,7	14,7	14,7	76,5	53,2	42,7
*PRICE*DENSITY*	53,133	66,483	133,233	590,744	2301,6	5744,41	585,06	2352	5880	3863,25	5905,2	8540
Transparency	Opaque	Opaque	Opaque	Opaque	Opaque	Opaque	Opaque	Opaque	Opaque	Opaque	Opaque	Opaque
MECHANICAL PROPERTIES												
Shear modulus (GPa)	0,00245	0,00346	0,00894	0,00429	0,0387	0,167	0,0126	0,0659	0,183	0,0167	0,049	0,122
Shear strength (MPa)	0,0663	0,0866	0,447	0,416	2,89	11,4	0,199	1,7	5,61	0,283	1,39	3,25
Compression strength (MPa)	0,126	0,173	0,894	0,4	2,28	11,6	0,399	3,4	11,2	0,566	2,77	7,59
Tensile strength (MPa)	0,224	0,297	1,1	0,603	2,89	14,1	0,54	4,46	11,6	1,6	3,7	6,8
MECHANICAL PROPERTIES	0,161683333	0,215553333	0,965646667	0,613096667	3,6629	16,22233333	0,449866667	3,7753	11,401	0,916233333	3,099666667	7,004
THERMAL PROPERTIES												
Maximum service temperature (°C)	84,5	84,5	84,5	155	155	155	94,5	69,5	94,5	129	154	165
Minimum service temperature (°C)	-69,3	-69,3	-69,3	-195	-195	-195	-200	-96,4	-200	-200	-200	-200
Thermal expansion coefficient (µstrain/°C)	59,2	59,2	69,3	114	114	114	21,9	35	23,9	46,9	46,9	46,9
DURABILITY												
Water (fresh/salt) resitance	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Alkalis resistance	Acceptable	Acceptable	Acceptable	Limited use	Limited use	Limited use	Excellent	Excellent	Excellent	Unacceptable	Unacceptable	Unacceptable
Acids resistance	Acceptable	Acceptable	Acceptable	Acceptable	Unacceptable	Unacceptable	Excellent	Excellent	Excellent	Acceptable	Acceptable	Acceptable
UV radiation	Fair	Fair	Fair	Fair	Fair	Fair	Good	Good	Good	Good	Good	Good
Flammability	Highly Flammable	Highly Flammable	Highly Flammable	Highly Flammable	Highly flammable	Highly flammable	Self-extinguishing	Self-extinguishing	Self-extinguishing	Highly flammable	Highly flammable	Highly flammable
DURABILITY	2	2	2	1	0	0	4	4	4	2	2	2
RECYCLING												
Recycle	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Downcycle	no	no	no	no	no	no	no	no	no	no	no	no
PERFORMANCE												
*PRICE*DENSITY*	4	4	4	4	3	1	4	3	1	2	1	0
MECHANICAL PROPERTIES	0	0	1	1	2	4	1	2	3	1	2	3
THERMAL PROPERTIES	1	1	1	2	2	2	2,5	2	2,5	3	3,5	3,5
DURABILITY	2	2	2	1	0	0	4	4	4	2	2	2
PERFORMANCE	1,75	1,75	2	2	1,75	1,75	2,875	2,75	2,625	2	2,125	2,125
GENERAL PERFORMANCE	1	1	1	1	1	1	4	4	4	1	2	2

FIBER COMPARISON	Glass			Aramid			Polyethylene		Basalt	Carbon			
	C	E	S	kevlar 29	kevlar 49	kevlar 149	spectra 900	spectra 1000	-	high modulus	hign strength	ultra high modulus	very high modulus
GENERAL INFO													
Density (kg/m^3)	2490	2570	2490	1440	1440	1470	970	970	2690	1820	1820	2100	1920
Price (EUR/kg)	4,82	2,11	23,1	28,9	108	130	101	101	2,29	42	26,6	129	65,1
*PRICE*DENSITY*	12001,8	5422,7	57519	41616	155520	191100	97970	97970	6160,1	76440	48412	270900	124992
Transparency	Transparent	Transparent	Transparent	Opaque	Opaque	Opaque	Transparent	Transparent	Opaque	Opaque	Opaque	Opaque	Opaque
MECHANICAL PROPERTIES													
Young's modulus (GPa)	68	78,2	89,4	70,4	123	180	115	143	88,4	380	235	757	554
Tensile strength (MPa)	3250	2000	4750	3230	2740	3390	2550	3090	2650	2400	4650	2350	2060
Elongation to failure (% strain)	4,75	2,7	5,25	3,32	2,32	1,14	3,97	3,19	3,2	1,9	2,1	0,548	0,748
MECHANICAL PROPERTIES	3327,5	2083,6	4849,9	3307,04	2867,64	3572,28	2672,94	3239,38	2744,8	2783,8	4889,2	3108,096	2615,496
THERMAL PROPERTIES													
Maximum service temperature (°C)	444	355	310	245	245	245	110	110	652	554	554	554	554
Minimum service temperature (°C)	-273	-273	-273	-200	-200	-200	-184	-184	-	-273	-273	-273	-273
Thermal expansion coefficient (µstrain/°C)	6,37	5	2,87	3,3	2,83	2,45	12	12	5,29	0,283	0,283	0,0316	0,245
DURABILITY													
Water (fresh/salt) resitance	Excellent	Excellent	Excellent	Acceptable	Acceptable	Acceptable	Excellent	Excellent	-	Excellent	Excellent	Excellent	Excellent
Alkalis resistance	Limited use	Acceptable	Limited use	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	-	Acceptable	Acceptable	Acceptable	Acceptable
Acids resistance	Excellent	Excellent	Excellent	Unucceptable	Unucceptable	Unucceptable	Limited use	Limited use	-	Excellent	Excellent	Excellent	Excellent
UV radiation	Excellent	Excellent	Excellent	Fair	Fair	Fair	Good	Good	-	Excellent	Excellent	Excellent	Excellent
Flammability	Non-flammable	Non-flammable	Non-flammable	Highly flammable	Highly flammable	Highly flamable	Highly flammable	Highly flammable	Non-flammable	Non-flammable	Non-flammable	Non-flammable	Non-flammable
DURABILITY	3	4	3	1	1	1	2	2	0	4	4	4	4
RECYCLING													
Recycle	no	no	no	no	no	no	no	no	no	no	no	no	no
Downcycle	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
PERFORMANCE													
*PRICE*DENSITY*	4	4	4	4	2	1	3	3	4	3	4	0	2
MECHANICAL PROPERTIES	2	0	4	2	1	2	1	2	1	1	4	1	0
THERMAL PROPERTIES	2,5	2	2	2	2	2	0	0	3	4	4	4	4
DURABILITY	3	4	3	1	1	1	2	2	4	4	4	4	4
PERFORMANCE	2,875	2,5	3,25	2,25	1,5	1,5	1,5	1,75	3	3	4	2,25	2,5
GENERAL PERFORMANCE	3	2	3	2	1	1	1	1	3	3	4	2	2

Appendix 2- Municipality data

	Number	Type	Function	Materials	Construction year	Monument	Length	Width
	Tanthof-west							
1	2201	1	1	1	1990	0	17	3.3
2	2202	1	1	1	1990	0	12.5	3.3
3	2204	1	1	2	1991	0	15.6	4.85
4	2206	1	1	2	1991	0	15	3.4
5	2207	1	1	1	1991	0	12.7	3.2
6	2208	1	1	2	1989	0	13.55	3.35
7	2210	1	2	2	1986	0	12.4	3.3
8	2211	1	1	2	1986	0	15.4	4.8
9	2212	1	1	1	1989	0	11.8	4.7
10	2213	1	1	1	1989	0	12.2	3.7
11	2214	1	1	1	1989	0	12.2	3.7
12	2215	1	1	1	1989	0	12.2	3.5
13	2216	2	1	3	1983	0	4.2	4
14	2217	1	1	2	1995	0	3.4	2.15
15	2218	2	1	3	1995	0	4.4	4.4
16	2219	2	1	3	1995	0	2.4	4.4
17	2220	2	1	3	1995	0	2.4	4.4
18	2221	2	1	3	1995	0	6.4	4.4
19	2222	2	1	3	1995	0	4.4	4.4
20	2223	1	1	2	1985	0	15.4	4.8
21	2225	1	2	1	1984	0	13	1.7
22	2227	1	1	2	2010	0	15.3	4.8
23	2228	1	1	3	1984	0	9.3	5.8
24	2230	1	2	1	1985	0	11.9	1.85
25	2231	1	1	4	2015	0	14.9	4.5
26	2232	1	1	1	2004	0	6	1.9
27	2233	1	1	1	2004	0	6	1.9
28	2234	1	1	1	1985	0	15.5	1.7
29	2236	1	1	2	2005	0	15.5	3.3
30	2237	1	1	2	2010	0	15.5	4.8
31	2238	1	1	1	1991	0	14.2	3.5
32	2245	1	1	3	1960	0	2.1	2.7
33	2246	1	1	2	2000	0	13	3
34	2247	1	1	2	2000	0	13	3
35	2251	1	2	1	2010	0	11	1.5
36	2252	1	2	1	2010	0	10	1.5
37	2257	1	1	2	2010	0	4	1
38	2258	1	0	1	2013	0	22.5	2.5
39	2259	1	2	1	2013	0	7	2.5

	Tanthof-east							
1	2322	1	1	5	2010	0	12	3.7
2	2323	1	1	1	2013	0	10.2	1.5
3	2324	1	1	1	2012	0	13.9	2.3
4	2327	1	1	2	2010	0	2.75	2.2
5	2328	1	2	1	1978	0	16	1.8
6	2329	1	1	2	1978	0	15.3	4.8
7	2330	1	2	1	1978	0	13.9	1.8
8	2331	1	2	1	2012	0	14.78	2.55
9	2333	1	1	1	2012	0	14.8	4.55
10	2334	1	1	2	2014	0	15	3.28
11	2335	1	1	2	2014	0	10	1.9
12	2337	1	1	1	2005	0	4.9	1.7
13	2338	1	1	1	2005	0	5.75	3.35
14	2339	1	1	2	2005	0	6.1	1.6
15	2340	1	1	2	2012	0	15.4	4.75
16	2341	1	1	1	2012	0	12.85	1.7
17	2342	1	1	1	2012	0	12.85	1.7
18	2344	1	2	1	2010	0	14	2.3
19	2346	1	1	2	2012	0	13.1	3.2
20	2349	1	1	1	2014	0	12.7	1.7
21	2351	1	2	1	2014	0	12.4	1.7
22	2352	1	1	1	2014	0	13	3.2
23	2353	1	1	1	1986	0	6.4	3.3
24	2355	1	1	2	1980	0	11.9	1.95
25	2356	1	1	2	1980	0	11.9	1.9
26	2357	1	1	2	1981	0	11	2.25
27	2358	1	1	2	1981	0	8	2.1
28	2359	1	1	1	1981	0	13.2	3.2
29	2360	1	1	1	1981	0	8	3.2
30	2361	1	1	1	1980	0	12.8	3.2
31	2362	1	1	1	1985	0	6.1	3
32	2365	1	1	2	1981	0	8.45	1.85
33	2366	1	1	2	1981	0	8.45	1.85
34	2368	1	1	1	1989	0	11.8	4.7
35	2373	1	2	2	2014	0	1.6	2.15
36	2375	1	1	2	1990	0	10	1.9

Appendix 3- Structural calculations

Maple File sandwich FRP material, acceleration. All units in kN and mm
Y DIRECTION
Input

> $restart:$

CALCULATION OF YOUNG MODULUS :

> $E1 := 0.0299 : \#GPa;$

$E2 := 39.7 :$
$w1 := 1000 :$
$w2 := w1 :$
$w3 := w2 :$
$h1 := 90 : h2 := 8 :$
$d1 := \frac{(h1 + h2)}{2} :$
$I1 := \frac{1(w1 \cdot h1^3)}{12} :$
$I2 := \frac{(w2 \cdot h2^3)}{12} + (w2 \cdot h2 \cdot d1^2);$
$\boldsymbol{Iy := I2 \cdot 2;}$

$$\frac{57752000}{3}$$

$$\frac{115504000}{3} \quad (1)$$

$BS2 := E2 \cdot Iy :$
$BS1 := E1 \cdot I1 :$
$BS0 := BS1 + BS2 :$

$I0 := I1 + 2 \cdot I2 : \#mm^4;$

$h3 := 105 :$
$I3 := \frac{w3 \cdot h3^3}{12} :$

$\boldsymbol{E3 := \frac{BS0}{I3}; \#GPa;}$

$$15.86336879 \quad (2)$$

CALCULATION OF SHEAR MODULUS :

$v0 := 0.141 :$

$$G := \frac{E3}{2\cdot(1+v0)};$$

6.951520066 **(3)**

CALCULATION OF DENSITY :

$p1 := 29.9\cdot 10^{-9}:$
$p2 := 1770\cdot 10^{-9}:$
$V1 := 1000\cdot 100\cdot 1000:$
$V2 := 1000\cdot 2.5\cdot 1000:$
$m1 := p1\cdot V1 : m2 := 2\cdot p2\cdot V2:$
$m3 := m2 + m1:$

$$p3 := \frac{m3}{w3\cdot h3\cdot 1000};$$

$1.127619048\ 10^{-7}$ **(4)**

$pnew := p3\cdot 10^{9};$

112.7619048 **(5)**

CALCULATION OF PRICE :

$price1 := 14.7 : \#\frac{E}{kg}:$
$price2 := 26.5 : \#\frac{E}{kg}:$

$Price1 := price1\cdot m1 : \#euro:$
$Price2 := price2\cdot m2 : \#euro:$

$$Price3 := \frac{(Price1 + Price2)}{m3}; \#\frac{euro}{kg}:$$

23.52010135 **(6)**

CALCULATION OF FLOOR LOAD :

$u := 0.5:$
$l1 := 4:$
$l2 := 8:$
$l3 := 12:$
$l4 := 16:$
$p := 30:$

$Load1\_floor := p\cdot l1\cdot 0.001;$

0.120 **(7)**

$Load2\_floor := p \cdot l2 \cdot 0.001;$

$$0.240 \tag{8}$$

$Load3\_floor := p \cdot l3 \cdot 0.001;$

$$0.360 \tag{9}$$

$Load4\_floor := p \cdot l4 \cdot 0.001;$

$$0.480 \tag{10}$$