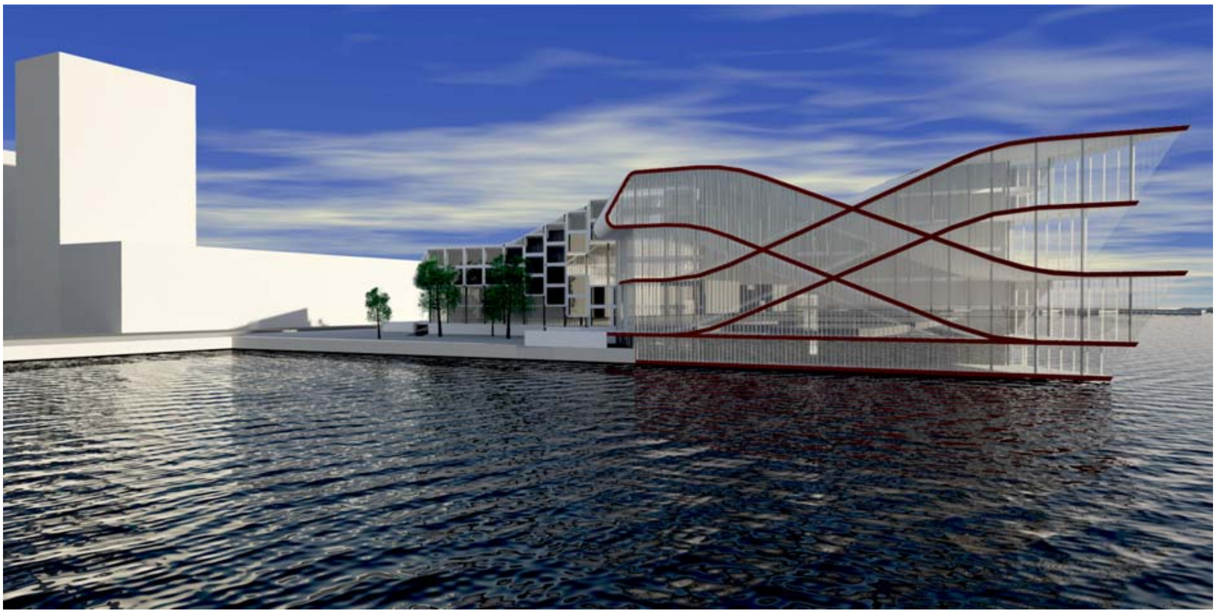
Composite - Hotel Design



Architectural Engineering
&
Building Technology

Dual Graduation Track

Research & Design Report
09-11-2012

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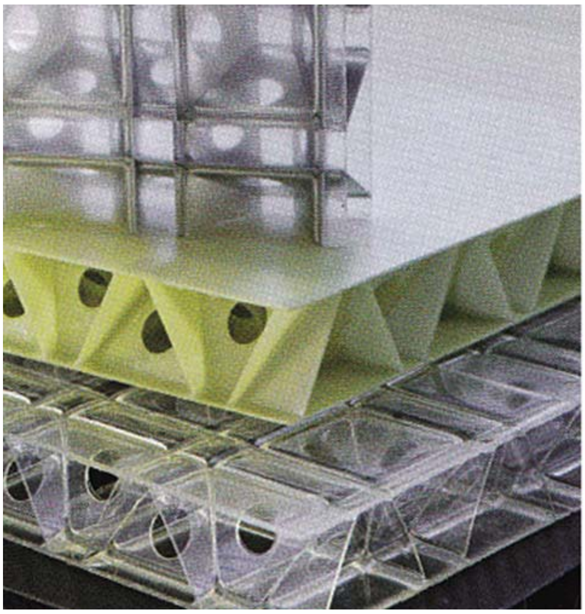
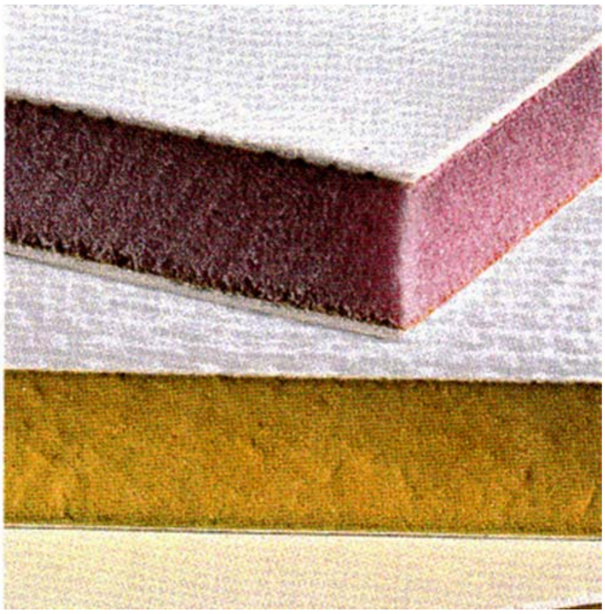
Preface

This report explains the research, process and design steps, thereby contributing to the graduation project. The graduation project consists of two parts thereby being a dual graduation project. Architectural Engineering and Building Technology represent these two parts. Based on a technical fascination an architectural design has been made for the Architectural Engineering part. The Building Technology part is an in depth exploration of the façade. Both tracks are based on the composite materials like Fiber Reinforced Plastics in a structural position. The result of this is a highly experimental design in which the material properties are used to shape the building. The report consists of four parts, each part representing a separate part of the process. Starting with material research in Part A gives insight in the various material properties and application fields. Since the architectural design will be based on these results, this is the first part of the report. This is followed by the architectural design itself in Part B and the development of the façade in both architectonical and technical terms in Part C. Finally the results of both graduation tracks will be shown in Part D which is a presentation of the final design.

PART A

Material Research





Architectural Engineering

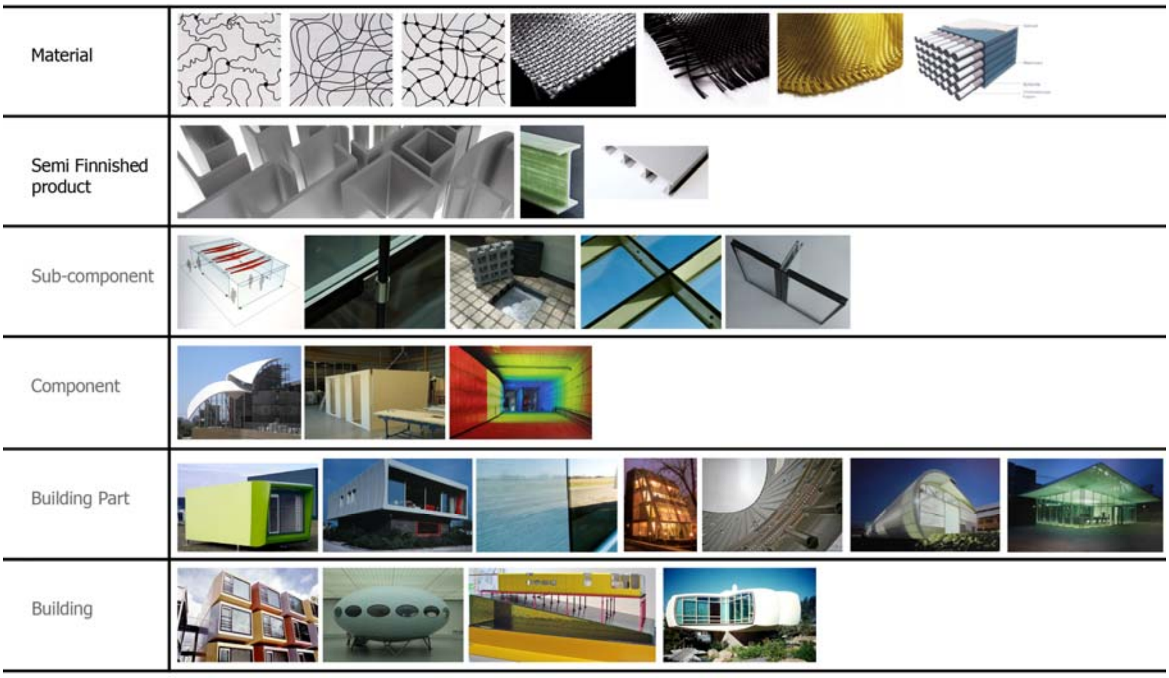
Dual Graduation Track

PART A

1 Research trajectory

Researching composites, when should they be used?

The goal of this research is to become able to tell in which specific situations one should use plastics. It emphasizes on Fiber Reinforced Plastics (FRP). The specific characteristics of plastics will be explored and linked to building situations. The outcome may suggest a direction on which the hotel design can or should focus. The FRP research starts with the basic material itself and from there work its way towards complete building components/buildings. Besides the exploration of the material properties itself, comparisons will be made between other materials and systems to point out the strong and weak points in that specific case.



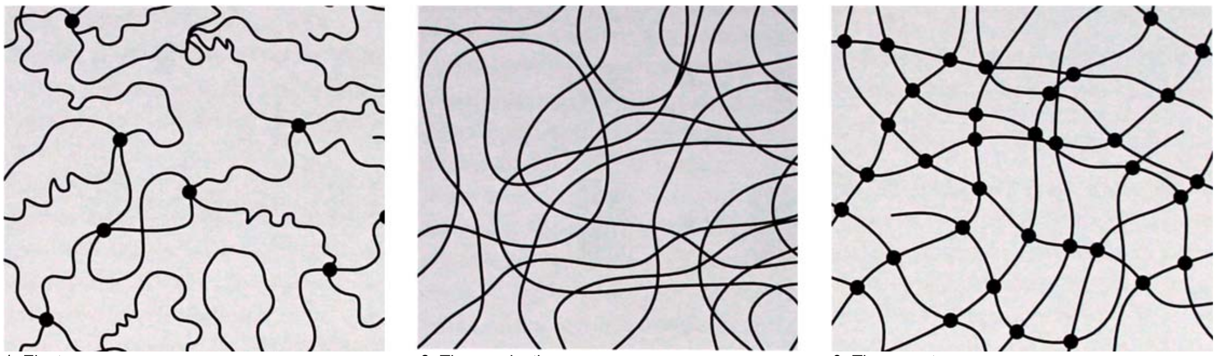
2 Fiber Reinforced Plastic (FRP)

What are the material properties and what is the relation with other materials?

Plastics have influenced our lives in various ways over the last couple of decennia. The bigger part of the products we use contains one or more elements which are made out of plastics. In architecture plastics are gaining field as well. However they do not always seem to be used in the most efficient way which in some cases contributed to a negative image of plastics as a building material. In order to use a material in the right way one should know the properties and characteristics of that material. In construction and façade cladding fiber reinforced plastics are often used. In general can be said plastics are strong but not stiff, which is an essential property in building structures. The use of fibers improves the stiffness and could make plastic composites the next building material. The focus of this research will therefore be Fiber Reinforced Plastics (FRP). In what situation should one use plastics and how should they be applied? At first the material itself will be explored and compared with traditional building materials.

2.1 Composition of the material

Plastics are the combination of polymer chains. The components used in this chain and the type of bonding determine the properties of the plastic. In general there are three categories: elastomers, thermoplastics and thermosets. In which category a plastic is placed tells something about its properties. Elastomers have a structure which makes them very elastic and able to return to their original shape once the stresses are removed. As a result of their internal structure they cannot be heat-deformed, melted or welded. In particular the rubber family contains examples of elastomers. The difference between thermoplastics and thermosets is the cross link bonding which thermoplastics do not have and thermosets do. This means the thermoplastics can be heat deformed because the polymer chains do not form atomic bonds between each other but are linked only by secondary valence forces. The process of heat deformation is repeatable. Examples of thermoplastics are polyvinylchloride (PVC), PMMA, polystyrene (PS), polyethylene (PE) and polypropylene (PP). Thermosets have a tightly cross-linked three-dimensional structure. When subjected to heat, the freedom of movement of the individual atoms is so limited that the melting temperature lies above the decomposition temperature at which the atomic bonds break. Thermosets are hard and brittle because of this tight cross-link structure. Because of this they are resistant to acids and alkali solutions. In general they have much more strength and stiffness when compared with elastomers but because of their brittleness they are hard to use in construction. In practice thermosets are almost only used in combination with fiber reinforcement. Non-reinforced thermosets are practically not in use. Figure 1 gives an impression of the different structures and shows the differences in bonding.



1. Elastomer 2. Thermoplastic 3. Thermoset

Figure 1: Different types of polymers *(source: Plastics in architecture and construction)*

2.2 Matrix materials

The composites which are the result of combining fibers and polymer are called Fiber Reinforced Plastics (FRP). FRP consists in general thus out of two elements, a matrix (resin) and fibers (reinforcement). The resin used in the matrix is almost always a thermoset, thermoplastics can be used as well but since their mechanical properties are worse than that of the thermosets, this is of almost no use. The matrix has a couple of purposes: it fixes the fiber in the desired shape, it transfers the loads to the fibers and stabilizes them against compression loads, protection of the fibers against external influences and it also is responsible for the chemical, electrical and thermal properties of the material. The resin will be cured during the shaping process with in some cases, the help of a solvent, and heat. It is on that moment the three-dimensional cross-linked structure starts to exist. There are several groups of thermosets which can be used as matrix, not all of them are commonly known since they are hardly ever used or only used in very specific industries. For the sake of this research, only the most commonly used matrix materials will be discussed.

Polyester (PU) is the most frequently used matrix as it produces a composite with good all-round properties. Unsaturated polyester can be divided into three groups: orthopolyester, isopolyester and vinylester. Orthopolyesters are inexpensive and as a result of that they are frequently used for building elements with low strength and dimensional stability requirements.

Isopolyester is used when a high degree of moisture, temperature or chemical stability is required. These group is often used in the process of shaping profiles due to its better mechanical properties such as a higher modulus of elasticity and tensile strength. However they are more expensive than the orthopolyesters. The last group, the vinylesters are even better corrosion resistant and has better thermal properties. The impact resistance of the material is better than that of ortho- and isopolyesters due to its better elongation properties. This is also the most expensive polyester resin.

Figure 2: Principle of FRP *(source: Plastics in architecture and Construction)*

Epoxy (EP) resins do not use a solvent but instead are two-component systems by itself. The mixture of the two liquid components needs to be monitored very precisely. Compared with polyester, epoxy has better mechanical properties but its main advantage is better shrinkage behavior. Unlike polyester, the shrinkage occurs when still in a liquid state which results in a product with very precise dimensions and almost no internal stress levels. Epoxy is better resistant to thermal influences and has better electrical properties.

Phenolic (PF) resins are used when there are requirements to high fire resistance, temperature resistance, low smoke generation and flame retardation when subjected to fire. In the field of mechanical properties it does not stand out which in combination with its relative high price makes this a resin only used in specific situations.

2.3 Fibers

The real mechanical properties of FRP are derived from the fibers used. Inorganic fibers are most commonly used for building elements, glass and carbon are examples of this. In specific situations synthetic fibers are used as well, such as aramid. Glass fibers are the most used type of fibers, mainly due to their cost. Through the addition of extra constituents the glass fibers can be optimized for special purposes. E-glass which is cheap, C-glass which is optimized for chemical stability, R-glass which is optimized for temperature resistance and S-glass which is optimized for strength. Glass fibers are isotropic, this in contrast with carbon and aramid. When the strength and stiffness of glass is not sufficient carbon fibers are used, they are however more expensive. Carbon fibers are categorized according to their mechanical properties into standard modules: high tenacity fibers (HT), intermediate modulus fibers (IM) and high modulus fibers (HM). Aramid fibers also have good mechanical properties but they also have a couple of disadvantages which makes their use in building elements a bit more difficult. They intend to absorb moisture which affects the bond between the fibers and the matrix and the UV and temperature stability of aramid fibers is not very good. They are only used in specific situations when carbon and glass are no longer sufficient, also they are used in combination with carbon.

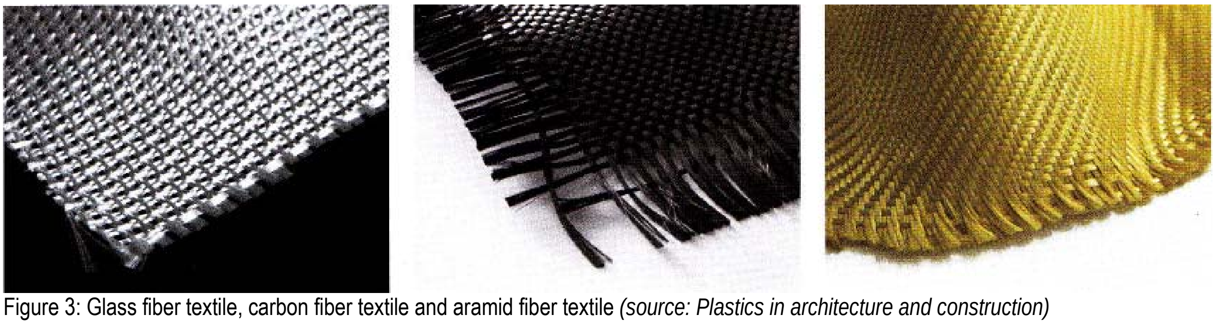


Figure 3: Glass fiber textile, carbon fiber textile and aramid fiber textile *(source: Plastics in architecture and construction)*

Besides the material used for the fibers, the direction of the fibers is of great importance as well. The mechanical properties are determined by this. The fibers occur in roving's or yarns. Roving's are bundles which are formed without twisting into bundles of parallel threads. Yarn are bundles of twisted and wrapped fibers, the fibers itself are in a way reinforced due to the twisting. Yarns and roving's can be woven into sheet-like textiles like chopped-strand mats, non-looped systems or looped systems. Chopped –strand mats consist of chopped, randomly orientated glass threads which are bound together in several layers with a bonding agent. This arrangement of fibers gives the laminates the mechanical properties of a material which is the same in all directions (isotropic). A combination of different types of mats is also possible. In general there is always a core layer of non-woven mats with on both sides textile mats. These sandwich constructions are often used in the production of curved building elements. Figure 4 shows different types of fiber mats.

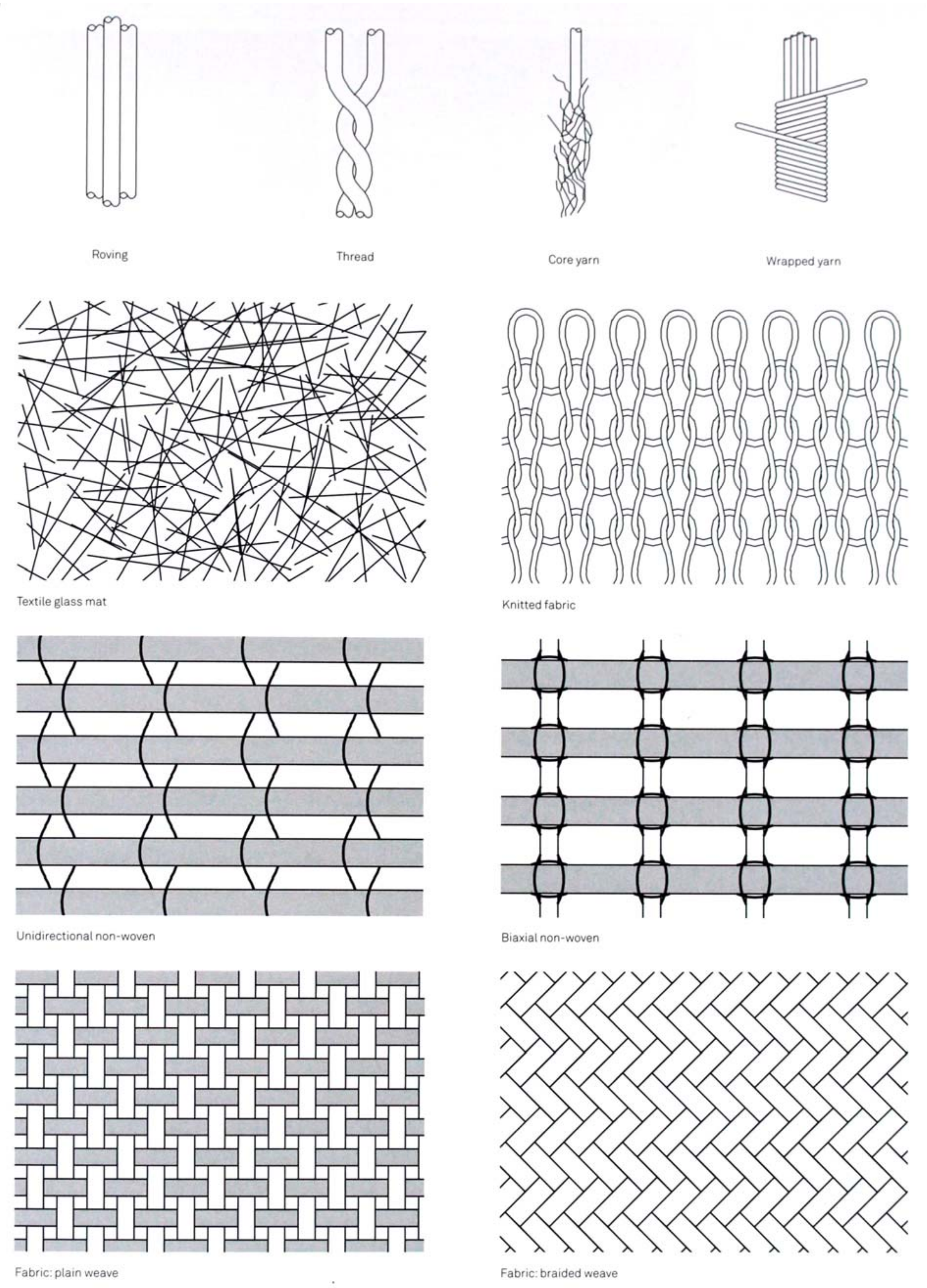


Figure 4: Different forms of fiber mats *(source: Plastics in architecture and Construction)*

The composite material which is the result of the matrix and the fibers can have very different properties since both ingredients are available in several models. In the next part these properties will be discussed.

2.4 Various material properties[1]

Blue: Polyester, Black: Phenol, Green: Epoxy

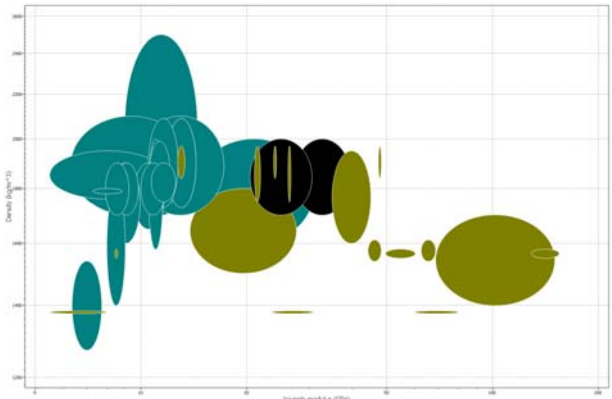


Figure 5: FRP – matrix – Y_density – X_youngs modulus

Blue: Glass, Black: Aramid, Green: Carbon

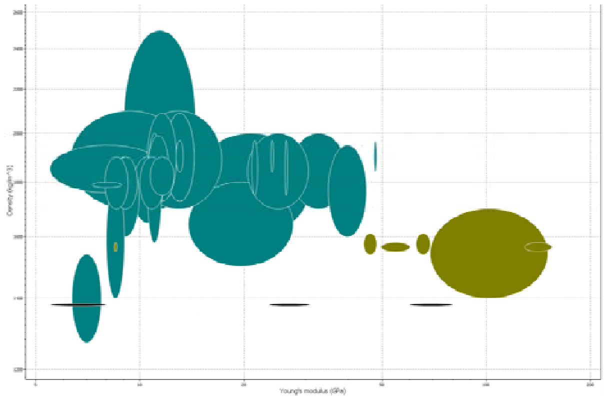


Figure 6: FRP – fibers – Y_density – X_youngs modulus

Figure 5 shows several different FRP's and their modulus of elasticity compared with their weight. The colors used in this graph are based on the type of resin used. Figure 6 shows the same graph but now the colors are based on the type of fibers used. Polyester has by far the most combinations but all are on the upper left side of the graph. This means they have the highest density and the lowest stiffness. Phenolic composites are located in between epoxy and polyester. The combination epoxy – carbon is the lightest and stiffest.

Blue: Polyester, Black: Phenol, Green: Epoxy

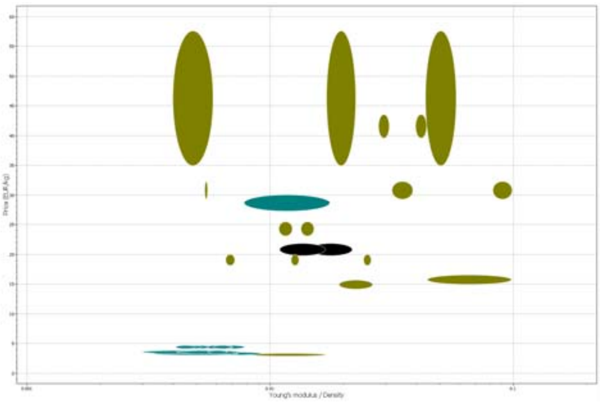


Figure 7: FRP – matrix – Y_price – X_youngs modulus

Blue: Glass, Black: Aramid, Green: Carbon

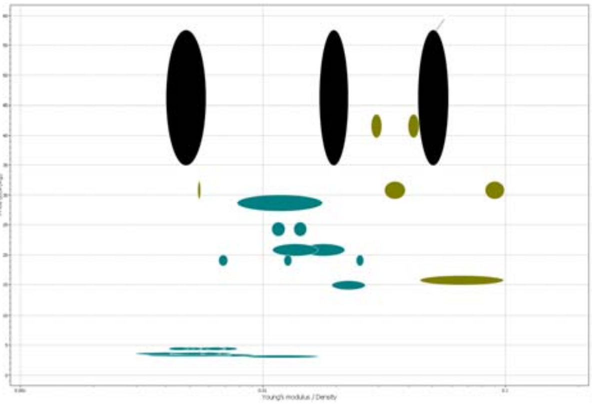


Figure 8: FRP – fibers – Y_price – X_youngs modulus

When comparing price and stiffness, there is less structure to be recognized. Figure 7 shows epoxy being all over the place but it also shows polyester being the most inexpensive by far. Phenolic based composites are somewhere between polyester and epoxy, this holds for price and stiffness. Derived from the graph above, one can conclude phenolic based composites are positioned between polyester and epoxy when talking about price, weight and stiffness. A said previously they don't stand out which means they only are to be chosen when very specific properties are required. Figure 8 shows the same ratio as figure 7 does, but this time the type of fibers used are shown. Aramid fibers are by far the most expensive but they also cover the whole range of stiffness. Carbon fibers are both expensive and strong which makes them a good material in certain situations, especially when strength and weight are more important than price. The combination glass and polyester is the most inexpensive one which explains why they are used most often.
Figures 9 and 10 show the relative stiffness of the materials compared with the relative strength. This ratio tells something about the strength and stiffness of the materials compared with their density. One can derive from these graphs the relatively strongest and lightest material. Since weight plays an important role in most building structure this ratio is a powerful tool when comparing materials based on their weight and stiffness. Figure 9 shows the matrix and figure 10 shows the fibers. Concluded from both these graphs, the combination epoxy-carbon is the lightest and stiffest. The combination glass-polyester does exactly the opposite. This is not an unexpected outcome but this is an outcome which really compares the relation between different material properties which gives more reliable results.

[1] All graphs are derived from CES EduPack 2011

Blue: Polyester, Black: Phenol, Green: Epoxy

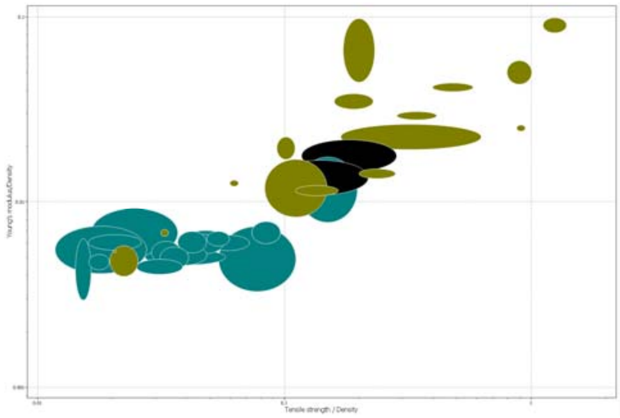


Figure 9: FRP – matrix – Y_relative stiffness – X_relative strength

Blue: Glass, Black: Aramid, Green: Carbon

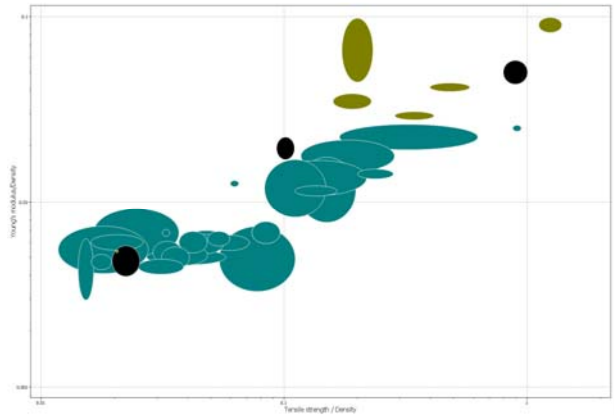


Figure 10: FRP – fibers – Y_relative stiffness – X_relative strength

The reason all these graphs show some mechanical properties is because they are in most scenarios the most prominent criteria. There are however other properties which are characteristic for FRP like their thermal behavior. Not all properties will be compared by graphs but the relationship between the thermal expansion coefficient and the thermal conductivity is an important one since FRP's are often used in situations insulation is required.

Blue: Glass, Black: Aramid, Green: Carbon

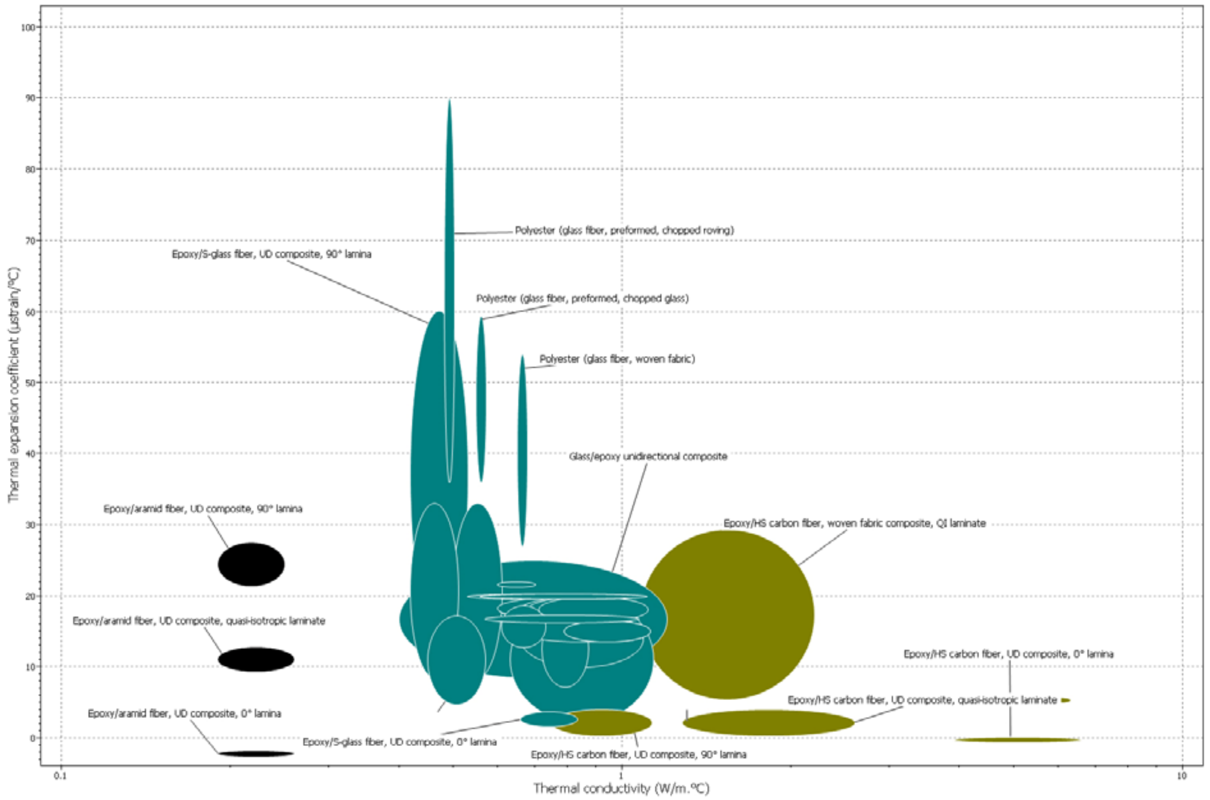


Figure 11: FRP – fibers – Y_thermal expansion coefficient – X_thermal conductivity

Aramid fibers have the best insulating properties while carbon fibers have the worst insulating properties within the range of FRP. The thermal expansion coefficient is a combination of the fibers used and the direction of the fibers. Zero degree lamina expands the least while 90 degree lamina intends to expand the most. This is only true when looking in the direction of stress, if not zero degree lamina will expand the most in the other direction since there are no fibers pulling the resin back.

As said before not all properties are compared using graphs. A list of material properties is given in figure 12, for the most commonly used types of FRP. These are also the materials which will be used to determine the place of FRP in the material universe of traditional building materials.

Properties	Polyester/glass	Epoxy/glass	Epoxy/carbon	Epoxy/aramid	Phenolic/glass		
	chopped glass			O-degree lamina	woven fabric		
Density	2100	1800	1700	1380	2000		kg/m3
Price	3,54	3,33	16,6	57,6	21,8		EUR/kg
Youngs Modulus	17,2	27,6	150	80	39,4		Gpa
Yield strength	55,2	193	276	1380	520		MPa
Tensile strength	69	241	345	1380	520		MPa
Elongation	1	2	2	1,7	1,91		% strain
Min service temperature	-27	-73	-73	-28	-30		°C
Max service temperature	190	190	184	220	210		°C
Thermal conductivity	0,572	0,7	6,3	0,26	0,87		W/m.°C
Specific heat capacity	1140	909	1340	1350	1160		J/kg.°C
Thermal expansion coefficient	59,4	22	5,51	-1,74	18		µstrain /°C
Electrical resistivity	1,00E+19	3,00E+22	1,00E+06	1,66E+21	1,40E+20		µohm.cm
Embodied energy, primary production	114	118	286	249	190		MJ/kg
CO2 footprint, primary production	7,88	8,25	18,1	20,1	14,7		kg/kg
Water usage	-	309	1370	-	-		l/kg
Flammability	highly flammable	slow-burning	self extinguishing	slow-burning	non-flammable		
Water (fresh)	excellent	excellent	excellent	excellent	excellent		
Water (salt)	excellent	excellent	excellent	excellent	excellent		
Weak acids	acceptable	acceptable	acceptable	acceptable	acceptable		
Strong acids	acceptable	unacceptable	unacceptable	unacceptable	unacceptable		
Weak alkalis	unacceptable	limited use	limited use	limited use	limited use		
Strong alkalis	unacceptable	excellent	excellent	excellent	limited use		
Organic solvents	unacceptable	limited use	limited use	limited use	excellent		
UV radiation (sunlight)	good	fair	good	fair	good		
Transparency	translucent	translucent	opaque	opaque	opaque		
Recycle	no	no	no	no	no		
Downcycle	yes	yes	yes	yes	yes		

Figure 12: Commonly used types of FRP and their properties *(source: CES EduPack 2011)*

The upper part of the table shows the mechanical and thermal properties of the selected materials. The lower part of the table shows the behavior of the materials in certain environmental conditions. Remarkable is their performance in both fresh and salt water. The flammability and the specific heat capacity tell something about the behavior of FRP during fire. FRP is not known for its outstanding performance when exposed to fire, quite the contrary. This however does not mean all FRP's behave the same. Carbon and aramid fibers are able to absorb a lot more energy before becoming warmer. Bottom line is that this is not enough to be used as a structural element in a building without additional protection.

Now an image has been given about the properties and behavior of FRP materials. The next section will implement this information next to that of traditional building materials. Since we know a lot of them it becomes easier to implement the information of certain values given. Besides that it is important to know what position FRP has between traditional building materials in order to determine specific usage of the material.

2.5 Comparison with traditional building materials[2]

The traditional building materials which are used for this comparison are:

- concrete
- wood (Spruce)
- steel S235
- laminated glass

These are the most commonly used materials; off course they also know a great variety of alternatives within their specific group of materials. It is not the goal of this analysis to compare them with all materials available but only to point out their specific place within the group of building materials. First the density will be graphed against the modulus of elasticity to show the stiffness of each material in relation to their weight (figure 13).

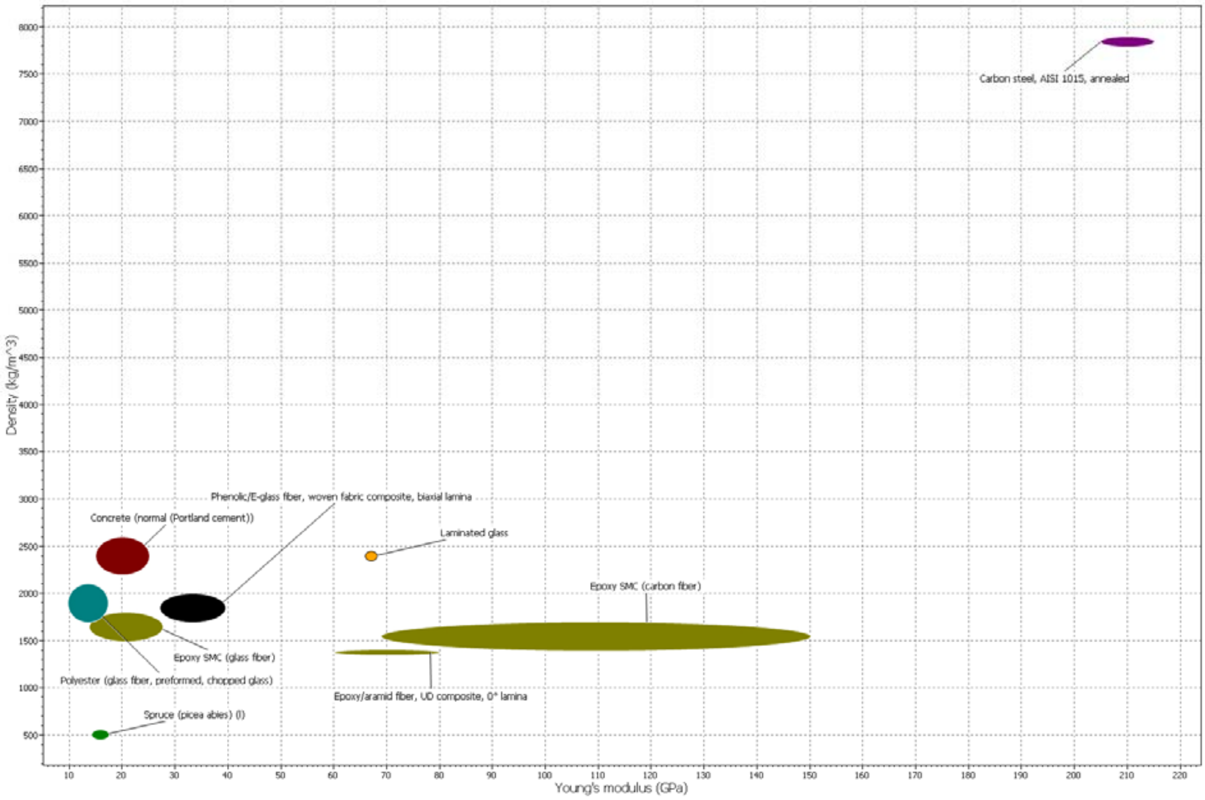


Figure 13: Y_density – X_youngs modulus

The most noticeable material in the graph is steel. This material has by far the highest modulus of elasticity also when compared with its weight. The other materials are more clustered in the lower left corner. The aramid and carbon fiber composites turn out to be stiffer than the remaining traditional building materials while the glass fiber composites are located between them. Wood is the lightest material but not the one which is most flexible. Concluded from this graph, when it comes to density and stiffness there is no specific place pointed out but the type of fiber used in combination with the resin used determines the location of the FRP materials. This position, when it comes to stiffness lies between the traditional materials. When it comes to density FRP turns out to be lighter than the traditional building materials. Wood is the exception here. From the looks of this graph FRP, especially the aramid and carbon based ones, seem to have a good position between the other materials but this is not the case when talking about costs.

Figure 14 shows the material costs compared with their relative stiffness. With the exception of laminated glass, all materials are less expensive than FRP. However the graph also shows the relative stiffness of FRP being higher than that of most traditional materials. The high price of FRP certainly is one of the reasons why this is not yet a commonly used building material. This price also demands the use of FRP in situations the other materials will fail or are less suitable. Conclusion: there needs to be a specific reason when one intends to use FRP since other building materials might be more attractive when considering the costs. One of these reasons might be the ratio between their stiffness and density since these materials can be considered lightweight building materials.

[2] All graphs are derived from CES EduPack 2011

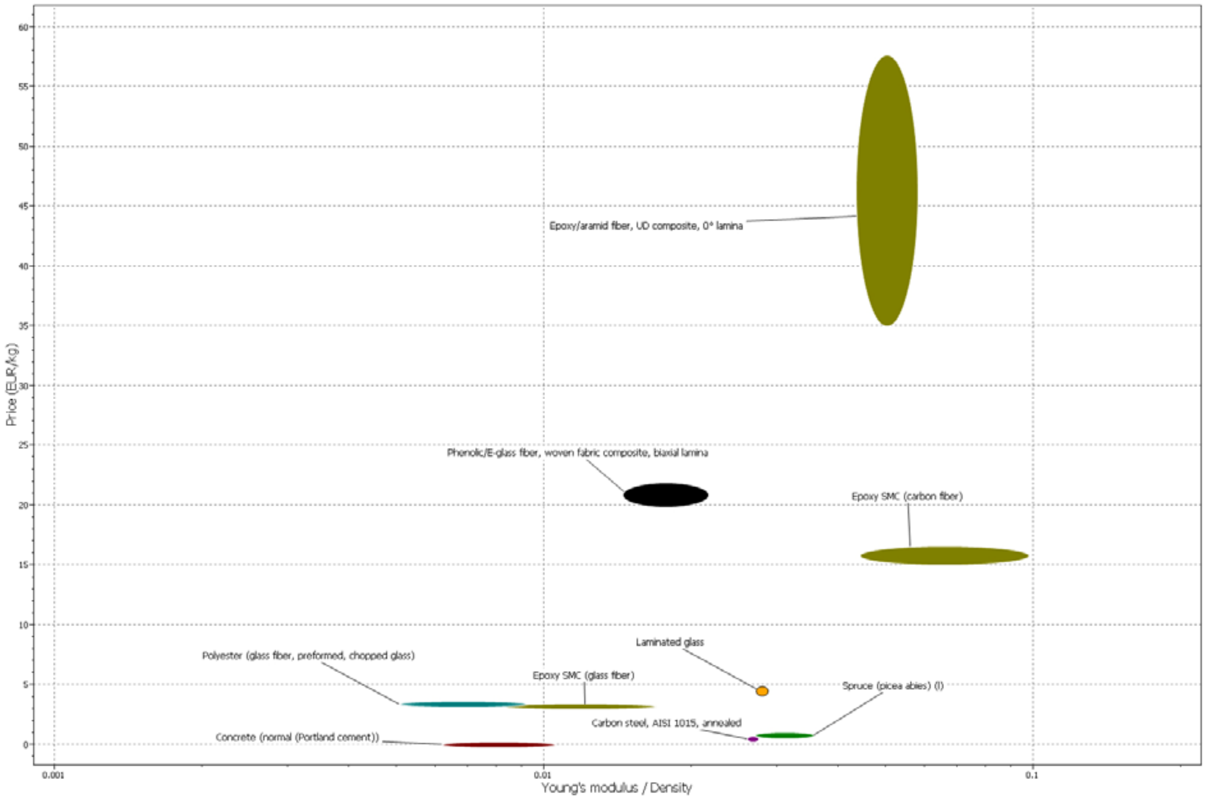


Figure 14: Y_price – X_relative stiffness

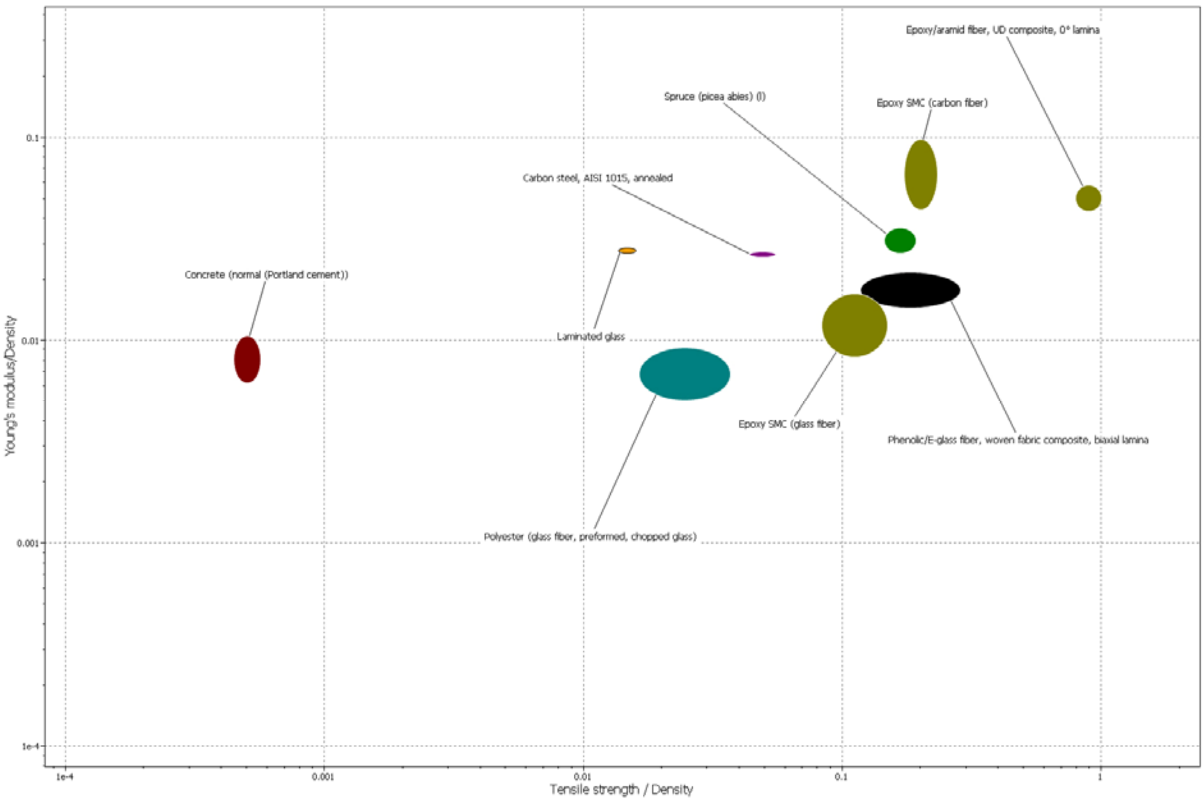


Figure 15: Y_relative stiffness – X_relative strength

The results in figure 15 show FRP as the most light and strong material when all of this is brought down to weight. Wood also shows great results but a note must be made about this. The properties used for wood in CES are that of the ideal piece of material, in reality this will certainly not always be the case. This does not mean wood shows wrong results but one should

take into account this is wood at its best, something which is hard to predict. The relative strength of FRP is the most noticeable in this graph, the differences between FRP and the traditional materials are larger than when it comes to relative stiffness. This means FRP is stronger than most of the materials but not always stiffer. This could be a problem when it comes down to the a building in which it is not preferred to have large deformations even if the material can withstand all of this. But on the other hand there is the possibility of FRP being just as stiff as the traditional building materials but still being lighter. This also depends on the type of profiles used since the deformation is the result of the modulus of elasticity and the second moment of inertia.
Besides the mechanical properties there is also the thermal behavior of the materials. Figure 16 shows the thermal conductivity compared with the modulus of elasticity to show the stiffness of the materials against their insulating properties.

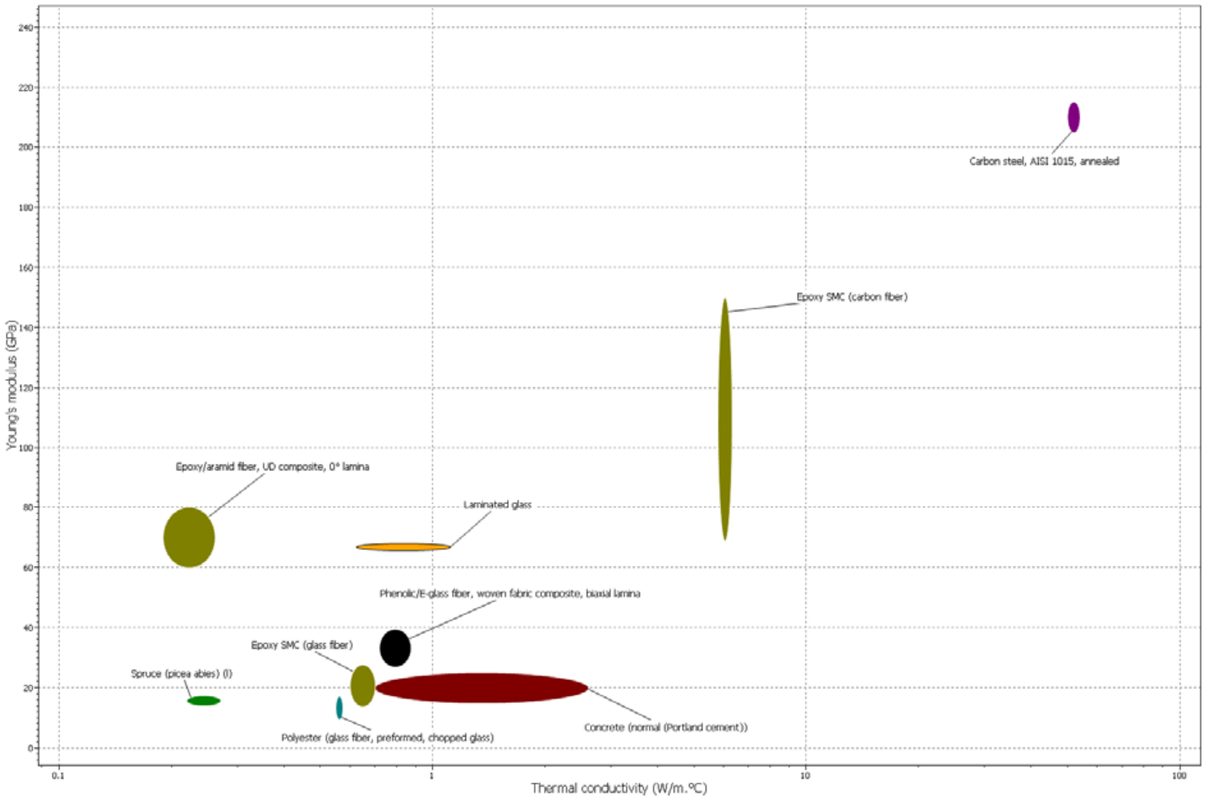


Figure 16: Y_youngs modulus – X_thermal conductivity

Wood as an exception, FRP shows better thermal conductivity values than the traditional building materials. This is even more interesting when also looking to the modulus of elasticity values which are also better in most cases. Epoxy – aramid fiber composites perform best in this graph. They however will only be used when this combination is required since they are also the most expensive. The influence of heat and cold has another effect on all of these materials, thermal expansion. The higher the value given for thermal expansion the bigger the difference in material size. This could lead to problems when materials are not properly used. Figure 17 shows the values for thermal expansion compared by their thermal conductivity. Phenolic/E-glass fiber composite and Epoxy/carbon fiber composite are on the same level as the traditional building materials. Polyester/glass fiber composite and Epoxy/glass fiber composite are above this, which means they need, in comparison with the other materials additional measures taken to prevent failure of building elements. Epoxy/aramid fibers are the other opposite, they intend to contract instead expand due to their negative thermal expansion coefficient. This can be a interesting property when combined with a material the same positive value, this could make a zero expansion composite material. Not all mechanical and thermal properties will be

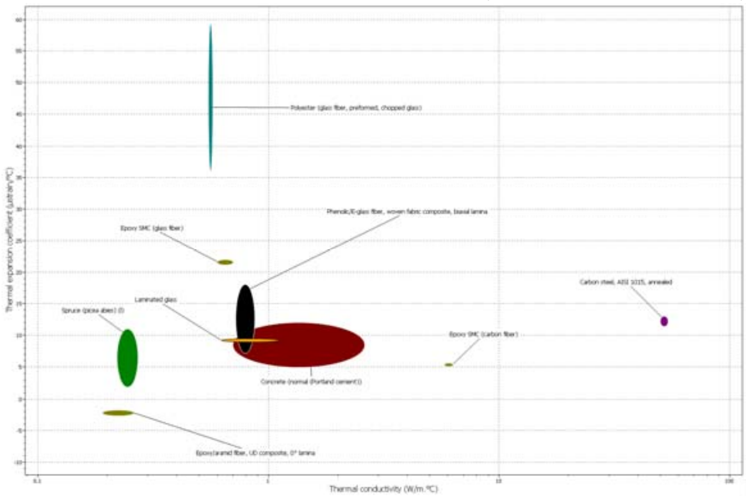


Figure 17: Y_thermal expansion coefficient – X_thermal conductivity

discussed by graphs, figure 18 shows the most important material properties including their behavior in specific environmental conditions.

Properties	Polyester/glass	Epoxy/glass	Epoxy/carbon	Epoxy/aramid	Phenolic/glass	Wood	Concrete	Steel	Glass	
	chopped glass			0-degree lamina	woven fabric	Spruce	Portland cement	S235	Laminated	
Density	2100	1800	1700	1380	2000	560	2600	7900	2450	kg/m3
Price	3,54	3,33	16,6	57,6	21,8	1	0,05	0,54	4,86	EUR/kg
Youngs Modulus	17,2	27,6	150	80	39,4	17,4	25	215	68	Gpa
Yield strength	55,2	193	276	1380	520	52,2	1,2	235	38	MPa
Tensile strength	69	241	345	1380	520	93,5	1,3	360	38	MPa
Elongation	1	2	2	1,7	1,91	1,77	0,01	45	0,06	% strain
Min service temperature	-27	-73	-73	-28	-30	-23	-150	-43	-	°C
Max service temperature	190	190	184	220	210	140	510	357	76,9	°C
Thermal conductivity	0,572	0,7	6,3	0,26	0,87	0,27	2,6	54	1,11	W/m.°C
Specific heat capacity	1140	909	1340	1350	1160	1710	1050	505	950	J/kg.°C
Thermal expansion coefficient	59,4	22	5,51	-1,74	18	11	12	13	9,5	µstrain /°C
Electrical resistivity	1,00E+19	3,00E+22	1,00E+06	1,66E+21	1,40E+20	2,00E+14	1,85E+13	1,80E+01	8,00E+18	µohm.cm
Embodied energy, primary production	114	118	286	249	190	7,96	1,3	35	30,2	MJ/kg
CO2 footprint, primary production	7,88	8,25	18,1	20,1	14,7	0,472	0,099	2,61	1,63	kg/kg
Water usage	-	309	1370	-	-	1500	5,1	68,6	31,8	l/kg
Flammability	highly flammable	slow-burning	self extinguishing	slow-burning	non-flammable	highly flammable	non-flammable	non-flammable	non-flammable	
Water (fresh)	excellent	excellent	excellent	excellent	excellent	limited use	excellent	acceptable	excellent	
Water (salt)	excellent	excellent	excellent	excellent	excellent	limited use	acceptable	limited use	excellent	
Weak acids	acceptable	acceptable	acceptable	acceptable	acceptable	limited use	limited use	limited use	excellent	
Strong acids	acceptable	unacceptable	unacceptable	unacceptable	unacceptable	unacceptable	unacceptable	unacceptable	acceptable	
Weak alkalis	unacceptable	limited use	limited use	limited use	limited use	acceptable	acceptable	acceptable	excellent	
Strong alkalis	unacceptable	excellent	excellent	excellent	limited use	unacceptable	unacceptable	limited use	unacceptable	
Organic solvents	unacceptable	limited use	limited use	limited use	excellent	acceptable	excellent	excellent	excellent	
UV radiation (sunlight)	good	fair	good	fair	good	good	excellent	excellent	excellent	
Transparency	translucent	translucent	opaque	opaque	opaque	opaque	opaque	opaque	optical quality	
Recycle	no	no	no	no	no	no	yes	yes	yes	
Downcycle	yes	yes	yes	yes	yes	yes	yes	yes	yes	

Figure 18: Commonly used types of FRP and traditional building materials with their properties *(source: CES EduPack 2011)*

The best outcomes are highlighted in green, something which not means other outcomes are not good enough, it just points out the best material in that category. Glass by far is the best material when it comes to environmental influences, it only has problems with strong alkalis. The FRP materials do not seem to perform very well at first sight but when taking a closer look the table reveals acceptable results for the contact with weak acids and UV radiation. With the help of UV stabilizing additives, which almost always are used, the resistance to UV radiation can become better. The problems with FRP is in its behavior towards strong acids, weak alkalis and organic solvents. In building environments it is not common to be exposed to strong acids and weak alkalis but organic solvents are always around. However with the help of additives and coatings this property can be upgraded. The strength of FRP when it comes down to environmental influences lies in the fact it handles both fresh and salt water quite well. Building on water without additional measurements taken might become much more accessible. But also the level of maintenance decreases because of its behavior in water.

The translucent properties of FRP can be of great importance in the experience of a design. They are not transparent enough to look through but they do emit light, which can be used as an architectonical instrument. During the shaping process there is also the possibility of adding color pigments to the resin which makes it possible to produce elements in all available colors. Only glass has the ability to do also but all other traditional materials need an extra layer when their original color is not good enough. FRP can change its original color and as a result of this does not need much maintenance since the color is inside and it behaves very well in watery conditions. This is a combination which saves money in the whole trajectory which follows when a building is completed.

As it comes to behavior during fire, FRP is not a very good material. It is not likely to catch fire very quick but the maximum service temperature is too low when compared with the temperature of fire. This means the construction will start to deform very quickly after being exposed to fire. Steel has the same problem but with a slightly higher maximum service temperature. Both materials need additional protection when they are to be used as structural elements. In case of steel ceramic coatings can be applied or in case hollow tubes are used, they can be filled with concrete. In case of FRP this is not this easy. Practical studies have showed these solutions do not apply to plastics. In principle the higher the mass the better the resistance since more energy can be absorbed before a material starts to transform. In case of FRP experiments have been done in which water was used in hollow FRP sections, to absorb the energy and take it away. The results of these experiments are very promising but since these experiments took place only recently, there are no actual situations in which these concepts are applied.

Compared to the traditional building materials, there is an extremely lot of energy needed to produce FRP. From this property it is not that easy to tell if this is a good or a bad thing. Primarily this would be considered bad since the use of energy needs to be reduced. On the other hand, FRP is a bad thermal conductor and it also needs very little maintenance which all save energy. Due to the properties of FRP it costs a lot of energy to produce but also a lot of energy can be saved due to the same properties. If both situation will become even is hard to tell since this is depended on a lot of influences which are hard to control. Besides the use of energy FRP is not up for recycling since the process of hardening the thermosets resins is irreversible. Since these materials form the basis of the composite this is unlikely to change in the future. Several research studies are being done at the moment to come up with alternatives for the thermoset used as matrix. These oil based products are for the bigger part responsible for its environmental load. Alternatives are polylactic acid (PLA) which is a biopolymer. The application of this material in building structures is still in a very early stage, on this moment the only real constructions being made are containers. It is not particularly the strength of the material holding its widespread use back but its building physics and environmental properties, which should be the biggest advantage in the use of plastics.

The strength of FRP is not the best one can get in the material universe but when it comes to the specific strength and stiffness these materials are performing better than the traditional alternatives. This however does mean it is not likely to use FRP primarily as a material for construction when lightness is not one of the properties needed. In terms of thermal conductivity FRP performs on the same level as wood which makes its constructive use in façades possible. Their environmental behavior and the possibility of directing light can both be very powerful properties in a design. The real potential of FRP lies in the fact it has properties which in specific situations are more than all others and, also in the possibility to combine several building elements into one component as a result of the material properties FRP has. During production and shaping processes several adjustments can be made to the material which optimizes its use in specific situations. For the sake of this research this means, specific situations will be explored and combinations of building physical aspects are investigated. These outcomes will form the guidance in materializing and constructing the design. Before these topics will be discussed, shaping possibilities and connection methods are reviewed to gain a complete understanding of the material.

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CES EduPack 2011

3 Production methods[3]

FRP can be considered a free form material, partly because of its chemistry but also because of the variety of processes which can be used to shape elements. These processes and their characteristics will be explained in the next chapter. On the one hand this freedom of form can be seen as a blessing but on the other hand it can also been seen as burden. Since everything is possible there is barely any guidance. The limits of materials and their shaping processes are often used to shape spaces and elements but in this case the sky seems to be the limit. During the design process this requires a different approach, one which uses the specific properties of the material and combines them into smart elements. The shaping processes can contribute to these developments and since not everything is possible in terms of costs, shape or section thickness, they will be explained to figure out the differences and the opportunities.

The composite forming processes are categorized into small groups of similar production techniques.

- Automatic lay-up
- Compression molding
- Continuous
- Manual lay-up
- Resin transfer
- Spraying

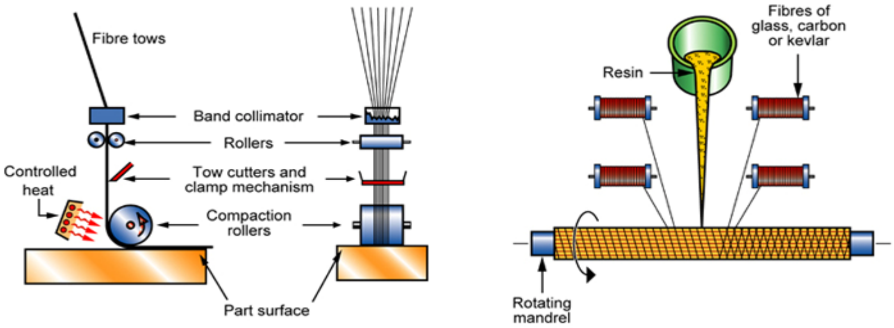


Figure 1: left - Automatic Tape Placement, right - Filament Winding

3.1 Automatic layup

Automatic tape placement deposited a pre-impregnated-fibers tape by a laying head carried by a numerically-controlled multi-axis machine. The process allows flexibility of part shape, laminate orientation and lay-up. Expensive method with slow production rates. Rarely used to produce FRP elements.
Filament winding is used to produce ax symmetric parts by winding the resin-impregnated reinforcement on a rotating mandrel. The orientation of the fibers can be adjusted to the application. The fibers can be placed in a high density and due to the high level of mechanization shapes can be reproduced with exactly the same properties. FRP can only be used for hollow shapes like pipes and vessels.

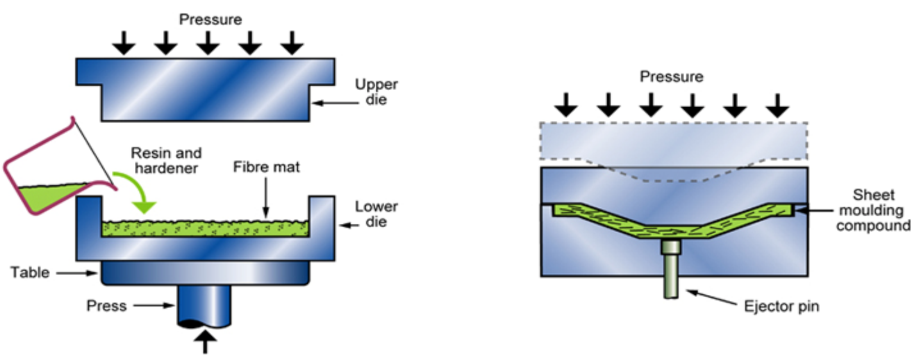


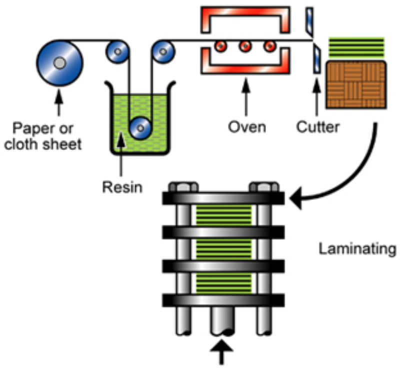
Figure 2: left – Cold Press Molding, right – SMS Molding

3.2 Compression molding

Cold press molding is an intermediate process between contact molding and hot press molding. The reinforcement is cut to shape and placed in the mold. The best fiber content that can be achieved is approximately 50%. The tools used in this

[3] All images are extracted from CES EduPack 2011, as is the information

process are partly only usable on one specific shape which makes this process in most cases only efficient when numerous copies need to be made of one element. Dependent on the type of mold used this can be a very expensive part of the process. SMC molding is one of the most economical processes for the high volume production of small-to-medium sized components. A sheet in which the reinforcement, resin and additives are already present is cut into shape and placed in the mold. With pressure and heat the form of the mold is applied to the sheet and the polymer is cured. UP is often used as resin in this process. Both processes have not yet found their way into architectural applications since the batch sizes are to large for usage in one single project.



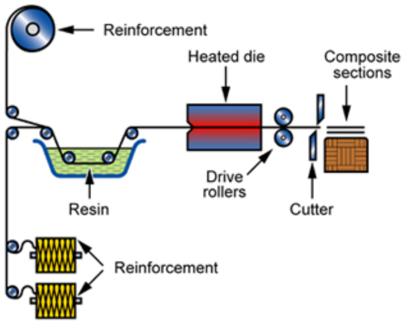
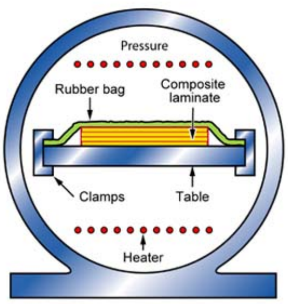
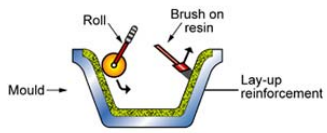


Figure 3: left – Continuous Laminating, right - Pultrusion

3.3 Continuous

Continuous laminating uses impregnated mats or fabrics which are pressed together until the desired thickness is met. The sandwich construction is cured at an elevated temperature and afterwards the sheets are cut into the desired length. As a result of the thin layer of resin on top and bottom, the products usually posses a smooth attractive appearance.
Pultrusion is currently the most used process in the industry of producing semi-finished products. In a relative simple way sections and sheets can be produced with a high fiber content and little scatter to the mechanical properties of the material. In the process fibers are being pulled through a bath of resin and through a die. After this the whole goes into a curing oven and is cut into the desired length. A fiber content of 70% can be achieved with this process. PU is most often used in combination with glass fiber and EP for carbon reinforced profiles. During the curing process the profiles intend to shrink which influences the tolerances. In case of using EP these tolerances can be minimized since there will be little to no tension in the material. In principle any cross-section can be produced, however the dimensions are limited. The wall thickness generally lies between 0.5 and 100 mm and the maximum overall dimensions are 650 – 1250 mm. Pultruded sections are normally straight but only recently curved sections can be made as well. Pultrusion requires comparatively elaborate and expensive tooling, and setting up the plant is very time-consuming. This means that custom sections only are worthwhile when producing larger quantities which usually come down to 1000 production meters. When this is not possible, profiles from the consumer market need to be used which limits the possible sections.





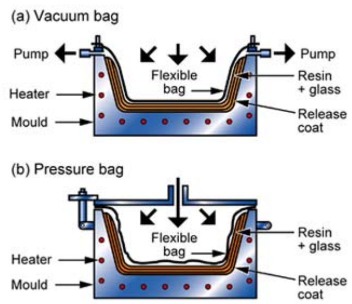


Figure 4: left – Autoclave Molding, middle – Hand Layup, right – Vacuum/Pressure bag

3.4 Manual lay-up

Autoclave molding is a technique not yet used in architecture but mainly to produce high strength aircraft and aerospace components which have thick parts and were high fiber volume is required. In the process, the resin and reinforcement are applied on the mold by conventional hand or spray lay-up techniques. A flexible bag is placed on top of the fiber layer. The laminate and the mold are then placed inside an autoclave and subjected to pressure which causes the bag to be drawn to the laminate resulting in enhanced densification. The autoclave is often heated to accelerate cure and increase productivity.
Hand lay-up is a much simpler technique and more widely used manufacturing method. A gel coat is applied to the surface of the mould on which, once sufficiently cured, the reinforcement is placed by hand and the resin is applied by brush or roller.

This process is repeated until the desired thickness is achieved. During the process additives can be applied to the resin. This method is used to produce components with irregular shapes in small batches, but also elements that due to their large shapes cannot be produced with automated methods. For small batches molds made out of foam are used. These are inexpensive elements but they are likely to damage after several times of use which makes them not suitable for larger batches. In that case, FRP molds are used since they last longer. The face of the element which contacts the mould has a smooth surface, the inside face has a rough surface. The quality of the produced elements may vary greatly since all work is done by hand which makes it inaccurate. The maximum fiber content to be achieved is 45%. Air bubbles, excessive resin and irregularities are very common.
Use of a vacuum/pressure bag is an addition to the hand lay-up method which minimizes the faults by applying a vacuum to the elements. Air bubbles, excessive resin and other irregularities can be controlled. In the process a bag is placed on top of the elements and negative pressure is applied. Not only the finished product is influenced by this technique but also the production speed increases due to faster curing of the resin. Composite structures with foam cores can be produced with this method.

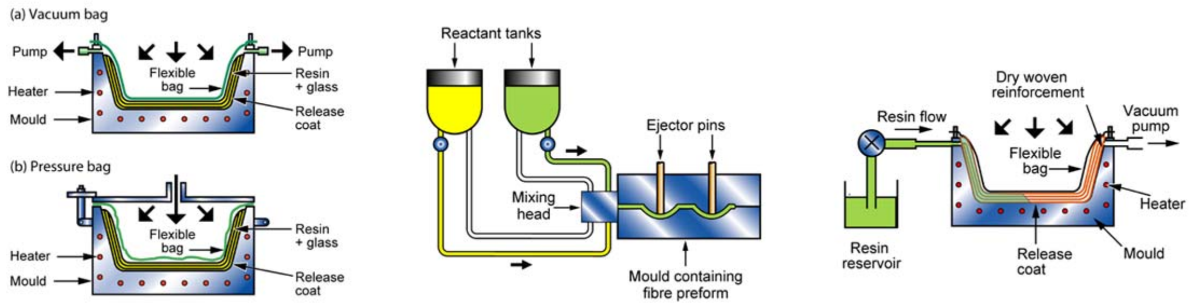


Figure 5: left – Resin Film Infusion, middle – Resin Transfer Molding, right – Vacuum Assisted rtm

3.5 Resin transfer

Resin film infusion uses dry layers of fabric as reinforcement on which the resin is applied in a semi-solid state on a release paper. A flexible bag is placed over the top layer and a vacuum pump removes the air from within the bag. The dry fabrics are compressed onto the resin after which the mold is heated to melt the resin causing it to flow into the fabric where it cures.
Resin transfer molding is an easy way of manufacturing complex shapes without high tooling costs. It uses a closed mold with injection points, which also has ventilation points to let the air escape. Reinforcement cut to shape is placed in the mold and the mold is closed. A low viscosity resin like polyester is injected under low pressure which pushes out the air through the vents. The result, is compared to hand lay-up, a very consistent laminate structure with fewer air inclusions and a smooth surface on both sides.
Vacuum assisted resin transfer molding is a method more time consuming than resin infusion but it gives better results. This is a low-cost tooling way of manufacturing large complex shapes of composite materials. Reinforcements are placed in the mold in the form of dry layers of woven fabric. A bag is placed over this and a vacuum is applied. After this the resin is released which is sucked into the bag by vacuum, flowing through and impregnating the fabric, which is then cured.

3.6 Spraying

Spray up is a relatively simple and inexpensive technique for making manual fabricating large laminates with a complex geometry but low demands regarding load-bearing capacity. A gel coat is first applied to the mold. Once this has cured, a mixture of chopped fibers and resin is sprayed onto the surface of the mold using a spray gun. Air bubbles are pressed out using a roller. When making thick laminates, this should be done in several layers allowing each layer to cure after each stage. The thickness of the laminate varies considerably with this method, and it is not possible to control the orientation of the fibers either. On the other hand this method is the minimum amount of work necessary and the option of being able to laminate vertical surfaces or membranes.

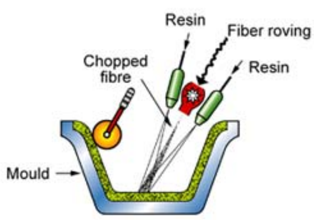


Figure 6: Spray up method

From all processes described, pultrusion, manual lay-up and vacuum techniques are used most often. High tooling costs and very expensive dies/molds are however in all of these cases present. Most of these processes only become economically efficient when producing larger batch sizes, something which in architecture is not always possible. A lot of semi-finished and finished products are available on the consumer market but these limit the freedom of form which the combination of these materials and production techniques offers. Custom elements can only be used when they can be applied repetitively.

4 I-beams compared

FRP I-beam vs. Steel I-beam

In order to make decisions on when to use FRP I-beams in stead of steel I-beams, the two of them need to be compared on several levels. The results of this comparison should give insight on the material and understanding of how it works. First the FRP profile will be compared with a steel profile because of its shape. On the consumer market the profiles shown below, can be bought which happen to look almost identical. However there are quit some differences in behavior and material properties which will be discussed.

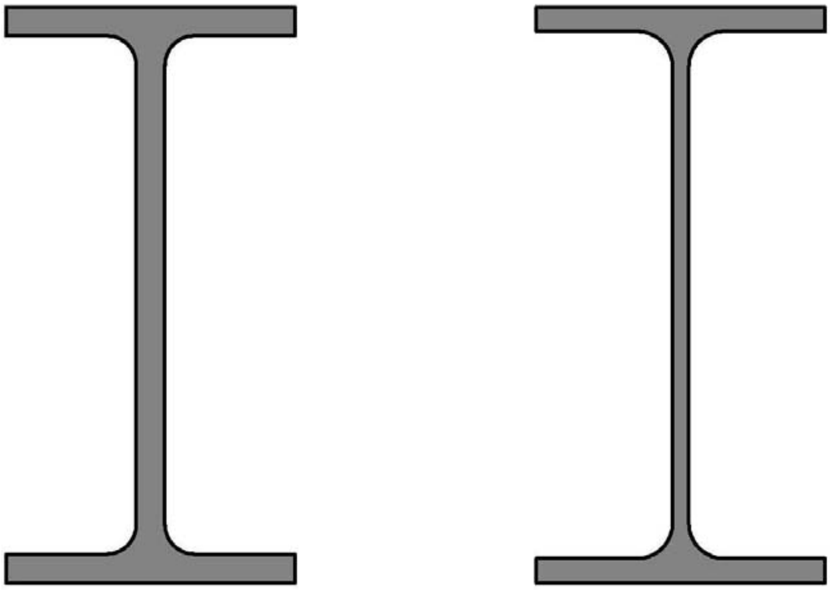


Figure 1: left, FRP profile – right, steel profile

4.1 Composition

At first the composition will be reviewed. The profile on the left is that made out of FRP and the profile on the right is a steel IPE-200 profile. Both have the same height and width but differ in thickness. For now it is enough to know they differ in profile thickness and corner radius. The result of this is a larger area for the FRP profile. The area of the FRP profile is almost a quarter larger which also results in a larger moment of inertia. When only looking to the aesthetics of the profiles it can be said they are the same.

4.2 Production

FRP profiles like these are produced by pultrusion. This is a process almost only used in the fiber reinforcement industries. In principle the profiles are being pulled through a mould instead of being pushed. This because its need to cure before getting some strength. Since the fibers form the heart of the profile and also form the beginning of the profile the process is continuous. The mould through which the profiles are pulled determines the shape. It may be clear these profiles are copied from steel profiles. This is mainly because these shapes are very efficient in their strength to weight ratio. However, in principle the FRP profile can almost have any shape as long as it has the same cross section on both ends. This means additional material can be introduced to increase the area and by that its moment of inertia. The mould which is used during the process is the most expensive part which only becomes efficient after producing a great amount of profiles. This in general means either you pay a lot of extra money for the profile you want or you have to choose one of the offered profiles on the consumer market.
Steel profiles like these are produced by hot or cold rolling. It could also have been done by extrusion but this is a more expensive production method. There is less freedom of form using this process which means possible adjustments to the shape are limited. When these profiles were produced by extrusion, which in general terms is exactly the same as pultrusion only the profile is being pushed through, they both would have had the same amount of freedom when it comes to the shape.

4.3 Structural

The differences in structural behavior are compared on a beam with on both sides a hinge, one of the most common situations in building constructions. The profiles are compared at the points of bending and bending stress. In most cases these two are determining the size of the profile. The calculations are included in the attachment. Two sizes are calculated and the last calculation compares a FRP I-beam with a solid wooden beam. Below the results are shown in the table.

Ipe-200

	Ixx	w	M	W	σ
GRP pultruded	2,36E+07	1,32E+02	43124400	2,36E+05	1,83E+02
Steel	1,94E+07	2,13E+01	43124400	1,94E+05	2,22E+02
GRP_*comparable*	1,19E+08	2,61E+01	43124400	7,93E+05	5,44E+01

Ipe-240

	Ixx	w	M	W	σ
GRP pultruded	4,89E+07	1,55E+02	67381875	4,08E+05	1,65E+02
Steel	3,89E+07	2,60E+01	67381875	3,24E+05	2,08E+02
GRP_*comparable*	2,92E+08	2,60E+01	67381875	2,43E+06	2,77E+01

Wood

	Ixx	w	M	W	σ
GRP pultruded	3,10E+06	9,35E+00	2405700	5,17E+04	4,66E+01
Wood	8,71E+06	8,47E+00	2405700	1,45E+05	1,66E+01
GRP_*comparable*	3,42E+06	8,47E+00	2405700	5,70E+04	4,22E+01

Figure 2: results max. deflextion and stresses

In all three cases the FRP profiles turns out to flexible. The deflection shown for steel is the max deflection allowed which means the deflection or the FRP profile is over six times too large. When both profiles would have been exactly the same this factor would be 7.5 since the young's modulus determines the stiffness at that point:

E_{steel} = 210.000, E_{GRP} = 28.000 210.000 / 28.000 = 7.5

This material property cannot be adjusted very easily so the simplest thing to do is to increase the moment of inertia. The last line in the tables shows the moment of inertia when the FRP profile is about to have the same deflection as the steel profile. In both the steel cases, the FRP would not be strong enough even if a solid profile would be used. A comparative profile in case of the IPE-200, would have a height of at least 300 mm. This increase in size however still means the FRP profile weight less. Some adjustments to the FRP profile could improve its behavior but in general the most interesting part will be the weight of the profiles.
The last table shows a comparison between wood and FRP. The wooden profile used is a solid one which has a moment of inertia about three times that of the compared FRP profile and a modulus of elasticity two and a half times lower.

I_{GRP} = 3.100.000, I_{wood} = 8.710.000 8.710.000 / 3.100.000 = 2.8
E_{GRP} = 28.000, E_{wood} = 11.000 28.000 / 11.000 = 2.55

This in principle means the wooden profile will be stiffer. The calculations indeed show this is the case but they also show the FRP profile can be just as stiff by simply increasing the thickness by a mm. This results in a profile which weights less than a wooden profile and about a fifth of the material is used. The conclusion from the above analyses therefore will be, the strength of a FRP profile is of a complete different scale then that of steel, in comparison with wood this is just the other way around. The stiffness of the material probably will not be the reason why one chooses a material like this. The weight on the other hand is far more likely to be the reason one chooses FRP as structural material. This is the result of the specific strength ratio of FRP being better than that of steel.

4.4 Thermal conductivity

The thermal conductivity of steel lays around 50 W/m.ºC while the thermal conductivity of FRP lies around 0.35 W/m.ºC. This thermal conductivity coefficient tells something about the insulation properties of a material. The measure of thermal resistance, the R-value of a material, combines the thermal conductivity and the thickness of the material into a comparable coefficient. The thermal conductivity of the materials which are considered good thermal insulators lies around 0.04, which makes FRP not in definition a good insulator but it conducts in such a way it could be used as window framing, something steel used to be but which as a result of all building regulations has become impossible. In theory one could use FRP constructional elements on the inside and outside of a façade. When designing details like this with steel, they would be considered huge cold bridges. However FRP materials can be used in situations like these.

4.5 Fire
Fire has always been one of the biggest issues with plastics. It is not their flammability but their service temperature which causes this problem. At a certain level steel suffers from the same problems but its operating temperature is higher. Steel can be used up to temperatures of 357 ºC and FRP can be used until a temperature of 190 ºC. Fire reaches easily temperatures above 1000 ºC, this means both materials are not able to stand. Due to the heat the materials will lose their strength and this eventually will result in a collapse of the structure. Building regulations dictate the duration of the structure standing. Both materials need additional protection in most cases to reach these limits. In case of steel this is not a problem since there are several solutions available. With FRP this is a problem since no solution has been offered yet. This generally means this material cannot be used in multiple story buildings. This problem needs to be solved in order to give FRP a chance on the consumer market as a constructional material.

4.6 Durability

	FRP	Steel
Flammability	slow-burning	non-flammable
Water (fresh)	excellent	acceptable
Water (salt)	excellent	limited use
Weak acids	acceptable	limited use
Strong acids	unacceptable	unacceptable
Weak alkalis	limited use	acceptable
Strong alkalis	excellent	limited use
Organic solvents	limited use	excellent
UV radiation (sunlight)	fair	excellent
Recycle	no	yes
Downcycle	yes	yes

Unacceptable: Do not use in the unprotected condition
Limited Use: Not recommended, although may be suitable for short term applications
Acceptable: May require additional protection
Excellent: No degradation in material performance expected after long term exposure.

Poor: days/weeks
Fair: moths/years
Good: years
Excellent: tens of years +

(Source: CES EduPack 2011, Granta Design Ltd)

Figure 3: Durability properties *(Source: CES EduPack 2011)*

The durability of both materials is very important if it comes to selecting one. The table above shows the behavior of FRP and steel in fluids and sunlight, on the right the terms are explained. These topics are less exact compared by the mechanical properties, hence they are not shown as numbers but in terms. The weak and strong alkalis are types of fluids which normally do not occur in building constructions which makes them less important. FRP does not perform very well when exposed to organic solvents and UV radiation. Steel on the other hand performs excellent which at first sight makes steel the prefect material when exposed to sunlight. However there is a large number of additives which can improve the performance of plastics. With the help of these additives FRP can also perform excellent when exposed to sunlight or organic solvents. The use of additives cannot be applied to steel this is the result of the chemical components and the bonding between them. As a result of this, steel cannot easily be transformed into a material which performs well on a specific topic. For FRP this means its biggest advantage lays in its performance in water, both fresh and salt. With the help of coatings, steel can be adjusted but these wear off and need a lot of maintenance. It is therefore FRP profiles are widely used on offshore projects like oil platforms and windmills in structural way. This property makes the material interesting in certain design fields.

4.7 Finishing
Steel profiles are completely opaque. FRP profiles on the other hand can be translucent as well. The amount of translucency is determined by the amount of glass fiber used. The more fibers, the more transparent the profile becomes. This transparency can contribute to the architectonic visions and design. A semi transparent construction could be a possibility.
All colors are possible with FRP profiles. During the production process, pigments are added to the matrix which paints the profile through and through. This could influence the translucency of the profile. Steel profiles cannot be colored during the process but only afterwards. This in general means maintenance. Without surface treatment, the FRP profile has a rough surface compared to steel. This is the result of the production process, the curing. This should not be a problem in most cases but if so, the surface can be made perfectly flat by grinding.

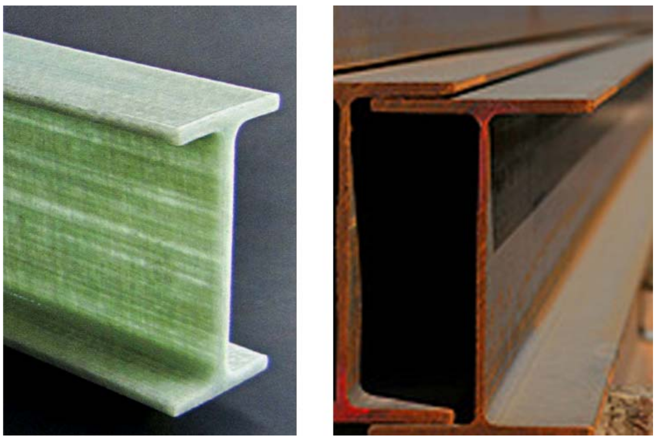


Figure 4: left-FRP profile, right-steel profile

4.8 Cost

What are the costs of these profiles? The prices of the profiles are determined by the material used, production method, badge size, tooling costs, popularity etc. Because all of this it is difficult to determine a realistic comparative price for these profiles, on the other hand the price used on the consumer market is the one to be paid.

	Weight kg/m	Material Price €/kg	Profile /100kg in €	Profile €/kg	Profile /m in €
FRP	6,99	3,33	699,00	6,99	67,95
Steel	22,40	0,54	112,00	1,12	25,09

Figure 5: Price per meter profile *(Source: www.bouwkosten-online.nl, shop.fibrolux.com)*

Figure 5 shows the costs per meter profile. FRP is about 2.5 times as expensive as steel. If we take a look at the costs per kg this factor is almost 7. The material costs play a big role in this since they in both cases represent half of the price. The other half is determined in the production and the popularity of the profiles. Steel profiles are far more common than FRP profiles. This results in smaller badge sizes and higher unit costs. However it is unlikely the FRP profiles will ever reach the same level in price as steel since the material costs itself are 7 times higher. The large difference in costs plays an important role in the decision process especially when combined with the strength of the profiles. When talking about maintenance costs, the FRP profiles are more interesting.

4.9 Working and connection possibilities

Steel is often connected using bolts or being welded. Both these options result in strong connections. Welding is permanent while bolting can be used as a temporary connection. It are the working possibilities of steel witch can hold back the use of steel. In principle one needs special tools to make adjustments to a profile.

FRP profiles can be connected using bolts or making a glue connection. Using bolts delivers a strong connection but often additional reinforcement is needed since the holes in the profiles, needed for the bolts, damage the fibers and therefore affect the strength of the profile. The alternative to this is gluing the profiles, this however is not very common in structural situations. The possibilities to make adjustments to the profile are much larger for FRP since almost all conventional tools can be used to make adjustments. This can be an advantage in the use of FRP profiles, however the connection possibilities are far more likely to form a disadvantage.

4.10 Material alternatives

Fiber Reinforced Plastics know many compositions with all different properties and thus behavior. The most common combination, polyester matrix with E-glass reinforcement, has been calculated. However there are alternatives which are stronger but also more expensive. The figure below shows a graph with the specific strength compared by material price. The blue dot represents the material used in this comparison. The orange ones are the only materials which would give better results when it comes to strength, however they are also far more expensive and as a result of that not a real option.

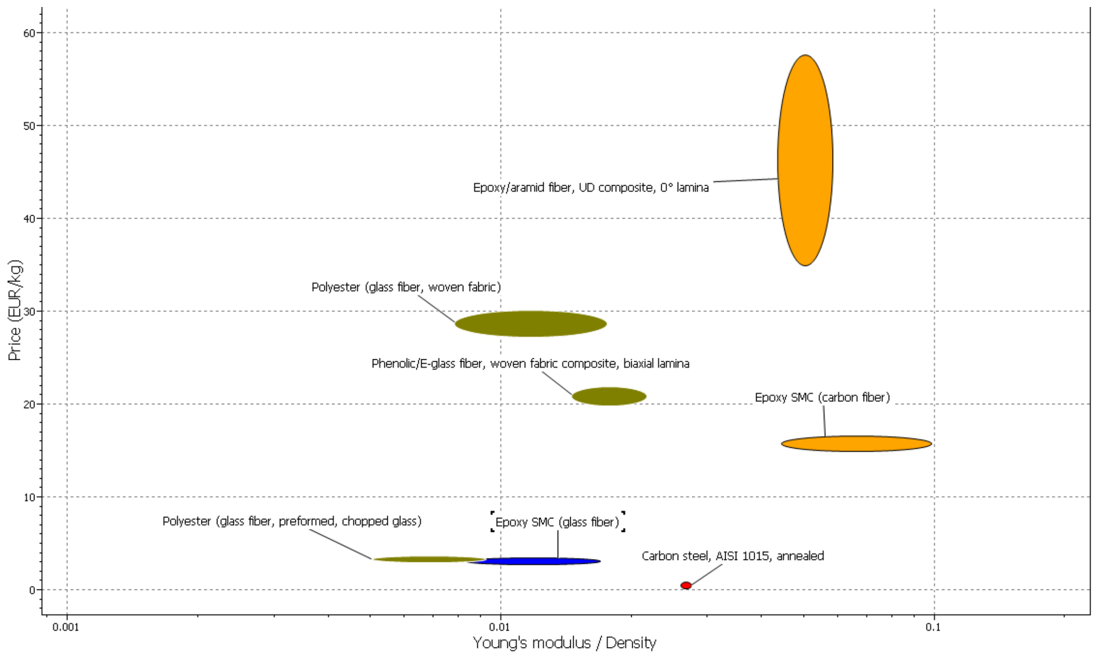


Figure 6: Alternative composite materials *(Source: CES EduPack 2011 Granta Design)*

4.11 Conclusion

Which material should one choose in combination with the profile? The answer to this question would be a combination of the previously discussed topics. If strictly speaking every aspect and every property would have the same value one should choose the FRP profile above the steel profile (figure 7). However in reality this would never be the case, especially since money almost always is one of the discussion topics. The combination of steel performing better in a structural way and being cheaper makes this material in a lot of situations the perfect choice. On the other hand, FRP profiles do have properties which makes them irreplaceable. FRP-profiles could be considered a product only to use in special situations.

	Shape	Production	Strength	Weight	Insulation	Fire	Durability	Color	Costs	Connection	Working		Score
FRP	1	1	0	1	1	0	1	1	0	0	1		7
Steel	1	1	1	0	0	0,5	0,5	0	1	1	0,5		6,5

Figure 7: Results of the compared beams

In general one should choose FRP profiles if:

- the specific strength, and therefore weight plays an import role
- the construction is located on the outside or in-between the façade elements
- the construction will be exposed to fresh or salt water
- the construction is part of the architectonic expression, translucency, color and possible adjustments to the shape
- the profiles need to be worked on site as a result of the type of project

Steel profiles should be chosen when:

- strength is extremely important
- money is a serious issue
- extremely strong connections need to be made

5 Floor Systems Compared

What are the specific properties of pultruded planks compared by traditional flooring systems?

Hollow core composite elements used for pedestrian bridges or on offshore structures might be suitable for the use as a flooring system in buildings. Since floors are more than just the walkable surface on the visible side, research needs to be done about the specific properties in order to tell if composite elements can fulfill this role. If so, are their advantages in their use compared to traditional flooring elements and systems? In this case only hollow core elements are reviewed, sandwich constructions will be discussed in chapter 6.

5.1 Composition

Figure 1: Fiberline plank HD *(source: www.fiberline.com)*

Figure 2: Bothwell plank *(source: www.bothwellplanks.com)*

Figure 1 and 2 are examples of hollow core planks which are used on bridges and scaffold constructions. Traditional flooring elements are often made of wood or concrete. Depending on how one looks at these, a wooden deck consists of planks and beams which can be considered one which means the FRP elements are both planks and beams. The Scandinavian company Lignatur produces hollow core elements which can be used as flooring and at the same time fulfill a constructive role. They are assembled out of several wooden elements to receive their final shape. Concrete elements are most of the time a lot bigger since they are less strong, the principle however is the same. These hollow compositions offer the possibility of putting in cables or other devices which need to be transported without being seen. They also reduce weight as a result of the hollow sections.

Figure 3: Lignatur surface element *(source: www.lignatur.ch)*

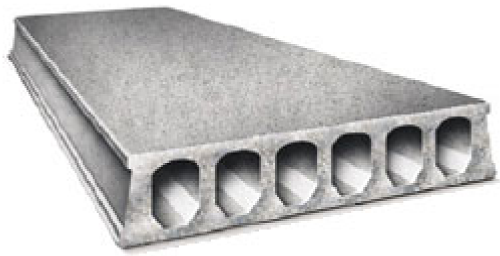


Figure 4: Hollow core slab *(source: www.concreteindustries.com)*

5.2 Production

The biggest difference between the three materials and its elements is the production of the wooden element. Both composite and concrete are build from a liquid substance which cures having its final shape as a result of the used molds. Wood on the other hand is harvested from the woods and sawn into useable elements. These elements are used to assemble the Lignatur element. By doing so the size of the elements is completely free and can therefore be adjusted to whatever the situation might be. The concrete hollow core slabs are produced by casting with lengths up to 130m. Steel reinforcement bars are placed in the gabs between two slabs, since concrete is unable to handle large bending forces. The size of the element is determined by the size of the mold, which virtually can have any size. The standard hollow core slabs have a width of 1.20m and a variable length, depending on the span. The FRP elements are produced by pultrusion. In this continuous process the length of the elements can be anything but the width is limited to certain sizes. The overall size of the element should not exceed 650 – 1250 mm and the section thickness must lie between 0.5 – 100 mm. The upper limit is one only specialized companies can make. A large difference between the process used for the FRP elements and the ones used for wood and concrete is that they can take in additional elements and shapes which is something the pultrusion process does not support. All adjustments have to be made afterwards.

5.3 Structural

The concrete hollow core slab elements are of the three elements the ones which are most standardized. Therefore their sizes will be used in the calculations. HPV 150 is the smallest element, this is the one which is used. Figure 5 shows the allowable load on different elements. 13.5 kN/m^2 is allowed by a span of 5 meter. This graph is based on a deflection of 1/300 of the length. Figure 6 shows the allowable load on a Lignatur element. In case of the 5 meter span and an element with a height of 160 mm, 5.3 kN/m^2 is allowed. Both figures have taken the own weight of the elements into account.

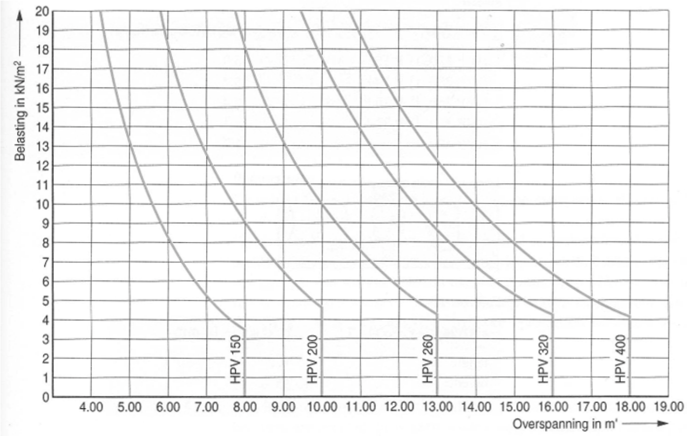


Figure 5: Loads and spans, hollow core slabs *(source: bouwkunde tabllenboek*

The FRP elements which are shown in figures 2 and 3 are planks and no floor elements. A larger version of these elements however could become part of a flooring system. The dimensions used for these elements are the same as the Lignatur element: 1000*160 mm with a section thickness of 31 mm. The element has 5 ribbons that connect the lower and upper part of the element. Figure 7 shows the results of the calculations on the FRP element accompanied by the results of wood and concrete. Calculations are based on a maximum deflection of 1/300 of the length.

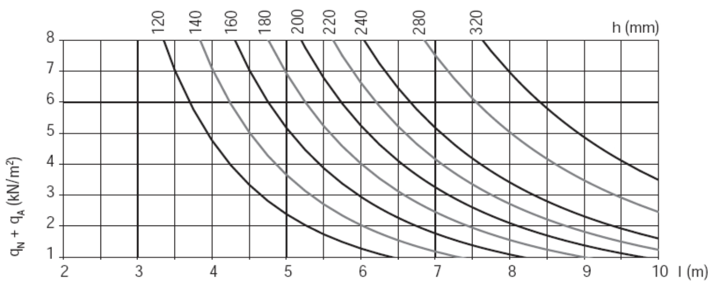


Figure 6: Loads and spans, Lignatur elements *(source: www.lignatur.ch)*

Max deflection	Load kN/m2	Weight kg/m2	Ratio load/weight
FRP	15,75	139	0,11
Wood	6,15	36	0,17
Concrete	13,5	263	0,05

The calculations show that the FRP element is the stiffest since it is able to hold 15,75 kN/m^2. Wood turns out to be the weakest but it is also the lightest. The last column shows the ratio between the load and the weight. Wood shows the best results in that case. However, the load given for wood is good enough for dwelling but it is too low for utility buildings which means the profile needs to be bigger if it want to meet the requirements. The Lignatur element will not stand during fire since this element is based on a fire endurance of 30 minutes. The section thickness is to be doubled if this element is used in a multiple storey utility building. This increases the weight but since the overall dimensions of the element are not changed the stiffness changes only a little. Concluded from the calculations:

- FRP should be used when construction height and stiffness are more important.
- Wood should be used when the lightest element is wanted
- Concrete should be used when weight is important

5.4 Thermal Conductivity

The thermal conductivity of FRP lies between 0.7 and 0.35 W/m.ºC depending on the composition of the material. Wood has a thermal conductivity of 0.27 W/m.ºC which is slightly better than FRP. Concrete on the other hand has a thermal conductivity of 2.7 W/m.ºC which is worse than FRP. In case of FRP and wood elements with exactly the same dimensions, the wooden element performs better. However the difference between the two is very small which makes this not a criteria to decide on. The hollow cores can be filled with isolating material in order to make its performance better. The result of this will be an element which can be used on the outside and inside, if only considering the insulating properties.

5.5 Fire

Fire endurance is probably the most important criterium for these elements. Since they are part of the primary construction in most cases, they need to stand at least 60 minutes under fire load. As buildings become higher this time increases to 120 minutes. None of the elements is able to reach that time limit. The concrete hollow core slab can only withstand 60 minutes of fire. When the elements would be 260 mm height, this could be 90 minutes and a height of 320 mm can withstand 120 minutes of fire load. Normally, there are on both sides of the concrete element other layers like pressure layers, which can help increase the fire endurance. The Lignatur element is based on a fire endurance of 30 minutes which is not enough, this can be upgraded to a maximum of 90 minutes. 120 minutes should be possible but then the element would be solid which in the end is not the concept behind this product. The elements from Fiberline and Bothwell are not tested for fire endurance since they are not supposed to be used on the inside of buildings. Given their density, specific heat capacity and maximum service temperature, they might perform slightly better than the wooden elements but it still would not be enough. Additional measurements need to be taken. Liquid cooling might be an option. As mentioned before, this is an experimental idea which gives promising results. If a m² of the FRP element is filled with water this comes down to 82.5 kg. In this case the element is still lighter than concrete and it is likely to perform better during fire. If this concept turns out to work, this might be the lightweight solution for flooring systems.

5.6 Durability

	FRP	Wood	Concrete
Flammability	slow-burning	highly flammable	non-flammable
Water (fresh)	excellent	limited use	excellent
Water (salt)	excellent	limited use	acceptable
Weak acids	acceptable	limited use	limited use
Strong acids	unacceptable	unacceptable	unacceptable
Weak alkalis	limited use	acceptable	acceptable
Strong alkalis	excellent	unacceptable	unacceptable
Organic solvents	limited use	acceptable	excellent
UV radiation (sunlight)	fair	good	excellent
Recycle	no	no	yes
Downcycle	yes	yes	yes

Unacceptable: Do not use in the unprotected condition
Limited Use: Not recommended, although may be
Acceptable: May require additional protection
Excellent: No degradation in material performance expected after long term exposure.

Poor: days/weeks
Fair: moths/years
Good: years
Excellent: tens of years +

Figure 7: Durability properties *Source: CES EduPack 2011*

If it comes to the durability of the elements, there are several differences. If it comes to chemical resistance and water, FRP performs best. However recycling and UV radiations are weak points. In most cases the UV radiation is upgraded to excellent due to UV stabilizers in the resin of the product. Like wood, FRP is insensitive for deformations like warping and splitting, this makes the material more reliable. These elements could be used on the inside and the outside at the same time since they form no thermal leakage and they, unlike wood, do not absorb water.

5.7 Finishing

In principle the surface of a FRP pultruded element is smooth and flat. Every desired structure other than this comes in the form of additional material. Wood has its fiber structure but other than that it has a smooth surface. Concrete hollow core slabs are smooth but it is possible to add structure to the mould. FRP can be translucent were as wood and concrete are always opaque. FRP and concrete can be colored during curing but in case of concrete colors are limited.

5.8 Cost

The costs of these elements are difficult to compare since the FRP profile is not on the market. However since the raw material prices of both concrete and wood are comparable with steel it is likely these floor elements will be less expensive. A concrete hollow core slab of 160mm costs about €40,-/m² which includes labor. The costs of the Lignatur elements are not found but a composed wooden floor costs about €55,-/m² including labor. Since the Lignatur elements are of a unique kind they probably are a bit more expensive. The costs of FRP planks with a width of 500mm and a height of 40mm are €95,-/m² according to Fibrolux. This element is only a fourth of the calculated profile. The die costs are the most expensive and determine the bigger part of the element price. However an element this big is likely to cost at least €200,-/m² which makes it far les interesting to use than ones made of traditional building materials. The price tag on these elements will be in many cases the most important decision criterium.

5.9 Conclusion

Just as with the I-profiles, the decision on which material to use depends on a combination of the topics discussed topics. Again FRP scores well and on first sight seems to be the material of first choice but also this time topics like costs weight far more than others in many cases. Concluded form the above, FRP flooring elements in this shape probably only will be used in very specific situations.

	Shape	Production	Strength	Weight	Insulation	Fire	Durability	Color	Costs	Connection	Working		Score
FRP	1	1	1	0,5	0,5	1	1	1	0	0,5	1		8,5
Wood	0,5	0,5	0	1	1	0	0,5	0	0,5	1	1		6
Concrete	0	0	0,5	0	0	0,5	0,5	0	1	0	0,5		3

Figure 8: Results of the compared flooring systems

6 Sandwich Constructions

How do sandwich constructions work and what are their specific possibilities?

Sandwich elements are responsible for two main functions when building with fiber reinforced plastics. Increasing the load-carrying capacity beyond that of a thin laminate, and thermal insulation. Besides these possibilities there are some other advantages to sandwich elements.

- Huge potential for lightweight structures due to high specific strengths
- Resistance to aggressive media
- Low thermal conductivity
- Diverse design options in terms of form and transparency
- Adjustability of material properties through additives
- Integration of functional and constructional components

6.1 Composition

Sandwich elements consist of several material layers. The basic composition of a sandwich element consists of two surface layers and a core. In most cases the surface layers consist of a fiber reinforced plastic and the core of a foam (figure 1.2). These are the combinations which can fulfill a load bearing function. Sandwich elements can also exist of different thermoplastics (figure 1.1). These lightweight building element are used as insulating panels or façade cladding, in which case these products can be translucent or even transparent. However these types of sandwich elements are unable to fulfill load bearing functions. In the framework of research topic, they will not be reviewed. Only the combinations with FRP will be discussed. It will become clear that even in that category a great variety of combinations can be made. Recent research has shown promising results on combinations of several sandwich elements, which opens the door for new combinations. One of the options could be the assembly of a sandwich panel which contains several different layers which all fulfill different functions. The research will be reviewed in paragraph 6.8 of this chapter. The maximum dimensions of a sandwich element are difficult to determine since different materials can be used but for example a length of 15m and width of 3m can be reached. Besides that several elements can be combined into one single shape. In paragraph 6.14 about connection possibilities more about this will be explained.

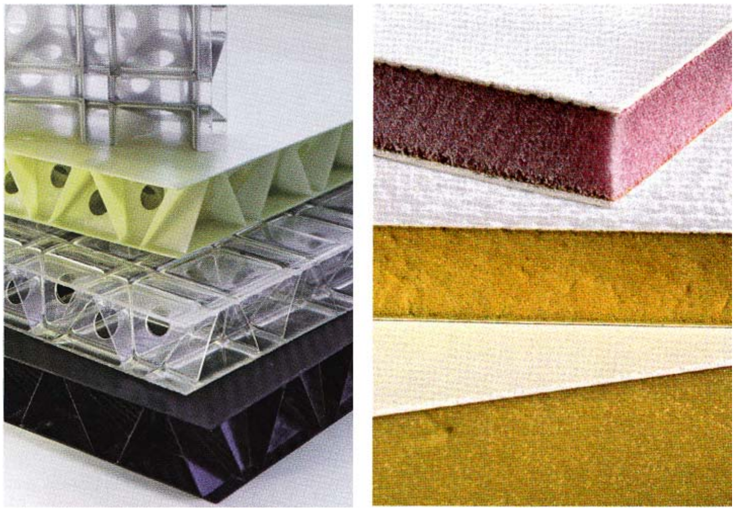


Figure 1: 1. Thermoplastic 2. Thermoset + foam *(source: Plastics in architecture and construction)*

6.2 Core materials[4]

There are various types of core materials available which can be used in sandwich elements. Figure 2 shows a graph with the main categories. Foams represent the largest group mainly because they are superior in transferring the loads compared to the other groups. The main focus will be on foams in this part of the research but the other groups will be discussed as well. In principle the core transfers the shear between the facing plies and at the same time can function as thermal insulation. The lower self-weight of sandwich elements enables economic forms of construction and longer spans than are possible with solid components like the ones discussed in previous chapters. Sandwich elements made from polymer foams in most cases have the best building physical and mechanical properties. When the elements do not have to be translucent they are material of first choice in most cases. Three-dimensional forms can be made with foams but this is an expensive process, in this case hollow

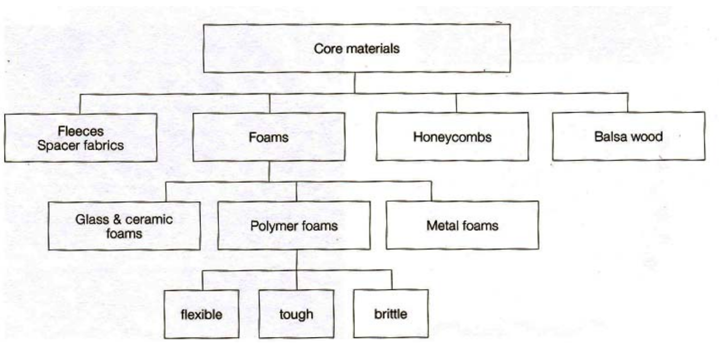


Figure 2: Systematic classification of core materials *(source: Construction manual for polymers + membranes)*

[4] Knippers J., Cremers J., et al, *Construction Manual for Polymers + Membranes,* (Munich, 2011)

structures with honeycomb cores are more economical but they on the other hand have poorer insulation properties and are more difficult to work with. They also have poor drapeability properties which limits the freedom of form. The biggest advantage of honeycomb cores when used in combination with transparent plies is the ability to make light-permeable elements. Balsa wood is another material used for cores but this is mainly used for thin structures. In case the sandwich element has a load bearing role, balsa wood is not often used. The sensitivity to moisture can be a problem in some cases but mainly the mechanical properties of balsa wood lie below those of rigid foams which makes them less interesting. Sandwich elements require local reinforcement with steel, aluminum or polymer sections in order to carry loads at supports or connections because the core materials usually have only relatively low strengths.

6.3 Foams

Foams either have interconnected open cells or closed cells with continuous, enclosing walls. This depends on the material used and the production method. A combination between open and closed cells is also possible, hybrid forms. The closed cell variants protect against infiltration of fluids. Figure 3 shows different types of foams with some properties. One might notice the bigger part of the materials having a closed cell structure.

Polymer	Class	Density [kg/m³]	Form of supply	Cells	Applications
PE	flexible	25–40	Sheets, blocks, moulded items	closed	Cushioning, packaging (particle foam)
PE-LD	flexible	10–35	Sheets	closed	Thermal & impact sound insulation
	flexible	200	Structured foam boards	closed	Impact sound insulation
PP	flexible	10–35	Sheets		Thermal & impact sound insulation
	flexible	20–90	Moulded items, sheets		Energy absorbers in cars (bumpers, seats, roof lining – textile-covered), filling foam behind facing plies, in-mould skinning
	flexible	100–500	Foils, suitable for deep-drawing	closed	Meat packaging, meal trays, cutlery, bungs
	flexible	500–700	Structured foam foils & tapes		Packaging tapes, insulating foils
EVAC-X	flexible	40–260	Coiled	closed	Insulated clothing, rubber-like
PS	tough	10–30	Blocks, moulded items		Thermal insulation, packaging (particle foam)
	tough	>20	Extruded sheets & tapes with/without skin	closed	Frost protection for pipes, roads & railways
	tough	60–200		closed	Cardboard packaging, paper coating
	tough	60–200	Hot-formed foils		Egg-boxes, meal trays, disposable cutlery
	tough	approx. 60	Sheets, milled (felted)		Impact sound insulation
	tough		Sheets	closed	Road sub-bases (for increasing load-carrying capacity)
	tough	400–500	Sheets, sections	closed	Interior fitting-out with surface texture, decorative panels
	tough	20–25	Moulded items (lost foam), also PS/PMMA copolymer		Models for lost-foam casting, e.g. lightweight metal cylinders, casting foam technology
PS/PP-E	flexible/ tough		Sheets, moulded items		As for PS but better thermal stability, car linings, lightweight cycle helmets
PVC-U	tough	40–130	Panels & blocks	closed	Core material for sandwich panels, liquid gas insulation, life-rafts, etc.
	tough	500–700	Extruded sheets, suit. for hot-forming, d = 2–20 mm		Building material, linings & cladding
PVC-P	flexible	50–150	Panels & blocks	closed	Exercise mats, attenuation of machine vibration
	flexible	70–130	Panels & blocks	open	Sound insulation, gas-permeable foam cores
	flexible	250	Rolls		Backing to floor coverings
MF	flexible	approx. 10	Sheets	open	Sound absorbers, heat shields, decorative panels, preformed insulation for pipes & vessels
PMI	tough	30–300	Panels, d = 1.65 mm	closed	Structural components in aircraft construction, core material for sandwich panels
UP	brittle		Lightweight elements	hybrid	Reactive resin foamed concrete
PUR	flexible/ tough	30–300	Blocks, sheets, moulded items	hybrid	Furniture, mattresses, vehicle interiors, preformed insulation
PF	brittle	40–100	Sheets		Insulating material

Figure 3: Forms of supply and applications *(source: Construction manual for polymers + membranes)*

There are three types of polymer foams: flexible, tough and brittle. The sandwich element has a load bearing function only the tough foams are optional since the others lack of mechanical properties. However all types can be used as insulating product. Generally the choice on which foam to use will be based on a compromise between strength, thermal performance and cost. For sandwich structures with FRP as ply material only closed cell foams can be used. Open cell structures absorb the resin material which compromises the structure. PVC-U is a particularly suitable material for FRP sandwich structures, but there are others as well which can do the job. As figure 3 shows, there are large differences in density. Generally, the heavier the foam within one type of material, the better the mechanical properties. This means that in case of structural elements a consideration has to be made about the strength, weight and in particular the ratio between those two. In case of sandwich panels it possible to foam up the core directly between the facing plies instead of using blocks. However the accuracy of a method like this is not always good enough. Figure 4 shows the relation between ultimate stress and thermal conductivity for different types of foams. The three tough types will be reviewed a bit more in depth.

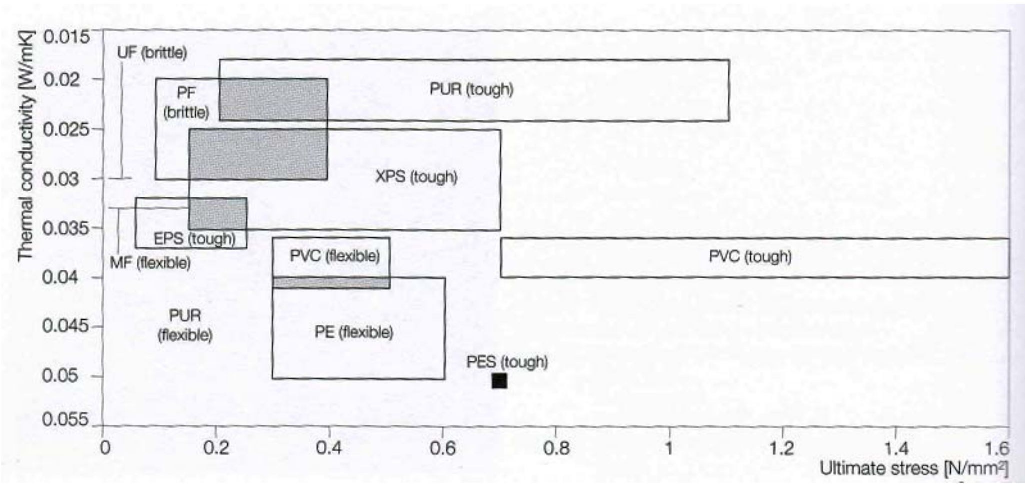


Figure 4: Ultimate stress vs. Thermal conductivity *(source: Construction manual for polymers + membranes)*

Polystyrene foams (EPS, XPS)
Polystyrene foams are tough and exhibit relatively good thermal insulation properties, but have a rather low load-carrying capacity. EPS has a white color and is primarily used for insulation applications where there can be no direct contact with water. XPS has a finer pore structure and is available in various colors depending on the manufacturer. This type is waterproof because of its closed cell structure. The mechanical properties of XPS compared to EPS are much better. Both types can be used as core material in sandwich elements made with FRP's. Compared to other types of foam they are weak but on the other hand they are cheap as well.

Polyurethane foams (PUR)
Polyurethane can be used as the raw material for foams with very diverse properties. Elastomeric foams and tough rigid foams with good load bearing properties can be produced. PUR has very good adhesive properties and they are therefore often used in a process where they are directly foamed against the facing plies. One disadvantage of PUR is their urge to absorb the resin material when this is curing. Nevertheless this material is often used as a core material in sandwich structures given its good ratio between strength and price. Besides that the shaping processes which can be used on this material are very accurate for example CNC milling.

Polyvinyl chloride foams (PVC)
Polyvinyl chloride foams are also available in flexible and tough variants. They have better mechanical properties than the other polymer foams. PVC hardly absorbs any resin material which makes it a perfect core material. The high production costs make that PVC is only used when the load-carrying capacity is very important. Their thermal insulation properties are almost half of that of PUR.

Figure 5 shows the relation between the modulus of elasticity and the density. As said before, the heavier the foam, the stiffer it becomes. There is a very clear linear line visible between these material properties. However what their real relation is, is shown in figure 6. Relative strength and stiffness are compared and show surprising results. The foam types that score best in this comparison are not the ones with the largest modulus of elasticity. In practical terms this means, when one uses the best results from the graph with the relative strength and stiffness, the construction will be the lightest but probably also will have larger dimensions since the strength requirements need to be reached. Depending on the span length and the type of design this might be a problem or not.

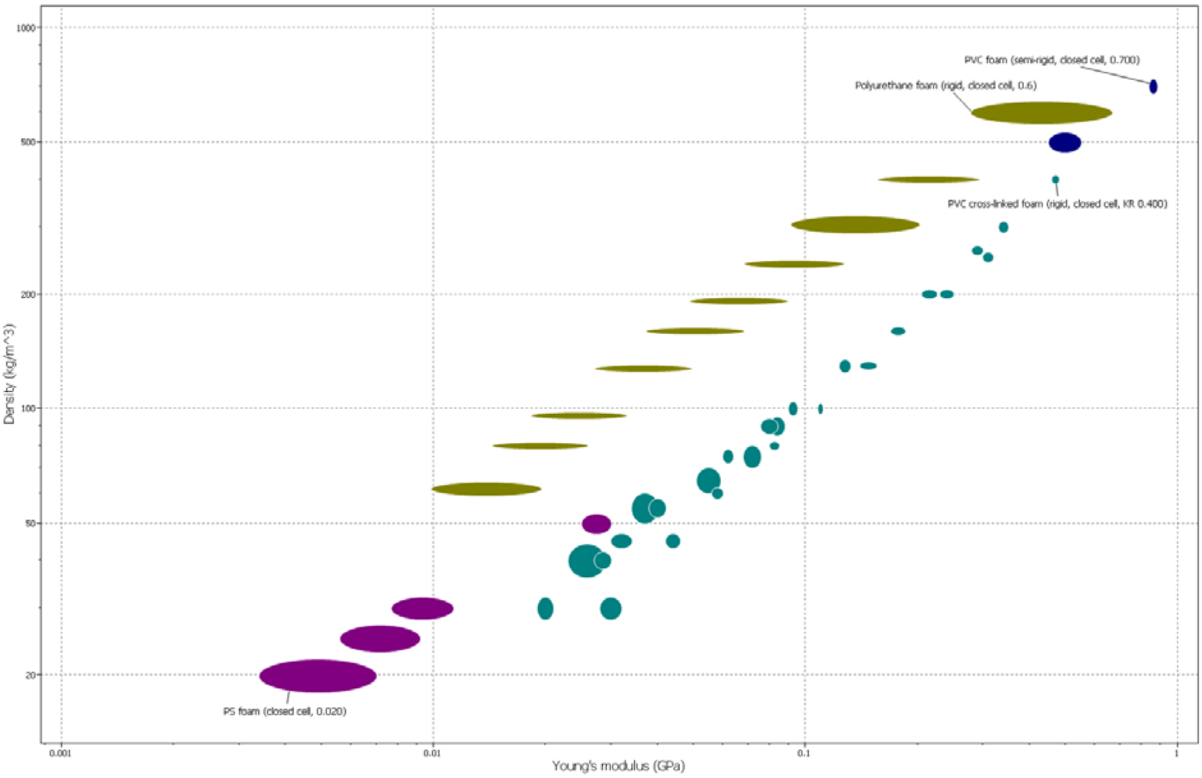


Figure 5: Y_density – X_youngs modulus *(source: CES EduPack 2011)*

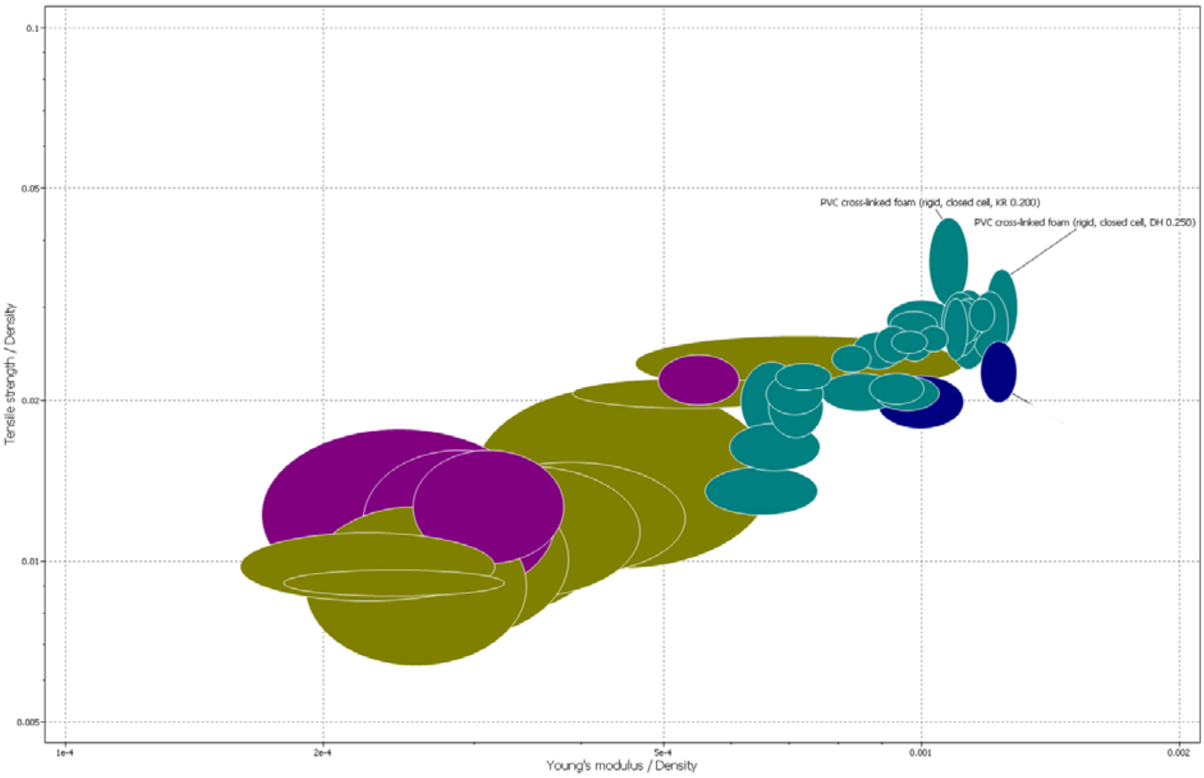


Figure 6: Y_relative strength – X_relative stiffness *(source: CES EduPack 2011)*

Figure 7 shows the relation between the thermal conductivity and the modulus of elasticity. Again the PVC foams perform best but it is also visible there are various options available within one material type, all with specific properties. In principle PVC would be the material of first choice but after listing the requirements for the element to be made, this might change. The PS foams only perform good when it comes to thermal insulation as mentioned before. PUR seems to have a position between PS and PVC when it comes to strength but not when it comes to thermal insulation.

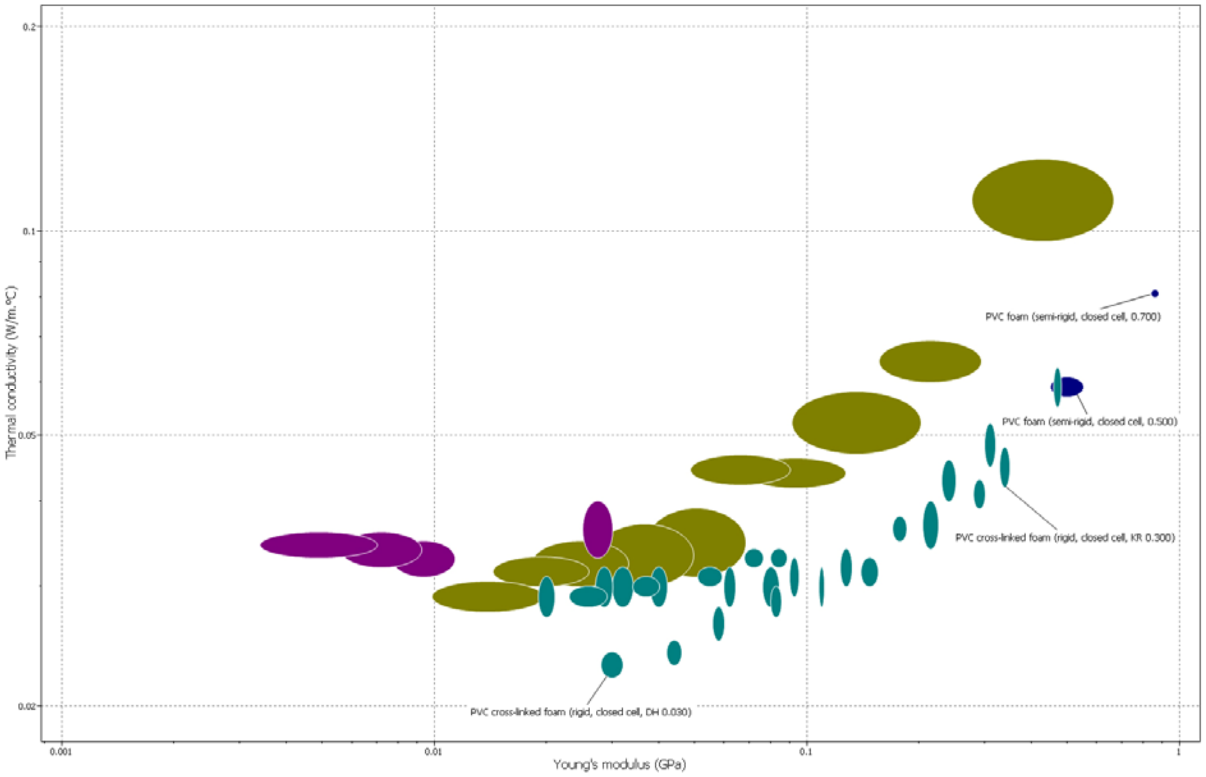


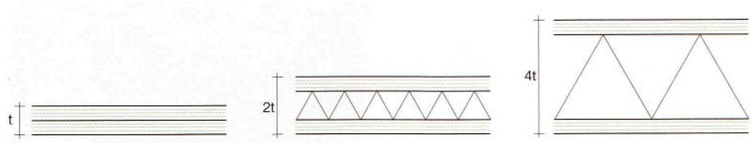
Figure 7: Y_thermal conductivity – X_youngs modulus *(source: CES EduPack 2011)*

6.4 Honeycomb cores

Honeycomb cores are even more lightweight than foam cores and they also offer the possibility of permitting light. In general they are less expensive and depending on the system used, very high load-carrying capacities are possible. Honeycombs are used in combination with FRP and translucent thermal insulation. However, the voids of the honeycomb elements are much larger than the ones form the foam core which makes them a poorer insulator. Materials which can be used to create a honeycomb are: aluminum, aramid impregnated with phenolic resin, PP, PET and glass fiber reinforced polymers. The facing plies will be bonded or laminated directly to the honeycomb core in order to produce a sandwich element. The drapeability of honeycomb cores is limited, which is why they are primarily used for flat or only gently curved sandwich panels. The thickness of a honeycomb lies normally between 1.5 and 90 mm.

6.5 Production

Why one should use sandwich elements when it comes to strength and weight is shown in figure 8. The middle part of the element contributes little to nothing when it comes to load-carrying capacity. So when this is made of a more light material which is able to bond the outer layers together a reduction in weight can be achieved. In terms of production there are in principle two outer layers made from a fiber reinforced polymer and a core material most likely to be made out of foam. The connection between the facing plies and the foam is made by the resin itself. The foams used can be shaped by using CNC milling machines. They then also function as mould. Depending on how one reviews this principle it can be economically or not. The foam shapes can be considered permanent formwork with little need for additional moulds but on the other hand only one element can be made in a way like this. Foams are relatively expensive materials which makes the use of them in some cases not profitable. Voids with ribs are a more economic way of producing larger elements but they are on the other hand more complex to produce. When there are complex shapes involved almost all elements will be made with hand-lay-up methods. Compression moulding and vacuum techniques are also possible but in most cases larger batch sizes are required. However the results are more reliable since the placing of the fiber can be automated which results in a very constant quality regarding the mechanical properties. All methods are explained in chapter 2.



Depth of element	t	2 t	4 t
Stiffness [1]	1.0	7.0	37.0
Load-carrying capacity [1]	1.0	3.5	9.2
Weight	1.0	1.03	1.06

[1] in bending

Figure 8: Sandwich principle *(source: Construction manual for polymers + membranes)*

6.6 Calculating

Calculating composite structures on bending stress and deflection cannot be done straight away with the normal formula's since they assume the elements are made of a homogeneous material. One method to work with these formulas is to transform the composite element in one made of a homogeneous material. This is called the transformed-section method. Figure 9 explains how this method works. If one considers a composite beam made of two materials which have the cross section shown in part a. If a bending moment is applied, the normal strains will vary linearly from zero at the neutral axis to a maximum in the material located farthest form this axis (part b). For each material the normal stress can be determined by: $\sigma = E_1\varepsilon$ and $\sigma = E_2\varepsilon$. If material 1 turns out to be much stiffer than material 2, which is the case with FRP and foam, most of the load will be carried by material 1 since $E_1 > E_2$ (part c). Location of the neutral axis and determination of the maximum bending stress will be based in this case on trial and error. A simpler way to deal with situations like these is to transform the composite element into one made of a single material. In this case the height of the element stays the same in all cases since the strain distribution must be preserved. The width of the elements will vary due to their different modulus of elasticity.

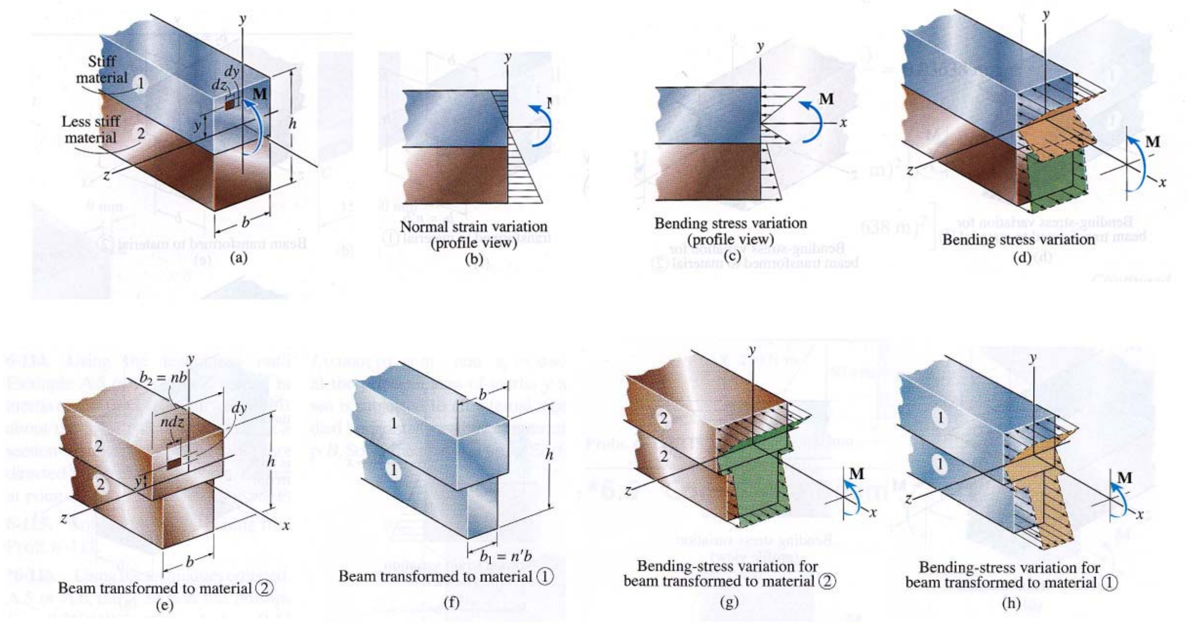


Figure 9: Explanation on the transformed section method *(source: Mechanics of Materials)*

The necessary width can be determined by considering the force *d*F acting on an area *d*A = *dz dy* of the beam. $dF = \sigma dA = (E_1\varepsilon)dz\,dy$. If the width of a corresponding element of *dy* is *n dz,* then $dF' = \sigma' dA' = (E_2\varepsilon)n\,dz\,dy$. Equating these forces , so they produce the same moment about the z axis:

$$E_1\,\varepsilon\,dz\,dy = E_2\,\varepsilon\,n\,dz\,dy$$

which results in:

$$n = E_1 / E_2$$

The dimensionless number *n* is called the transformation factor. It indicates that the cross section, having a width *b* on the original beam must be increased in width to $b_2 = nb$ in the region where material 1 is being transformed into material 2 (part e), or the other way around (part f).

6.7 Structural

Orientation of the fibers

The load carrying capacity of the elements is defined by the amount and direction of the fibers used. Especially the direction of the fibers plays a crucial role. This differs from pultruded elements in which almost all fibers are in the same direction. Hence the modulus of elasticity of for example GFRP differs when used in the pultrusion process or as part of a sandwich element since the fiber direction determines the stiffness. If the elements are only loaded in the direction of the span, it can be enough to have fibers only in that direction. However in this case transverse loads and shear stresses are directly carried by the matrix. Since this matrix can be considered only a stabilizing medium with very little load carrying capacity, these forces should be carried by the fibers. If not, delamination might occur. In sandwich elements often fiber textiles are used since they have fibers in various directions.

Creep
Polymers have an irreversible reaction to permanent mechanical actions. When under a constant load, the individual molecular chains of the polymer slide past each other which increases the deformations and can lead to failure. Depending on the amount of load, this process can come to a stop because the chains stick to each other. If the elements are subjected to high loads, the connection between the chains might break which then will result in failure. This behavior occurs more with thermoplastics than with thermosets, since they have cross linked connections between the chains. Creep is the increase in the plastic deformation of a material subjected to a constant load. This can be many times the original elastic deformation. Shortly after the application of the load this phenomenon start and continues until it reaches a maximum value. After the load exceeds a certain threshold, the deformation will start to increase disproportionately after a longer period of loading until the material finally fails. This limit is called the creep rupture strength. In calculations, the duration of the action must be taken into account. The estimation of the period of use and the conditions must be part of the design process. These criteria are incorporated directly in the calculations for the components by way of reduction factors.

Design concept
There are three influencing factors which have their effect on the mechanical properties of FRP. Also the material safety factors need to be taken into account. Especially the three factors, duration of loading, temperature and environmental influences are estimates. The advised safety factors for unreinforced and manually produced fiber-reinforced polymers is γ_m = 1.5 and for industrially produced materials γ_m = 1.2. These are however not the safety factors for the loads, they need to be included in the calculations as well.
Under normal circumstances, room temperature and no extreme environmental influences, it is the duration of loading that influences the mechanical aspects the most. The higher the fiber content, the less pronounced is its behavior over time because the fibers itself normally do not exhibit creep. When only loaded in the direction of the fibers the effect of creep will be minimal since it are the fibers who carry the load. This however only holds for tensional forces, in case of compression the matrix stabilizes the fibers against buckling which means the matrix carries the load. In case the matrix has to carry loads this changes since this increases the component's tendency to creep.
In a previous section of the report the behavior of polymers under certain environmental influences has been discussed. They show that especially FRP's can resist almost any kind of influence. Resistance to some of these influences can be improved by heat treatment, which is called annealing. The duration and temperature of the annealing process depend on the type of fibers, matrix and laminate thickness used.
Polymers lose their load-carrying ability when their maximum service temperature is exceeded. However the strength and elastic modulus are influenced at temperatures below the limit. This decrease is reversible as long as the service temperature is not exceeded. The type of load determines the influence, when only tensile forces are present the matrix does little to nothing if it comes to load bearing which makes it less vulnerable but in case compressive forces are applied the matrix has to stabilize which at a certain point will fail due to high temperatures.
A formula which can be used in order to determine the design value for the strength of the material is shown below.

$f_d = f_k / (\gamma_m * A_1 * A_2 * A_3)$

f_d = design value for strength
f_k = characteristic strength, taken from calculations or test for short-term loading at room temperature
γ_m = safety factor for polymer or FRP
A_1 = influencing factor 'duration of loading'
A_2 = influencing factor 'media class'
A_3 = influencing factor 'service temperature'

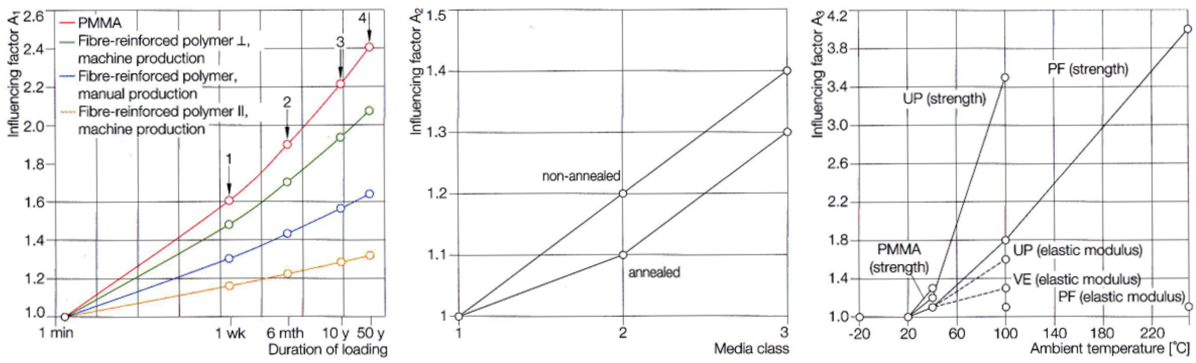


Figure 10: Influence on mechanical parameters *(source: Construction Manual for Polymers + Membranes)*

The first graph of figure 10 shows how the duration of loads influences the mechanical properties of polymers.
1 Wind, snow (H<1000m), imposed load in places of assembly, traffic on access roads.
2 Snow (H>1000m), imposed load in residential and office buildings, traffic on public roads.
3 Imposed load in factories, traffic on trunk roads.
4 Self-weight

The second graph of the figure shows how media classes influence the mechanical properties of thermosets.
1 Interior climate
2 Natural weathering
3 Severe UV exposure

The third graph shows the influence of ambient temperatures on the mechanical properties. Under normal circumstances this graph has no influence but the behavior of load bearing during fire will be influenced by this.

6.8 Experimental Research[5]

All sandwich constructions which are discussed so far consist of two facing plies and a core. The ability to incorporate other building components is not very easy and can damage the construction. This part contains information about a research study in which several sandwich elements are combined. In general they will be less stiff compared to a sandwich element which has the same amount of materials and the same height but with all the FRP on the outer leafs since the moment of inertia will in that case be larger. However failing of regular sandwich elements can go very fast. If there is little damage to the foam core it can split from top to bottom at once. When using multiple sandwich elements this process stops when the next FRP layer is reached albeit for only a short period since the construction height changes in that case. Also the enclosure of different types of layers might become possible to fulfill other needs of the elements and the design besides having a load bearing function. Figure 11 shows the composition of such elements, pictures are taken during the experiment. The beams shown are sawn from a larger plate which makes it possible to create floor elements as well.

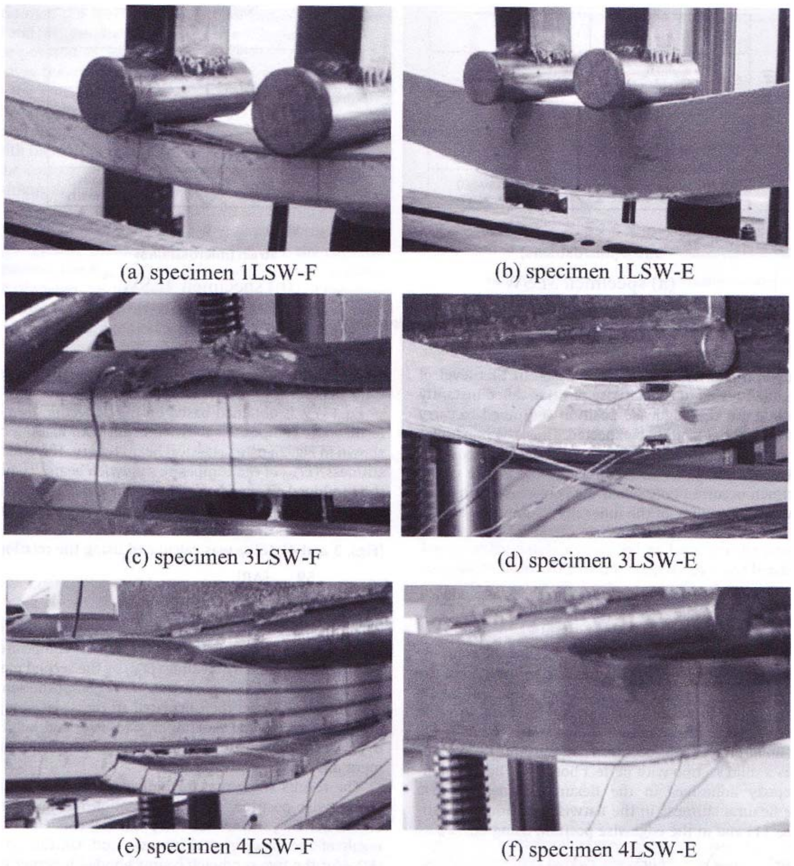


Figure 11: Laminated beams in flatwise and edgewise position *(source: Flexural behaviour of glue-laminated fibre composite sandwich beams)*

The study involved experimental investigation onto the flexural behavior of glue-laminated fiber composite sandwich beams with a perspective of using this material for structural beams. Sandwich beams with 1, 2, 3, and 4 layers were subjected to 4-point static bending tests in the flatwise and edgewise positions to evaluate their stiffness and strength properties. Figure 12 shows the different types of test specimen with their dimensions and support span.

[5] Manalo A.C., Aravinthan T., Karunasena W., *Flexural behaviour of glue-laminated fibre composite sandwich beams,* (Composite structures, volume 92 p. 2703-2711, 2010)

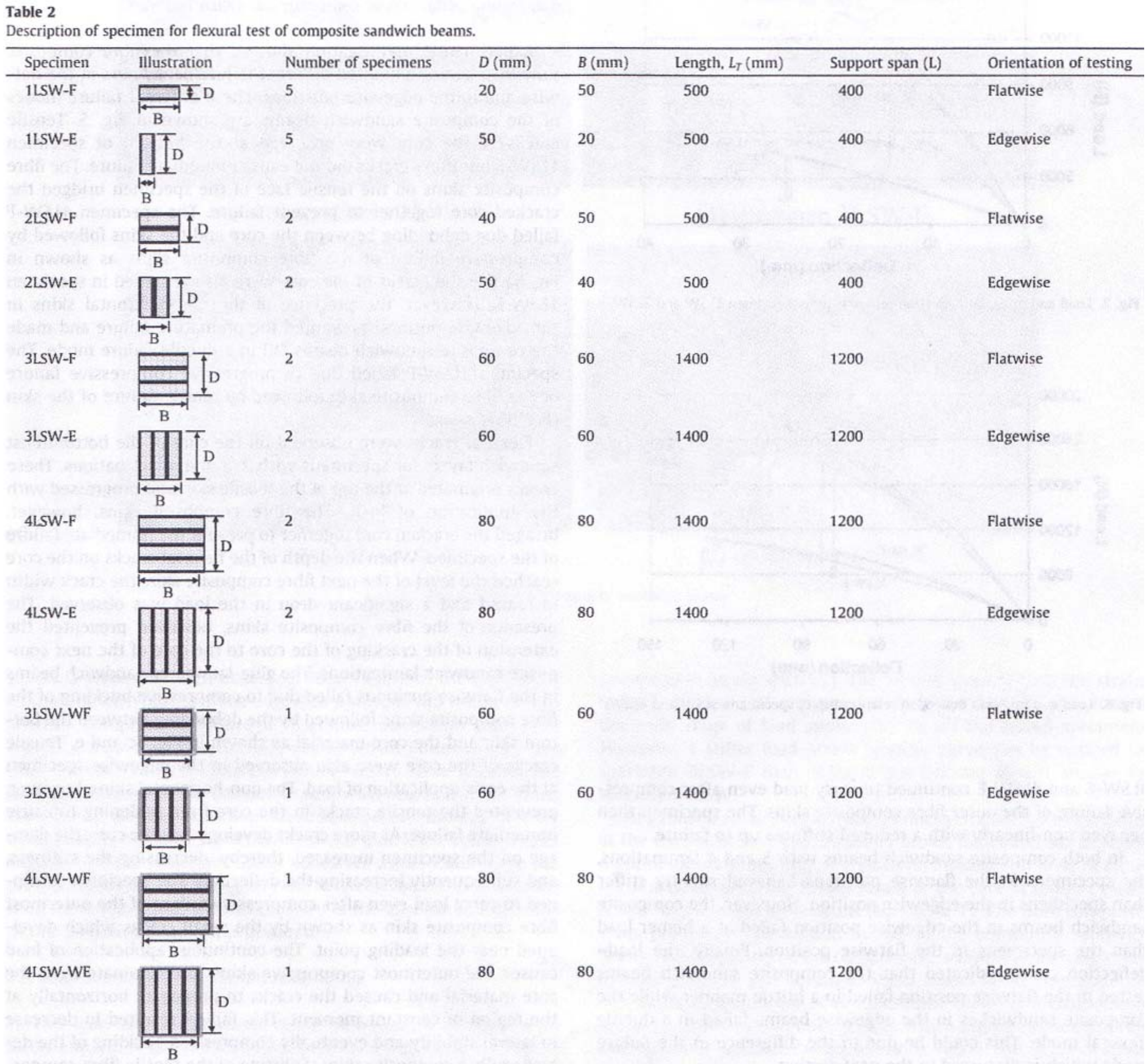


Table 2
Description of specimen for flexural test of composite sandwich beams.

Specimen	Illustration	Number of specimens	D (mm)	B (mm)	Length, L_T (mm)	Support span (L)	Orientation of testing
1LSW-F		5	20	50	500	400	Flatwise
1LSW-E		5	50	20	500	400	Edgewise
2LSW-F		2	40	50	500	400	Flatwise
2LSW-E		2	50	40	500	400	Edgewise
3LSW-F		2	60	60	1400	1200	Flatwise
3LSW-E		2	60	60	1400	1200	Edgewise
4LSW-F		2	80	80	1400	1200	Flatwise
4LSW-E		2	80	80	1400	1200	Edgewise
3LSW-WF		1	60	60	1400	1200	Flatwise
3LSW-WE		1	60	60	1400	1200	Edgewise
4LSW-WF		1	80	80	1400	1200	Flatwise
4LSW-WE		1	80	80	1400	1200	Edgewise

Figure 12: Different types of test specimen *(source: Flexural behaviour of glue-laminated fibre composite sandwich beams)*

The layers were bond together using epoxy resin. The sandwich elements itself consisted of glass laminates in combination with a phenolic resin. Also tests have been done with a wrapping of glass fiber textile around the whole sandwich beam, this however did not prove to be effective. In general it can be stated that the glue-laminated sandwich beams performed better than the individual sandwich beams. The construction height plays a critical role in this. The use of sandwich materials in a purely structural way has not been explored in depth yet. One of the main reasons for this might be that the currently used core materials are inappropriate for the task. Their mechanical properties differ too much from the ones of the facing plies. A new generation fiber composite sandwich panels made up of glass fiber reinforce polymer skins and modified phenolic core material has now been developed in Australia. In the research study the flexural behavior of this material has been investigated. The results of this research suggest that the strength and stiffness of this innovative composite sandwich structure are suitable for structural beam applications. These composite sandwich panels are produced in limited thicknesses, a structural beam section could be produced by gluing a number of sandwich panels together either in the flatwise or edgewise positions. This process is similar to that of laminated wooden beams. The lamination of the elements results in a more stable

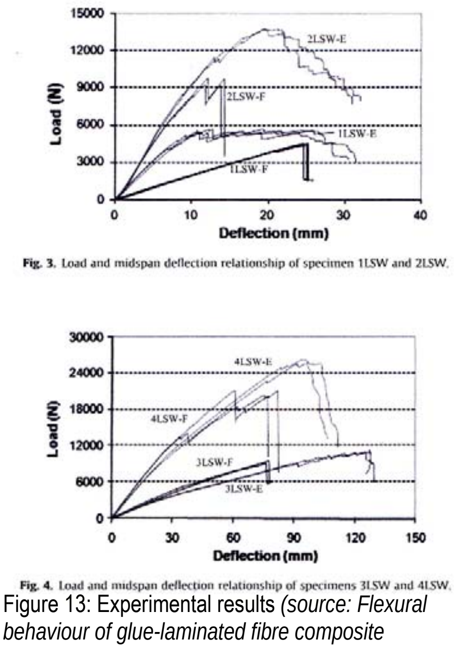
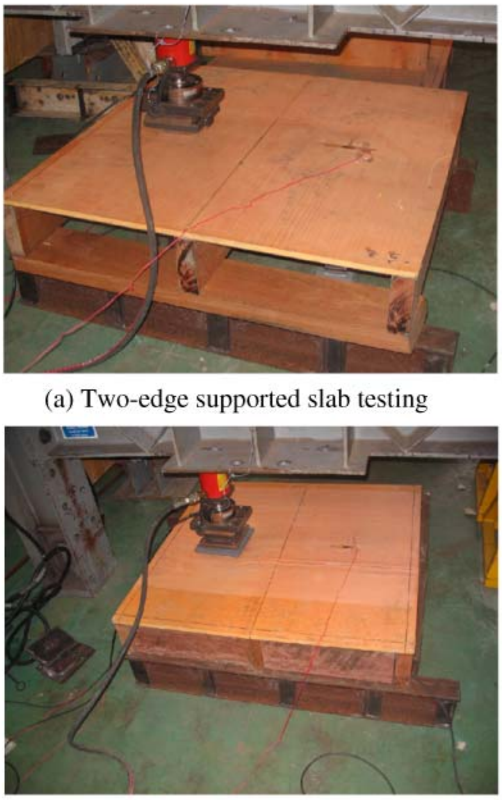


Figure 13: Experimental results *(source: Flexural behaviour of glue-laminated fibre composite sandwich beams)*

product when it comes to failure. In case of failure in the flatwise cases it is the compressive failure of the skin followed by debonding between the skin and the core which is responsible, thus resulting in brittle failure. Figure 13 shows some of the test results. The upper graph shows the result for the single and dual laminates. The lower graph shows the results for the sandwich elements which consist of tree and four layers, these also span a larger gap. The first peak of every line shows the rupture of one of the layers, after that moment the elements still keep their load carrying capacity however the graphs show a drop in applied load when this happens. This is probably due to the release of energy when a layer breaks.
Given the fact that the principle of connecting several sandwich elements together seems to work, other combinations can be made with foam cores which are normally not available in large dimensions. Specific material properties can be exploited.

6.9 Floor Application[6]

A major area where sandwich panels could be beneficial would be that of flooring systems. Due to their lightweight and strength properties, the use of sandwich panels proves a much better alternative to traditional wood or concrete flooring systems. The reduced dead weight of the floor results in reduced overall load and hence the need for smaller support elements. Experimental research has been performed which has resulted in an innovative fiber composite sandwich panel specifically developed for building and other structural applications. Besides being used as floors the product also has the potential for being used as wall or roof due to its multifunctional structural and insulation properties. The product developed is build from glass fiber composite skins co-cured onto modified phenolic core material, using a toughened phenol formaldehyde resin. The composite skins each have a thickness of 1,8 mm, the total thickness of the element is 15 mm. With the help of experimental studies the behavior of these elements has been determined. In these studies the elements have been tested as two-edge and four-edge support systems. Various test variables were considered to determine the effects of varying the sandwich skin fiber orientation, the fixity between slab and support, and the slab edge support on the slab properties under point load and uniformly distributed load (UDL). The results of the experiments suggest that fiber composite sandwich panels as slab systems behave similarly under point load and uniformly distributed load no matter the fixity, fiber orientation or slab edge support. Point loading turned out to be critical over UDL, this however was to be expected given the material properties and their behavior.



(a) Two-edge supported slab testing

(b) Four-edge supported slab testing

Figure 14: Test set-up *(source: Behaviour of structural fibre composite sandwich panels under point load and uniformly distributed load)*

Figure 15 shows some of the test results. The initial failure of the panels, no matter what the slab system, fiber orientation or fixity, was due to shear cracking of the core. In some cases this process was started by delamination of the facing plies. In general it could be said that the results were consistent and the information recorded was highly valuable in determining the behavior of fiber composite sandwich panels for slab system applications. However there is a need to investigate the behavior of such composite sandwich panels analytically and conduct a parametric study to have a better understanding of its behavior in flooring systems. It is one thing to determine at which point an element would fail during an experiment but it is another to determine this behavior in a theoretical way which than could lead to a standard for calculating sandwich structures. To a certain level this is already possible but there are however some difficulties. For instance the cracking of the core and delamination of the facing plies intends to happen at an uncertain point during loading. Therefore it is extremely difficult to state whether a construction can be trusted or not. The architecture of the material itself and the used elements play an important role in this. There is a great amount of different properties and variables which need to be taken into account. On this moment several experimental studies are under development and some have been done already which all have the goal of determining the behavior of sandwich structures. The most important topic in this will be the correspondence between the theoretical and experimental results. The control over the core behavior plays a key role in this.

[6] Aravinthan T., *Behaviour of structural fibre composite sandwich panels under point load and uniformly distributed load,* (Composite structures, volume 93, p. 206-215, 2010)

Table 2
Test results on load and deflection for all the specimens under point load.

Support condition	Slab fixity	Main fibre orientation (°)	Deflection at loaded span at 2.1 kN (mm)	Deflection at unloaded span at 2.1 kN (mm)	Core cracking load (kN)	Deflection at loaded span at core cracking load (mm)	Deflection at unloaded span at core cracking load (mm)
Two edges	Screw only	0	2.38	−0.06	22.88	22.57	−2.86
		90	2.31	−0.13	18.72	20.70	−1.92
Two edges	Screw and glue	0	1.96	−0.05	20.61	19.19	−1.67
		90	2.19	−0.40	21.05	22.56	−2.05
Four edges	Screw and glue	0	1.81	−0.04	22.44	21.36	−1.30
		90	2.34	−0.26	17.84	18.78	−1.19

Table 3
Deflections at different loads at mid-span of the slabs for different fixities under UDL.

Support condition	Slab fixity	Main fibre orientation	Deflection at mid-span at 0.005 MPa (mm)	Deflection at mid-span at 0.01 MPa (mm)	Deflection at mid-span at 0.02 MPa (mm)
Two edges	Screw only	0°	11.31	19.19	35.04
		90°	9.87	18.89	39.77
Two edges	Screw and glue	0°	6.67	13.74	31.02
		90°	8.41	17.23	33.98
Four edges	Screw only	–	5.64	9.82	16.13
	Screw and glue	–	3.52	6.64	12.95

Figure 15: Testing results *(source: Behaviour of structural fibre composite sandwich panels under point load and uniformly distributed load)*

6.10 Innovative 3-D Sandwich Panel [7-8]

Within the concept of the sandwich panel there consists a large contradiction in the functionality of the foam core. This core is responsible for two tasks, the first is to provide a certain distance between the two facing plies in order to generate the largest moment of inertia possible. The second is to distribute the shear forces which will occur as the result of loading and bending. The distribution of shear is not something the foam material is very good at, especially when the elements become thicker. It is here the contradiction can be found, the thicker the element the stiffer it will become as a result of the large moment of inertia, but at the same time it will become weaker due to the distribution of shear. A balance needs to be found between these two in order to make the element work properly. Besides this contradiction within the foam core there exists an other problem which already has been named before, the unpredictable behavior of the foam core. Experimental studies are under development and have been performed in which the rigidity of the core has been improved in order to make the elements more efficient and predictable.

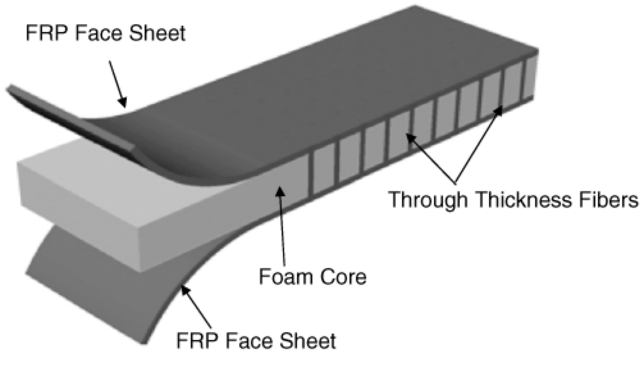


Figure 16: Schematic illustration of 3-D sandwich panel *(source: Material characteristics of 3-D FRP sandwich panels)*

In these experiments sandwich panels were used with inserted fibers which connected the two facing plies in order to help distribute the shear forces and as a result enhance the foam rigidity. Figure 16 shows the principle of such an element. Research indicates that the nature of the fatigue behavior is sensitive to the type of foam material used. The research also indicates that the fatigue failure of the panels was induced by shear cracking of the foam core which ultimately led to overall failure of the panels. In general the conventional sandwich elements are sensitive to a number of different failure modes. These include delamination of the skins from the core, buckling or wrinkling of the compression skin, core shear failure, localized punching or flatwise crushing of the core, rupture of the tension skin and global panel buckling. Since the failure mode is heavily dependent on the core configuration, a number of different configurations have been studied to enhance the panel behavior. These innovative core structures include 3-D woven composite core structures and metallic pyramidal lattice core structures. A number of studies have also been conducted to evaluate the behavior of sandwich panels with 'z-pinned` foam cores. In this configuration, pultruded FRP pins are inserted into the foam core with different inclination angles. The skins are subsequently bonded to the core and different techniques are used to anchor the pins to the skins. Research indicates that the presence of the z-pins helps to increase the strength and stiffness of the core of the panels under different loading conditions including through-thickness tension, through-thickness

[7] Reis M., Rizkalla S.H., *Material characteristics of 3-D FRP sandwich panels,* (Construction and Building Materials, volume 22, p. 1009-1018, 2008)

[8] Dawood M., Taylor E., Ballew W., Rizkalla S., *Static and fatigue bending behavior of pultruded GFRP sandwich panels with through-thickness fiber insertions,* (Composites: Part B, volume 41, p. 363-374, 2010)

compression, shear, combined shear, and flexure. Testing indicates that the strength, stiffness and failure mode of the panels are affected by the inclination angle of the pins and the method of anchoring the pins to the skins. In a similar type of system, dry through-thickness fiber insertions can be inserted into the core and impregnated simultaneously with the skins, thereby providing continuity between the skins and the insertions. The fiber insertions increase the shear strength and stiffness of the panels, help to prevent delamination of the skins, and enhance the flatwise compressive strength of the panels. Other research on similar stitched panels indicates that the presence of the through-thickness fiber stitches increases the in-plane compression strength by reducing the buckling length of the face skins.

The sandwich panels with through-thickness fibers are produced by a pultrusion process. Multiple plies of bidirectional glass fabric and a non-structural chopped strand mat and veil are continuously fed into a pultrusion machine along with a polyisocyanurate foam core. The glass fiber fabric consists of a balanced stitched fabric with an areal weight of the structural fibers of 1220 g/m^2. Through-thickness fibers are inserted using a specialized process to ensure that the insertions are well embedded and bonded to the GFRP skins in a fixed configuration. The entire assembly passes through a vinyl ester resin bath where the fabric and through-thickness fibers are impregnated. In the last stage of the process, the assembly passes through a heated die from which a continuous, cured panel is pulled. This process allows insertion of the fibers in several different patterns and allows optimization of the panel properties to achieve specific design objectives (figure 18). Figure 17 shows a panel with through-thickness fibers under compression.

Figure 17: 3-D sandwich panel during compression test *(source: Material characteristics of 3-D FRP sandwich panels)*

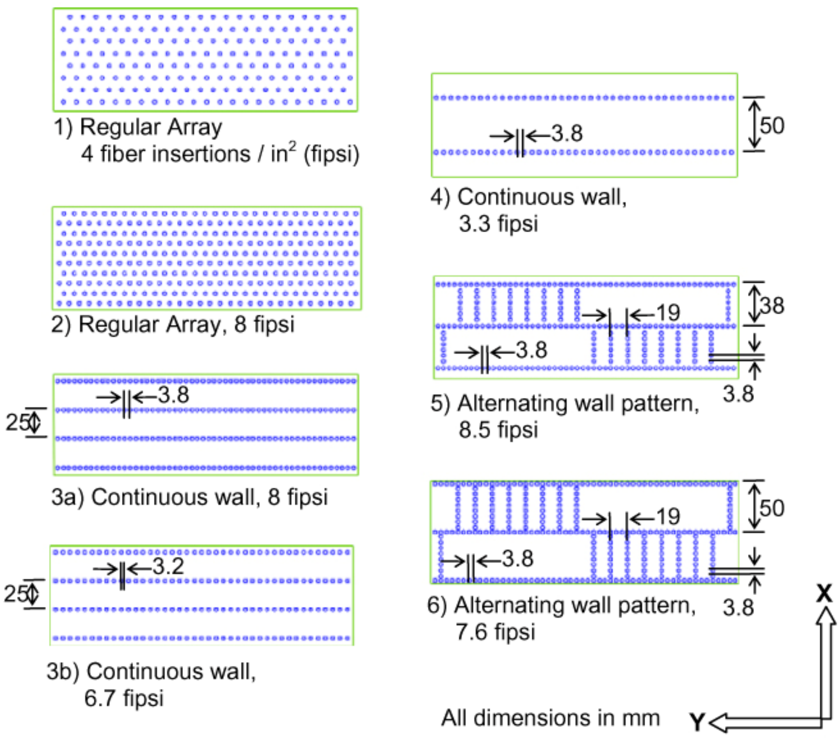


Figure 18: Fiber insertion patterns of 3-D GFRP sandwich panels *(source: Static and fatique bending behavior of pultruded GFRP sandwich panels with trough-thickness fiber insertions)*

6.11 Fire

When submitted to fire, sandwich elements will not last very long. The resins used can be slow-burning or even self-extinguishing. But as a result of the heat they will become weaker, allowing the fibers to slide past each other unable to transfer forces. In general the problem is not the burning of the material but the transmitted heat. The fibers are insensitive to the heat but the resin is unable to keep its strength. The foam core of the elements suffers the same problem which makes it very difficult to create a fire resistance barrier with sandwich elements. Several protective coatings are available to protect the elements against burning, but this is not the answer to the problem. When building steel structures foam coatings are used to protect the steel from melting and losing its stiffness. These foam coatings expand themselves when contact has been made with a fire. Fully expanded, an insulating layer around the steel construction has been generated to prevent failing. The temperature at which these foam coatings are developed completely lies around the 200 degrees Celsius. At first sight this seems a solution for the FFP construction elements as well. However when submitted to temperatures of 200 degrees Celsius, the matrix which holds the fibers loses its strength. The protective foam coatings will eventually protect the construction but at that point in time the construction has weakened too much. The first ceramic resin systems for FRP's have been introduced. The ceramic resin is incombustible but has poorer material properties which make such a type of resin no potential candidate for matrices used for structural purposes.

Protecting sandwich elements against fire could also be reviewed from a different point of view. There are active and passive fire protection systems. The material itself will be unlikely to receive the proper properties to fulfill this task itself which means external measurements need to be taken. So far most solutions used in the building environment are based on non flammability or insulating but there is also another potential way of handling fire, absorption of the transmitted heat. Experimental studies have been done in which water cooled elements are exposed to fire. In general water is transported through the elements absorbing the heat coming from the fire. A fire resistance of over 120 minutes was reached using this principle while the elements itself without the water did not last for even 60 minutes. One could imagine the water being used as part of the climate system as well. However, this idea has only been applied to a single element in a lab without the difficulty of connections and reliability of the system. But it are ideas like this which have great potential when it comes to whether FRP materials and sandwich elements can be used in a constructional way. At this moment there are no protective systems available but research done on this topic might change this situation in the near future. For now assumptions have to be made in order to apply systems like this in a design.

6.12 Finishing

The visible end result of a sandwich structure depends on various aspects. The finishing of the elements first of all things will be determined by the type and shape of the mould. The smoothness or roughness of the mold is copied by the elements, this way patterns can be included during the shaping process. In most cases an additional coating is added to the elements which help protecting the sandwich structure against environmental influences but in some cases this coating forms a layer which is aloud to wear. Especially in case of floor structures wearing can be a key design aspect. Particles can be added to coatings which offer more grip on the surface, like sand. Most of the coatings are polymer based as well which makes them resistant against almost all weather influences and offer the possibility to watertight surfaces. In some cases it could be wise to apply the coating after the elements have been assembled, this way seals can be covered. In general almost everything is possible when it comes to surface finishing.

6.13 Cost

Besides all positive aspects sandwich constructions offer, there are a couple of negative ones to. Fire has been called before as one of the difficult topics, cost could be considered another. There are several production methods available with which sandwich elements can be made, all of these processes require a mould or a die. In general this is the most expensive part which only becomes cost efficient when large batch sizes are produced. Repetition of limited types of elements can contribute to this. Besides the production processes there is also the material selection which holds different price categories. Figure 19 shows various fiber reinforced polymer materials with their stiffness and price. In general it is the type of fibers used who determine the bigger part of the price followed by the way the fibers are woven. The matrix hardly contributes to the price differences. Aramid fiber based products are ten times more expensive than glass based products. However they are also almost ten times as stiff which means less material is needed. When strictly looking at the cost of sandwich elements as a result of the materials used, the facing plies determine the height of the price. The foam core also contributes to this but in a less significant way. Figure 20 shows foam materials with their stiffness and price. It can be seen that the material used to produce the foam determines the cost and not the stiffness of the material. Only when working with glass fiber reinforced polymer facing plies, the cost of the foam core becomes relevant given the fact that both materials are almost equally valuable.

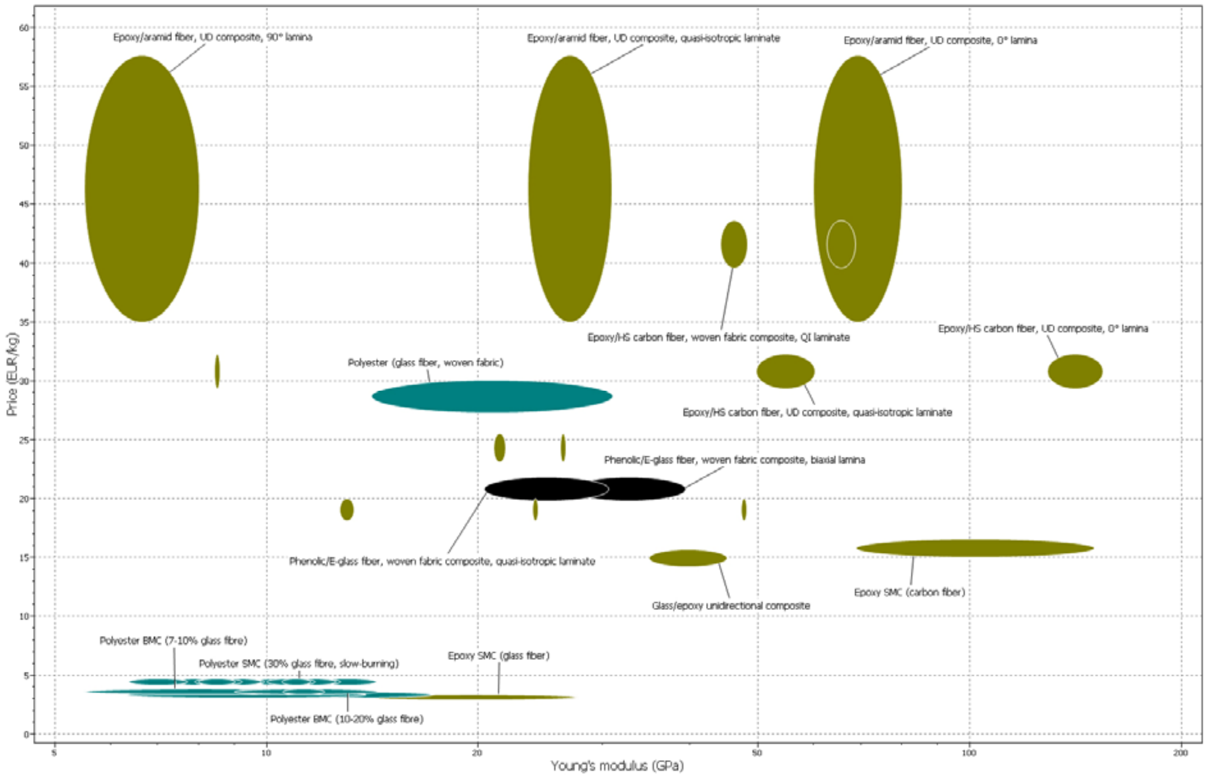


Figure 19: FRP Y_price – X_youngs modulus *(source: CES EduPack 2011)*

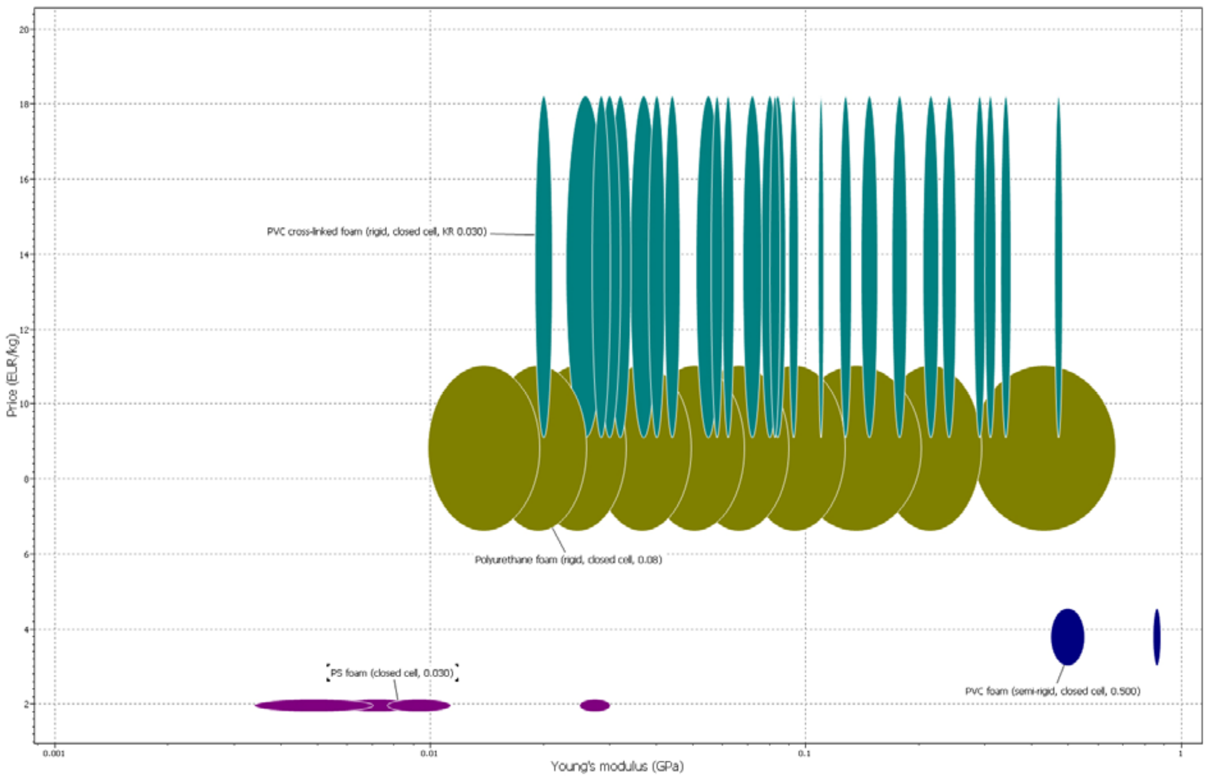


Figure 20: Foam Y_price – X_youngs modulus *(source: CES EduPack 2011)*

6.14 Connection possibilities

The connection between sandwich elements forms a critical point. In general sandwich elements are responsible for two main functions when building with FRP's. Most importantly they increase the load-carrying capacity beyond that of a thin laminate and besides that they have an insulating role. Having connections on itself decreases the functioning of the elements. Therefore the type of connection used needs to be chosen extremely carefully. Three connection types will be reviewed, starting with bolted joints.

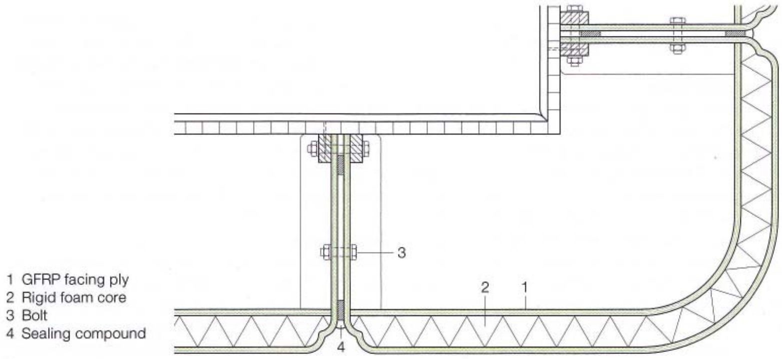


Figure 21: FG 2000, Altenstadt, Germany, 1968, Wolfgang Feierbach – connection detail *(source: Construction Manual for Polymers + Membranes)*

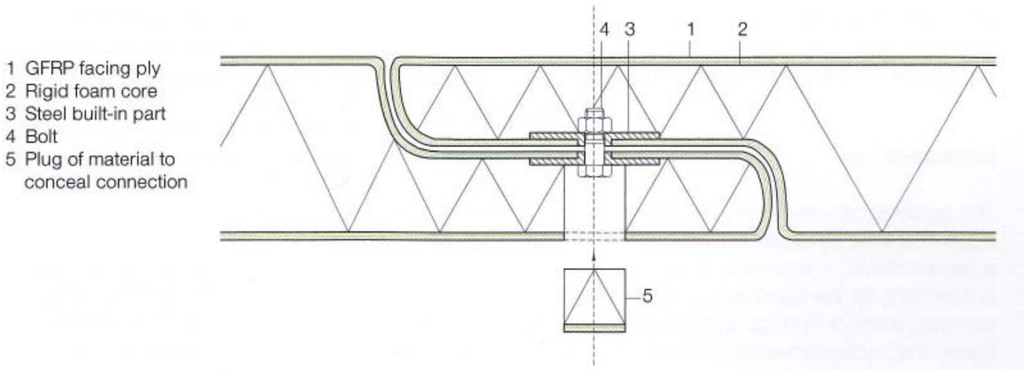


Figure 22: Stepped joint *(Construction Manual for Polymers + Membranes)*

In case of non-permanent structures, bolted connections might be an option. In order to function properly, local reinforcement of the elements is required to deal with the stress concentration at the joint. This usually results in a lower load bearing capacity and a lower thermal insulation value. Figure 21 shows a detail from the FG 2000 design dating from 1968. This is one of the first composite designs ever build. The upper level has load carrying walls and a roof made out of FRP sandwich elements which are interconnected through bolts. In this case fins made out of FRP are used to connect the elements and to separate the internal cladding from the sandwich elements. This however is not always a possibility given the fact that this solution consumes quite the amount of space. Besides this kind of connection will result in a thermal bridge. A stepped joint, shown in figure 22 can help to compensate for the building physical disadvantages. Such a connection can be viewed as a hinged joint.

Placing rigid foam inserts is another way of connecting sandwich elements. During construction the forces are transferred exclusively via the joint in the core material, which calls for the use of a material with a suitable load-bearing capacity, like PVC or PUR. Once the joint hast been finished, the facing plies are continuous, which makes the sandwich elements continuous. A final play may be added over the entire structure in order to achieve an adequate load-carrying capacity. Figure 23 shows a detail of such a joint, and an application in which these joints are used. The hemispherical radom shown is completely made out of FRP's. The different elements are connected by a loose rigid foam tongue which is glued in place. Afterwards the missing facing plies are added and a seamless design will be the result. The function of the domes explains why FRP was chosen over traditional building materials. In the domes radio antennas are placed which need to be protected against environmental influences but the transmitted waves are not to be stopped by the cover. The signal transmitted can pass right through the FRP materials without noticeable loss.

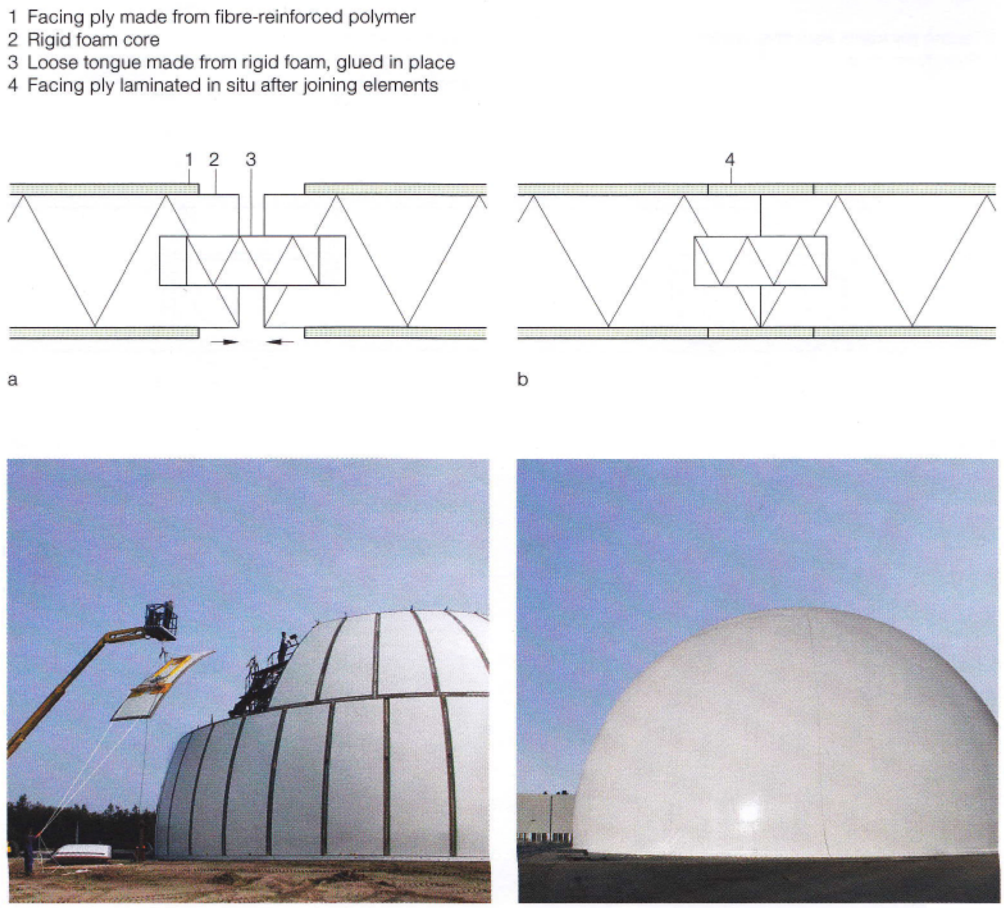


Figure 23: Laminated joint, hemispherical dome *(Construction Manual for Polymers + Membranes)*

In the dome, the forces applied can flow through the entire element till they reach the foundations. This however is not always the case, most of the time constructional elements experience line or point loads in the connections. The sandwich element itself cannot handle these forces very well without a severe reduction of their load-carrying capacity. In order to handle these forces well, large steel parts can be included which replace the core material locally. At those specific points the load-carrying capacity is increased without any visible disturbance at the surface. Figure 24 shows an example of a structure like this. The building shown is the Itzhak Rabin Centre, the composite roof is produced by Holland Composites. In order to support this roof only by columns, steel profiles are placed between the core elements. The entire element will be impregnated with the resin so it becomes a whole. The steel elements are part of the sandwich elements and are not an external addition. This allows one to make structures with minimalistic details since everything will be integrated.

Besides improving the load-carrying capacity at certain points, inserts are also used to integrate other functions. The roof of the Rabin Centre contains service ducts through which pipes and cables are routed. Other examples of integrated functions are: build-in light fittings, decorative features, thermal mass, sensors for measuring strains and temperatures and sunshade control systems. This aspect plays an important role in the future development of sandwich elements in a structural position. It is not only the strength to weight ratio which makes sandwich elements an interesting building material but also the possibilities they offer to design integrated elements.

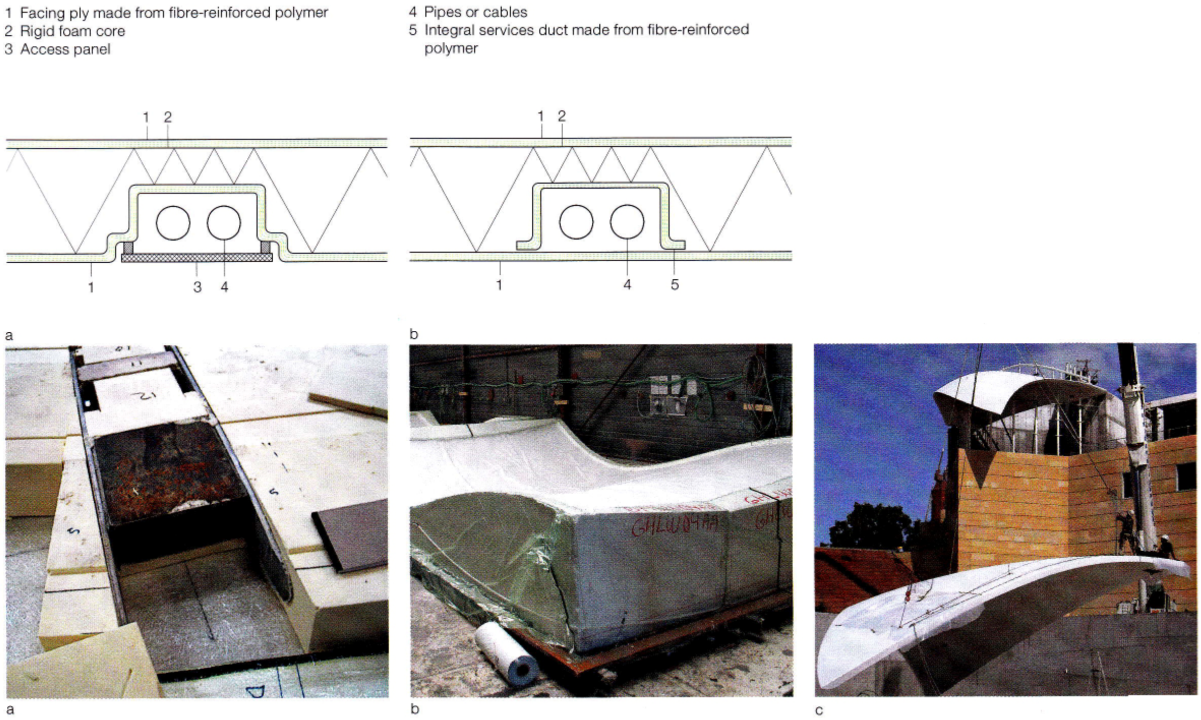


Figure 24: Itzak Rabin Center, Tel Aviv, 2005, Moshe Safdie, Mick Eekhout – built in steel parts *((Construction Manual for Polymers + Membranes)*

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PART B

Hotel Design

Architectural Engineering

Dual Graduation Track

PART B

1 Introduction on the design

This part of the report describes the design which has been made for this graduation project. This design is about a hotel situated in the Buiksloterham, Amsterdam. The research topics described in Part A of the report and especially the unique opportunities which sandwich constructions have to offer, are the starting point. They are used as input for the design of a hotel on a landmark location in the capitol of the Netherlands. How this hotel is to function will be explained in chapter 3. Before we jump to that, first the design location as well as the district it is situated in, are described in order to get an image of what the setting is like.

2 Urban environment

As is the case with every architectural project, a location has to be specified on which the design will be situated. Combined with the material research described in Part A of the report and the architectural concept for the hotel, this location will provide the input but also the boundary conditions for the design. This chapter will describe the development of the location and the envisioned redevelopment plans. The specific location of the design in combination with its rich potency for the design will be described as well.

2.1 Buiksloterham (BSH), Amsterdam

Figure 1: Plan of the city Amsterdam with BSH highlighted

The design location is situated on the north side of the IJ river in Amsterdam. The district, called the Buiksloterham(BSH) is shown in red in figure 1. This area was developed by the end of 1848 as a result of dredging the IJ river. The extracted mud and sand were brought to a creek on the north side of the IJ river. At low tide this place runs dry and in order to prevent all the material to slip back into the river a dike was constructed. In 1848 the city decided to drain the whole area, BSH was born. The decision to drain the BSH was partly the result of social tensions and unemployment in the city. In order to solve these problems, jobs were provided by draining the BSH. The land was separated in a traditional way with one road in the middle and plots perpendicular to this road. The plots were used as farmland till the end of the nineteenth century and were owned by private investors. After that period, the city bought back most of the land from the private owners because it had expansion plans for the city of Amsterdam on the north side of the IJ river. BSH became an industrial area with a lot of ship yards, figure 2 shows an overview of the BSH during the sixties of the 20th century.

Figure 2: Buiksloterham, the sixties of the 20th century *(source: bestemmingsplan Buiksloterham)*

Figure 3: Overview of the Buiksloterham nowadays

Up to today the BSH is an area of industrial companies, this however is about to change. Figure 3 shows an area overview of the situation nowadays. In 2002 the city of Amsterdam presented a master plan for the redevelopment of the north side of the IJ river. In coming years the area will change from a highly industrial area to a home-work environment. There still will be companies situated in the area but all of the heavy industry is about to leave. One of the biggest changes in the area will be the introduction of 'living'. By 2015 approximately 2000 houses will be build here. Figure 3 shows an impression of what the area could look like according to the master plan. These changes in the area offer the possibility for this design to make assumptions on how the area should function.

Figure 4: Artist Impression BSH *(source: bestemmingsplan Buiksloterham)*

2.2 Design Location

The specific design location is situated on the east end of the BSH. In the redevelopment plans for the area this part of the BSH is to become a green zone. The idea behind choosing this location is based on distancing the hotel partly from the rest of the area by placing it half on land half on water. Besides, this location offers a wide view over the IJ river which makes that this location has the potency to situate a eye catcher since it also can be seen from a wide variety of angles. The building on this specific spot should become an icon of plastics in architecture. On the north side of the location lies the Johan van Hasselt channel which makes that the site is almost completely surrounded by water. Figure 5 shows a couple of images which present the situation as it is now. The wide view across the IJ river start to become visible by this. On the other side of the channel lies the NDSM wharf which is being redeveloped currently as well. The characteristics of the NDSM wharf can be compared to the ones of the BSH.

Figure 5: View over the IJ river and the design location of the hotel

The specific design location is shown in figure 6 accompanied by a scheme of the accessibility of the area. A characteristic form of transportation is the ferry network between the BSH, the NDSM wharf, the Houthavens and the city centre. This free form of transportation is widely used by people by bike or by foot traveling between the various destinations. Besides the ferry there is also a direct connection over land. The BSH as a whole is about to be connected to the city center by the Noord-zuidlijn in the future. This is to become the one direct connection between the BSH and the city centre. An important point of interest, which can also be seen in figure 6, is the access roads passing by the location and the enclosing of the site by water. This offers great freedom in the design since the location is distanced by road, green zone and water from the rest of the BSH and other surrounding districts.

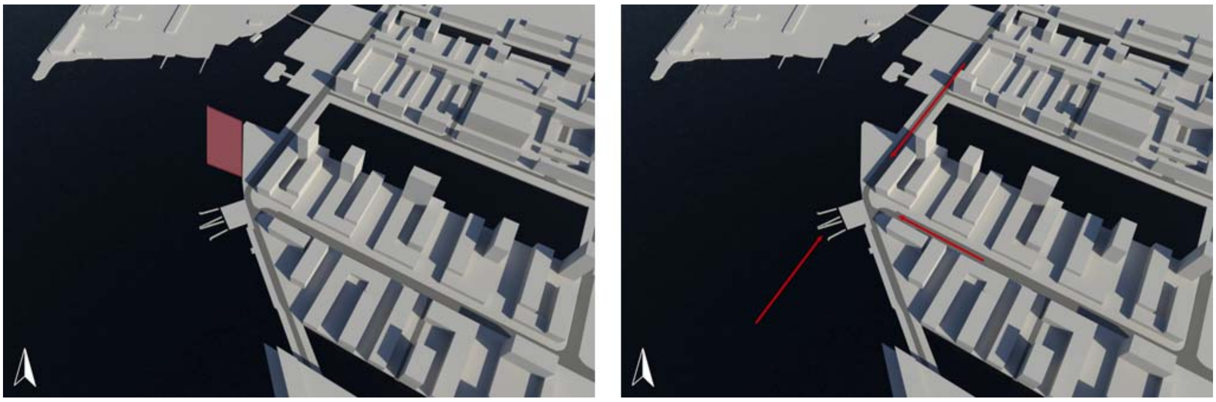


Figure 6: left - the specified design location, right - accessibility of the area

3 Architectural Concept

In order to structure the design as well as to set an image of what the hotel should be, a concept has been developed. This concept is based on the research topics combined with the envisioned ideas for a hotel in Amsterdam. Together, the research and the concept are to give a shape to the hotel and are to help in making the steps from scheme to building without losing the ideas. This chapter explains the architectural concept and also gives an impression on what this means for the interior of the building.

3.1 Design Concept

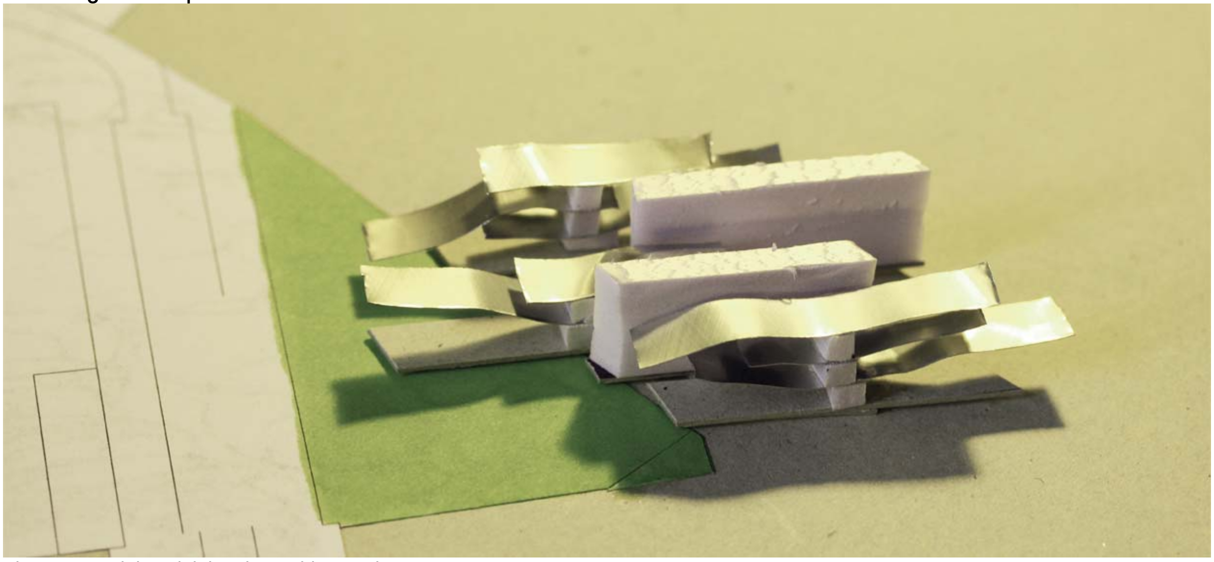


Figure 1: Model explaining the architectural concept

The technical fascination which forms the basis for the design is the use of composites in a constructive role. The hotel is split in several strips which alternately contain functions or hotel rooms. The hotel has to be accessible for guests of the hotel as well as for visitors of the district. This generally means that there has to be a separation between public and private parts of the building. The strips mentioned before visualize this principle. Figure 1 shows a small model which gives insight in this idea. The parts with the curved elements are to contain the functions of the hotel and the more orthogonal strips will contain the hotel rooms. These rooms are to be in the form of modules which makes it possible to increase or decrease the amount of rooms. The rooms will be subordinate to the function strips. The shape of the hotel will mainly be determined by the curved elements from the function strips. The freedom in form which can be achieved by using sandwich elements will be used to shape the building. The general idea behind this will be the transformation from floor-wall-roof and thereby taking over the role of various functions due to the shape chosen. The curved sandwich parts are to become more than just construction parts, they are to generate space and become a function as well.

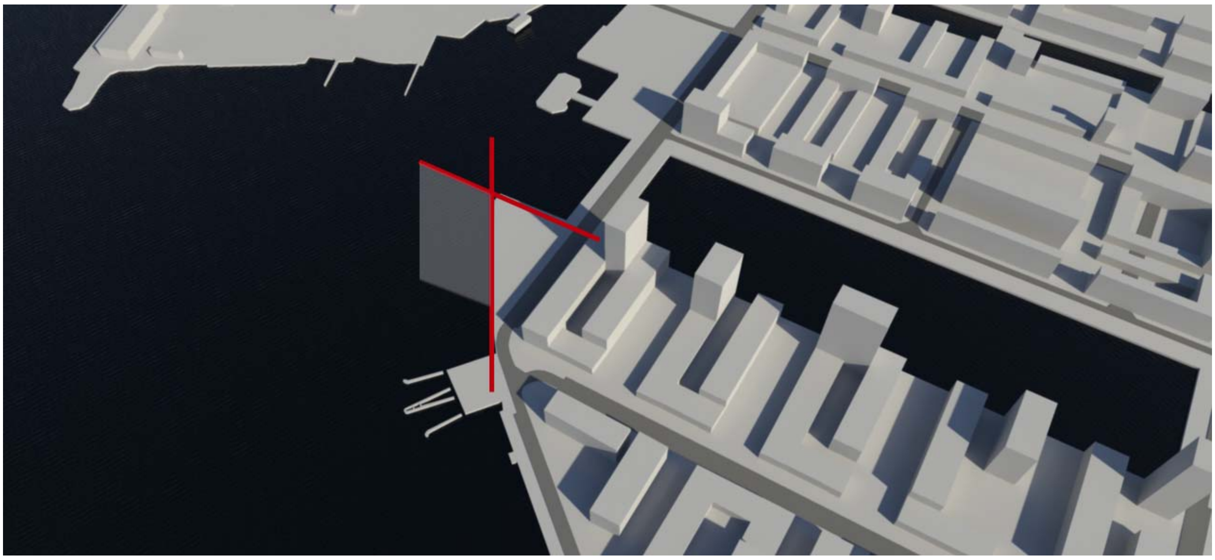


Figure 2: Structuring the design by using lines from the surrounding area

Besides the architectural concept there is another structuring part which is extracted from the location and the surrounding area. Figure 2 shows the design location with two red lines which are extensions of the land. The upper line follows the Johan van Hasselt channel. The vertical line represents the end of the BSH. Both lines are used to organize the hotel with its corresponding floor plans. The idea behind this is the hotel becoming an extension of the BSH by using reference lines from the area.

3.2 Translation and impression of the concept

Figure 3 shows two impressions of how the concept can be translated into the interior of the hotel. Left shows the entrance hall in which the ceiling flows into a transparent element which on the upper side contains the swimming pool. Right shows a lounge which offers various places to sit or lie down as a result of the shape in the floors.

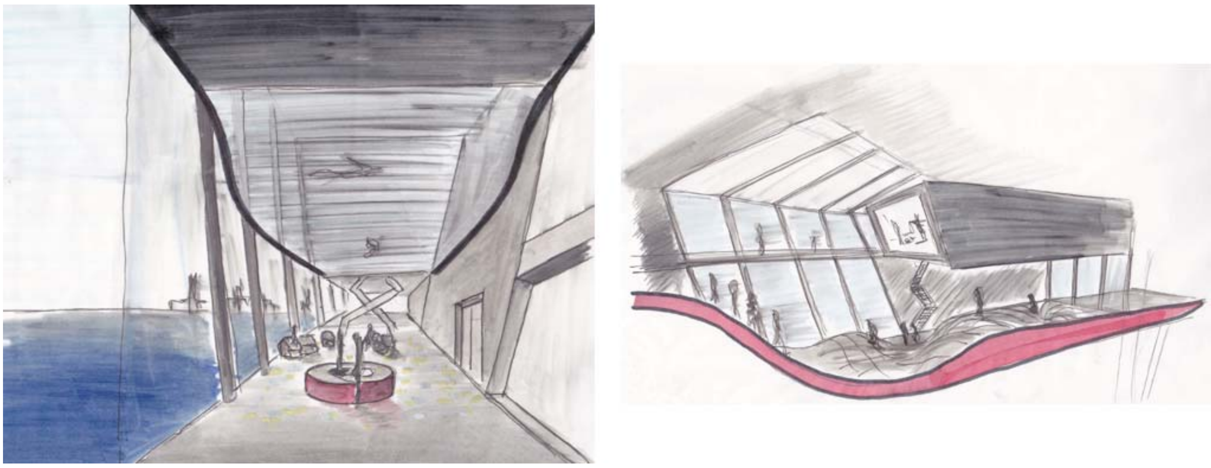


Figure 3: Impression of what the interior might look like

In order to structure the curved floor elements and to provide connection options for the rooms which will be hung from the function parts, a grid structure will be used. This grid will be based on the usability of the rooms, figure 4 shows the principle.

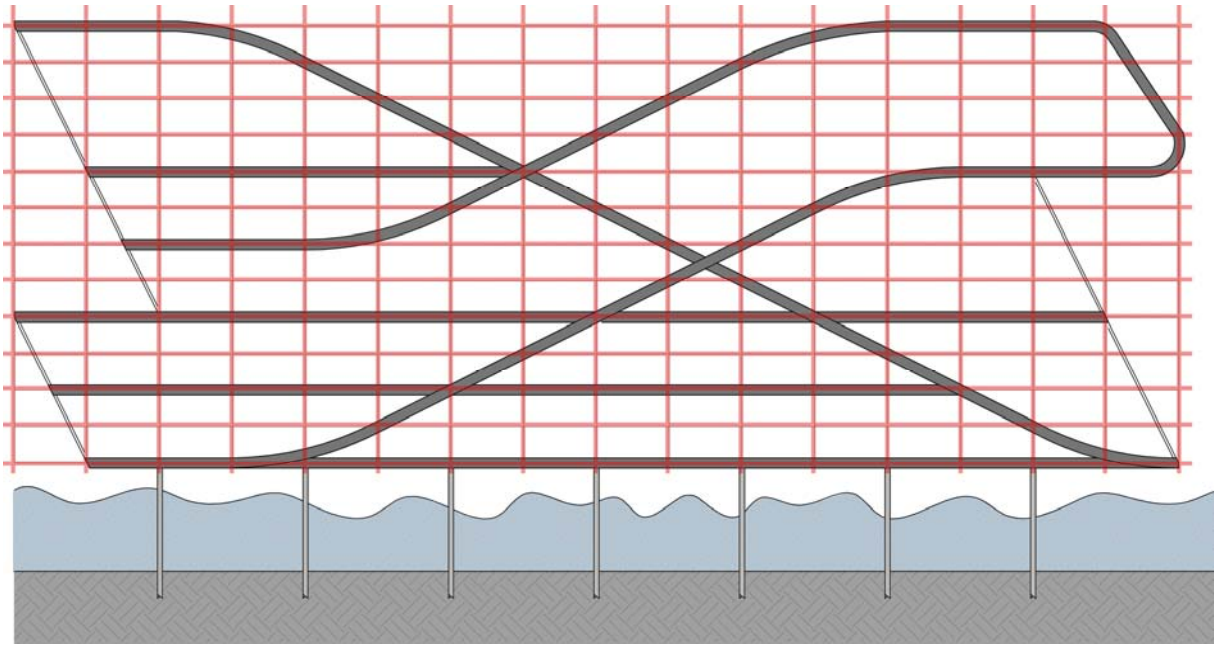


Figure 4: Grid structure applied to the curved floor elements

3.3 Reference Projects

Figure 5: Reference projects which visualize the envisioned design concept

Figure 5 shows several reference projects which as a result of their curved shapes create the spaces in between in a natural way. The construction of all these projects has not the visible curved shape. In these cases the visible shape is only the finishing of the surface. For example the Burnham pavilion, designed by UN-studios, on the upper left has a wooden structure which can be seen in figure 6. This is not the envisioned way of composing the hotel, however these projects do show the idea behind the freedom of form and the generation of space.

Figure 6: Building the Burnham pavilion designed by UN-studios

4 Hotel Design

This part of the report describes the architectonical elaboration of the hotel. The technical aspects will be explained in chapter 5. For now insight will be given in the spatial organization and the relation between the various functions of the hotel. The distribution of functions over the hotel is based on several routes through the building. These routes will be used to explain the design as well as the accompanying experiences. Finally the idea behind the modular rooms and their relation to the rest of the hotel will be explained.

4.1 Composition of the Hotel

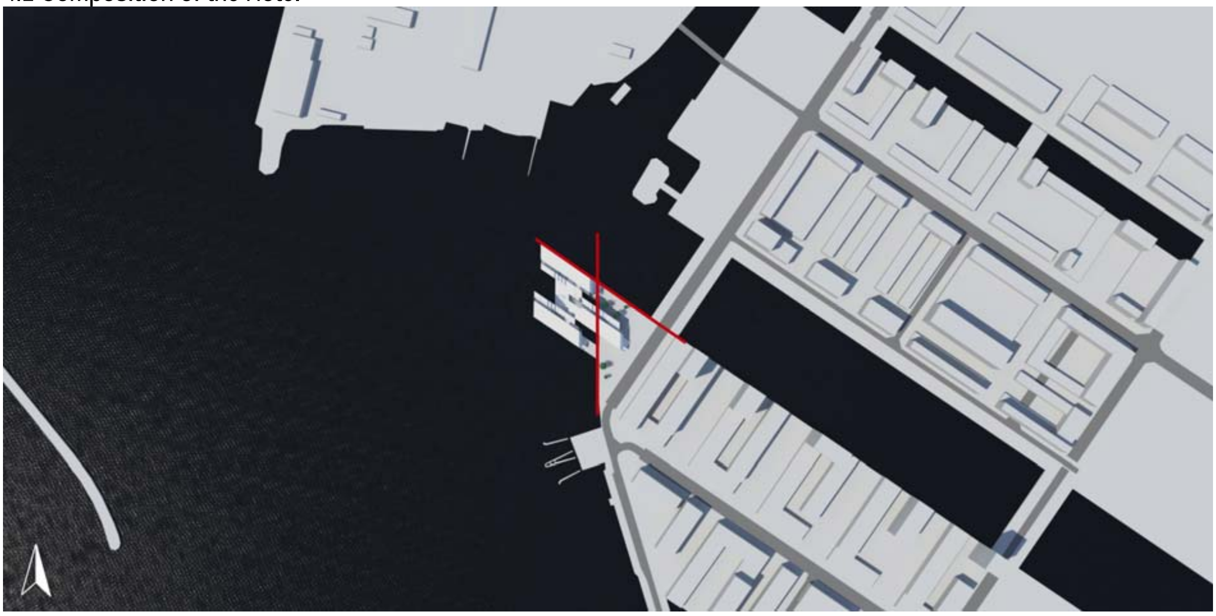


Figure 1: Composition of the hotel

The hotel and thereby all its functions will be divided into three parts which in relation to each other are placed in such a way view over the IJ river and daylight transmittance are optimal. Figure 1 shows how the three parts relate to one each other as well as it shows the reference lines used. As is mentioned before, the hotel is not only accessible for hotel guests but also for visitors of the area. This means a certain separation between public and private parts of the hotel is required. The three parts of the hotel are able to function completely without each other when it comes to the guests. However each of the three parts includes a couple of functions which are also accessible for visitors and at the same time challenge the guests to visit one of the other parts as well. Structure and organization are the same for all three, hence one of them has been appointed to be elaborated in depth.

Only one of the parts has direct contact with the main land, the other parts are built in the water. A deck has been positioned in between the parts which connects them from the inside.

Figure 2 shows the distribution of the hotel parts. The red strips represent the functions of the hotel, always with a view over the IJ river or the Johan van Hasselt channel. The grey strips are transition strips between the functions and the rooms (blue strips). These transition strips form the separation between the functions which is a public part of the hotel, and the rooms that are naturally a private part of the hotel. The rooms itself are positioned more inwards. This decision has been made on basis of the functions being accessible for everyone and the rooms only to one or two individuals. Without a doubt the rooms are subordinate to the hotel design. Figure 3 shows the ground level floor plan of all three parts. As a result of the reference lines used from the surrounding area, there are no 90 degree angles between walls present. This is something which contributes to the experience of the hotel by providing a clear direction towards the IJ river.

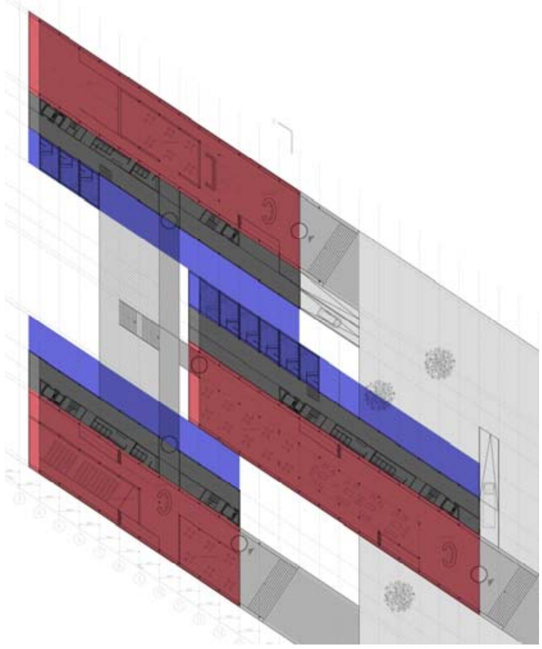


Figure 2: Distribution of the hotel parts

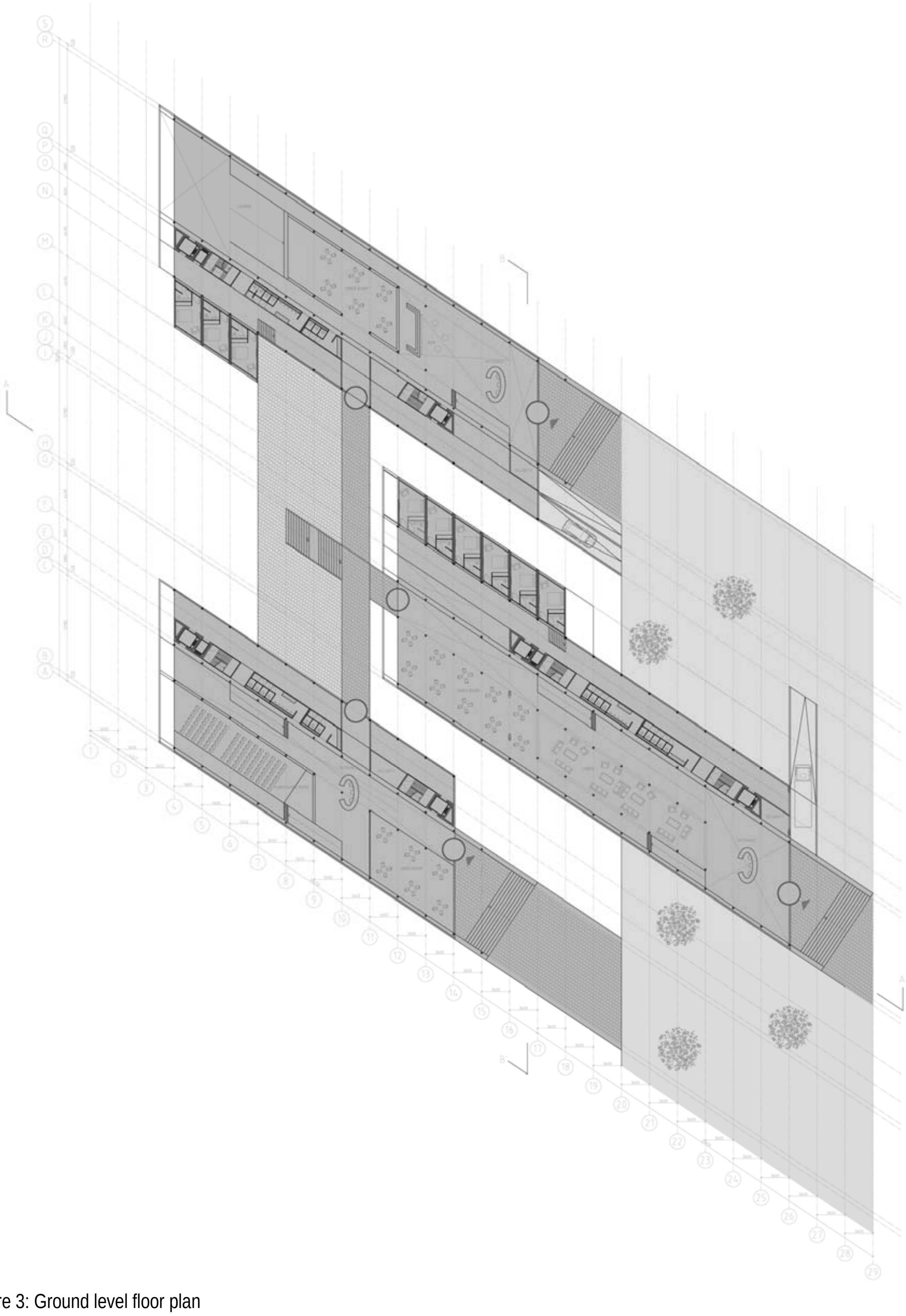


Figure 3: Ground level floor plan

4.2 Distribution of functions

Below the function distribution of all thee hotel parts is shown. In all three parts the lower layer is used for supporting functions, this will be explained in the next paragraph. Figure 4 shows the lower and the upper of the three hotel parts. As can be seen in the schemes, every part has space reserved for functions only intended for the guests and other accessible for the wider public.

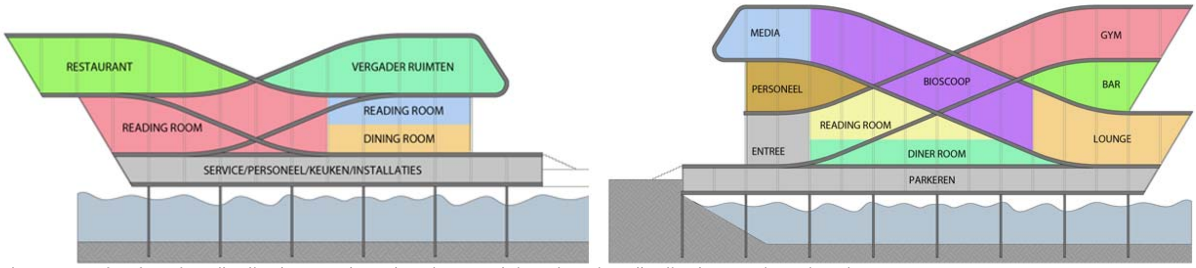


Figure 4: Left – function distribution southern hotel part, Right – function distribution northern hotel part

As is mentioned before, only one part of the hotel has been developed in depth, this will be the middle one of the three hotel parts. Figure 5 show a section in which all functions are highlighted. The most important functions of this part of the hotel are the swimming pool and the bar/restaurant. They determine on a high level the layout and experience of the building. With the help of a 3D model, the various routes will be explained starting by the route most attractive to the visitors.

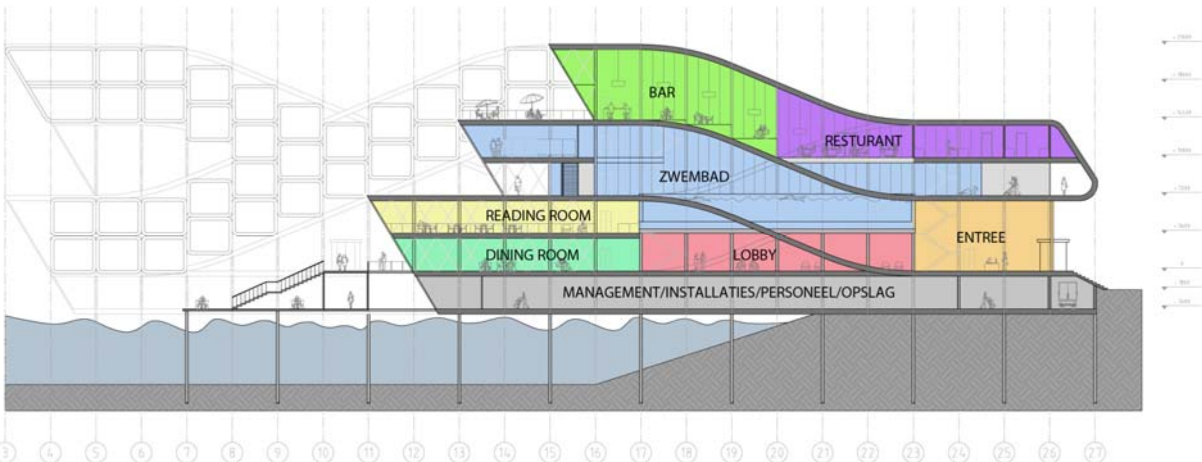


Figure 5: Section of the middle part of the hotel

The section as well as the 3D model in figure 6 shows the lines curving through the building. In some cases these curved floor elements are shaping a function and in other cases they are part of the routes circling their way up. The lines and thereby the floors are curved in one direction. This results in straight and curved surfaces which eventually connect all the functions present. There are two main routes through the building, one which is highly attractive for the visitors and one more attractive for the guests of the hotel. Both routes circle around each other in which one is able to see the other but no direct contact is possible. It is not impossible or forbidden for users to take the route not essentially meant for them however as a result of their positioning an unconstrained separation between guests and visitors is made. At first the route envisioned for the visitors will be explained. The left model in figure 6 shows how this route works its way through the building.

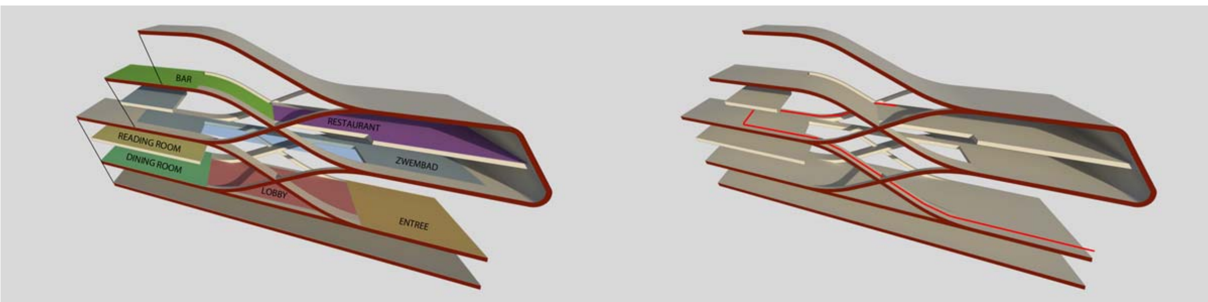


Figure 6: Left – 3D model with the distribution of the functions, Right – in red the visitors route

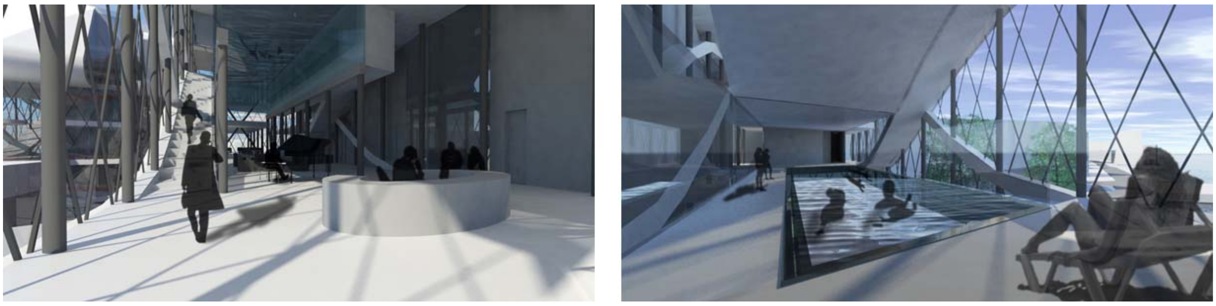


Figure 7: Left – Entrance hall, Right – Swimming pool

The route starts in the entrance hall (figure 7) in which on the left side the route up is visible. More to the back and to the right the route for the guests can be seen. Due to the distance between them and the difference in direction visitors will be using the route on the left. In principle there are no functions especially meant for visitors to be found on the entrance level. However in the centre of this level the lobby can be found which might in some cases be an exception to this. Also in the centre the swimming pool can be seen. This pool has a plastic transparent floor which gives the opportunity to watch people swim. This pool will be entirely made out of the material PMMA, acrylic glass. This is the same material used for large sea aquaria. The reason for this can be found in the material having the same refractive index as the water which results in zero visual deformations and thereby making the pool extremely transparent. Due to its weight the pool has its own construction which encloses the lobby on the ground level which as a result separates the traffic zones and the lounge area.
When the route up is taken, entrance to the swimming pool belongs to the options. The pool has a view over the IJ river and of course down. On both sides of the swimming pool routes passing by can be seen (figure 7).
Moving further along the route brings the visitors to the restaurant (figure 8). This is to be considered the end of the visitors route. From the restaurant visitors as well as guests have a wide view over the IJ river and the city centre. Besides this, the other parts of the hotel can be seen very clearly from this position as well. The highest point of this building part contains the bar however this is considered to be more a function meant for the guests as for the visitors.

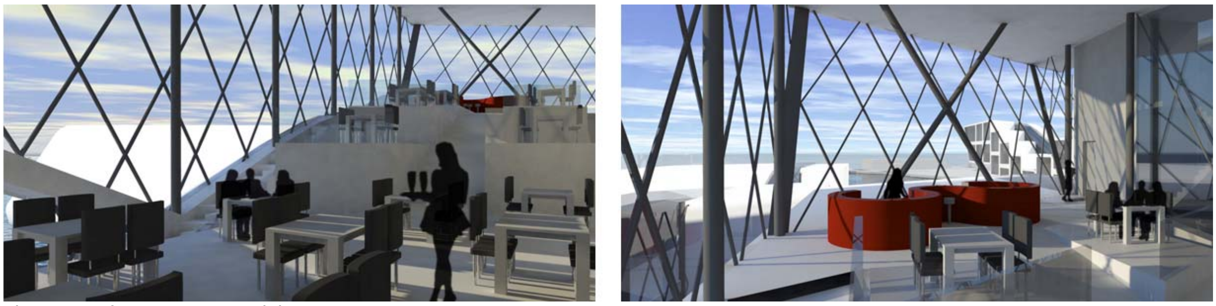


Figure 8: Left – Restaurant, Right - Bar

The guests' route (figure 9) starts at the dining room from which a tour upwards through the building can be taken by the therefore reserved route. Coming from the dining room it is also possible to go to the rooms directly via the transition zone on the left. Directly above the dining room the reading and relax room can be found. This is a place strictly meant for the guests and therefore not linked to the route. This room can be accessed via the transition zone. As is the case for the visitors, the first function on the route is the swimming pool (figure 10). Both visitors and guests have their own entrance to the pool accompanied with separate changing rooms and showers. This is not the result of the separation private-public but has to do with logistical reasons. For the guests the journey ends at the bar from which the wide view can be enjoyed. The bar area is partly placed on a curved slab with various terraces on it which offer separate seats. The curved floors and roof play an important role in this area when it comes to design and orientation of the building.

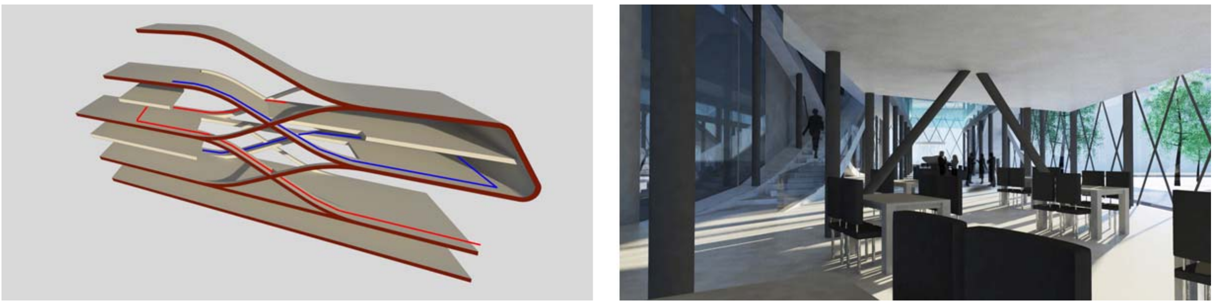


Figure 9: Left – in blue the guest route, Right – Dining room

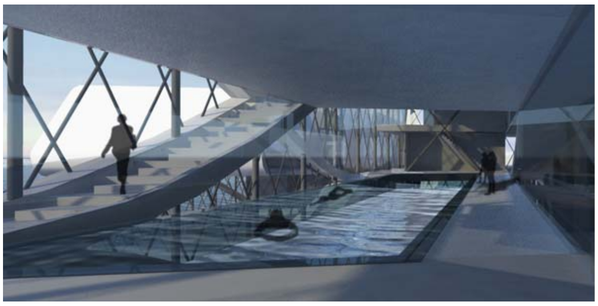
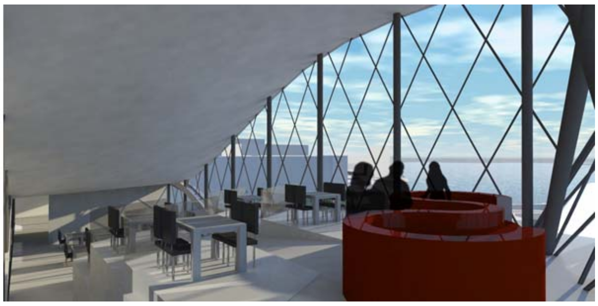



Figure 10: Left – Swimming pool, Right - Bar

Between the three building parts a deck on water level is situated (figure 11). During summer this can be used as lounge area but throughout the year it connects the three building parts. The raised part of the deck can be used by guest to enter all building parts. Underneath this part lies a connection meant for the staff of the hotel.

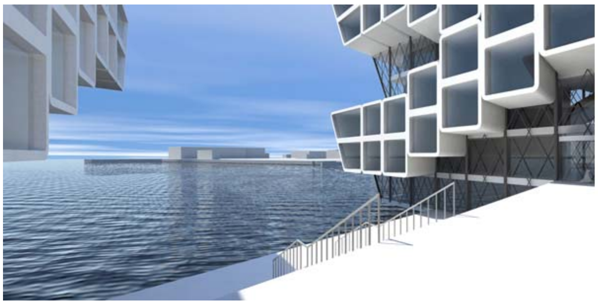
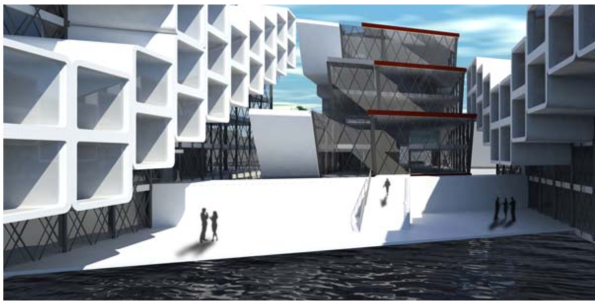



Figure 11: Deck

4.3 Support functions

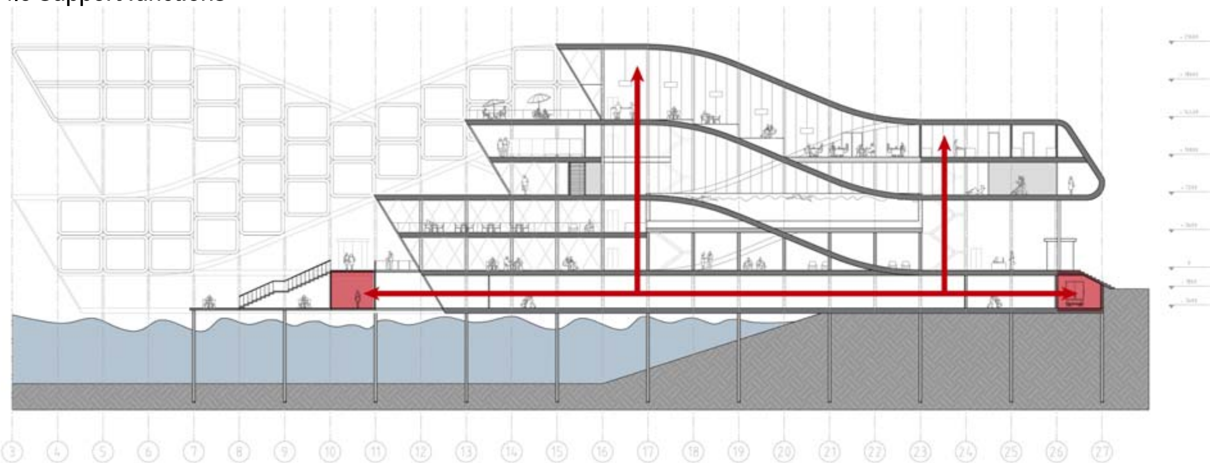


Figure 12: Routing Staff

Besides the described routes for guests and visitors there is a separate route for the staff of the hotel. The lower level of all three building parts is reserved completely for staff and other support functions. From this layer every room in the hotel can be reached with no or limited disturbance for the guests by being invisible. Vertical transportation will be done by the transition zone and the accompanying staff elevators. Figure 12 shows a section of the building with the transport route for the staff. The delivery of fresh food and other hotel equipment will be done by the middle part of the building since this is the only part situated on the main land. Underneath the main entrance a loading dock is situated from which all goods can be distributed over the other two parts by the tunnel on the deck. Figure 13 shows a section of the three building parts in which the relationships between the different parts can be seen. The middle part contains mostly management functions while the left part contains more support functions like a large laundry service. The right parts has been completely reserved for parking space. The garage can be entered on the left side next to the entrance of this building part. The result of using the complete lower level for staff and support functions combined with separate vertical transportation means will be the invisibility of the virtual engine of the hotel which should increase the experience of the guests and visitors of the hotel.

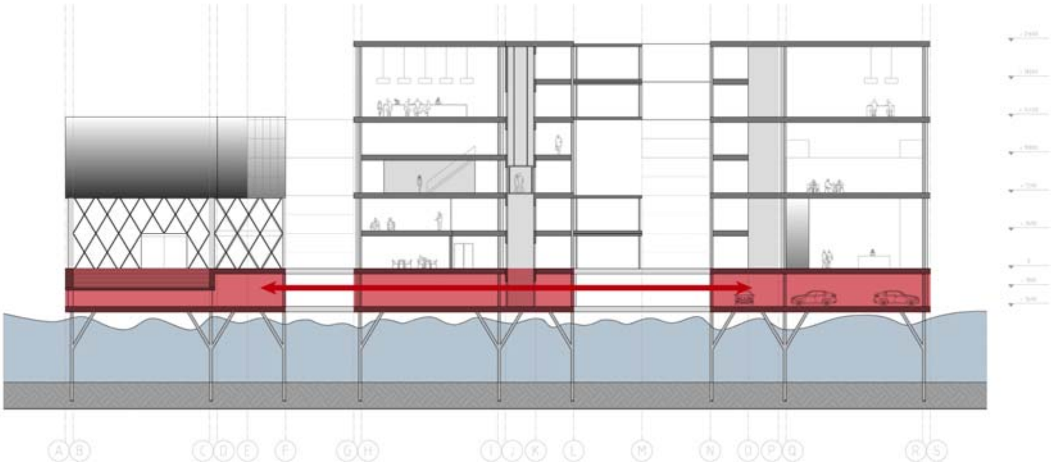


Figure 13: Section over the three building parts

4.4 Transition zone & Rooms

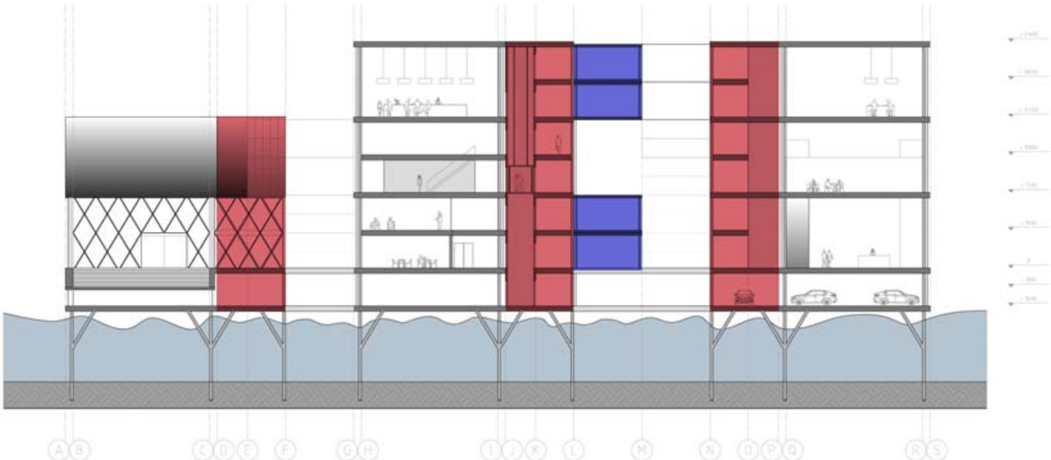


Figure 14: Transition zone in red, Rooms in blue

Right next to the function strips lie the transition zones which in figure 14 are highlighted in red. These separate the public zones from the private zones and also provide the vertical and horizontal transportation routes for staff members. Besides this it also forms the constructive connection between the rooms and the rest of the hotel. The transition zones are divided into three parts which can be seen in figure 17. The first part, highlighted red, contains support functions like elevators, cable shafts, staircases and toilet areas. They are all clustered in one block which on the outside is organized according to the grid structure and the used reference lines. The inside of this block is transformed in such a way 90 degree angles between the walls can be made in order to make every square inch as efficient as possible.
Accessing the rooms can be done via the blue part. The rooms follow the curved lines of the floors which means they vary in height taking steps of a half level. Due to this a bridge between the transition zone and the rooms was made which gives access to the rooms. Between the core and the rooms lies a zone which connects the two. In the façade and the roof, the core part acts the same as the public function parts. The other parts of the transition zone have the same curvature in the roof but this time it will be transparent in order to receive as much direct sunlight as possible. Figure 15 gives an impression of what the transition zone and the rooms might look like. In figure 16 the rooms and their organization can be seen.

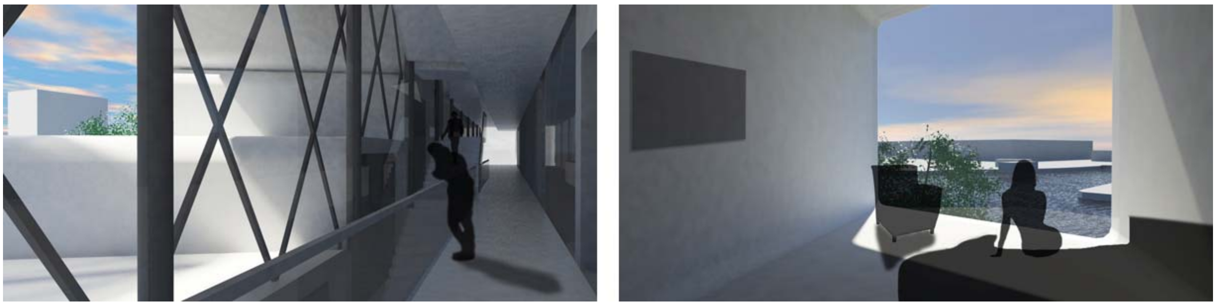


Figure 15: Left – Transition zone, Right - Room

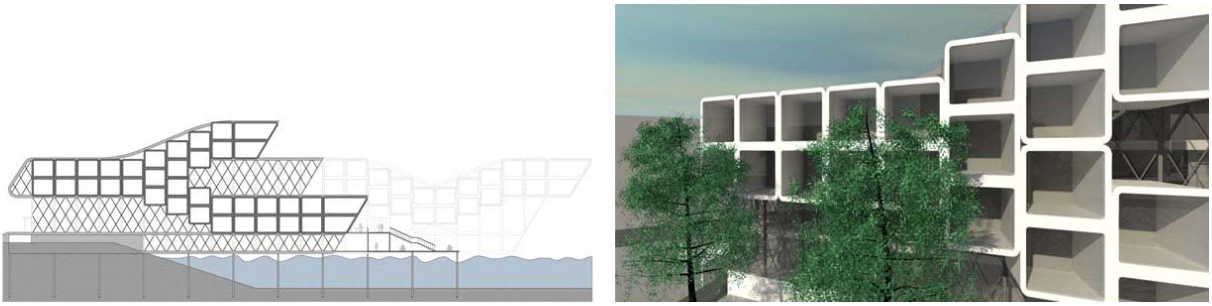


Figure 16: Left – North façade, Right – 3D impression rooms

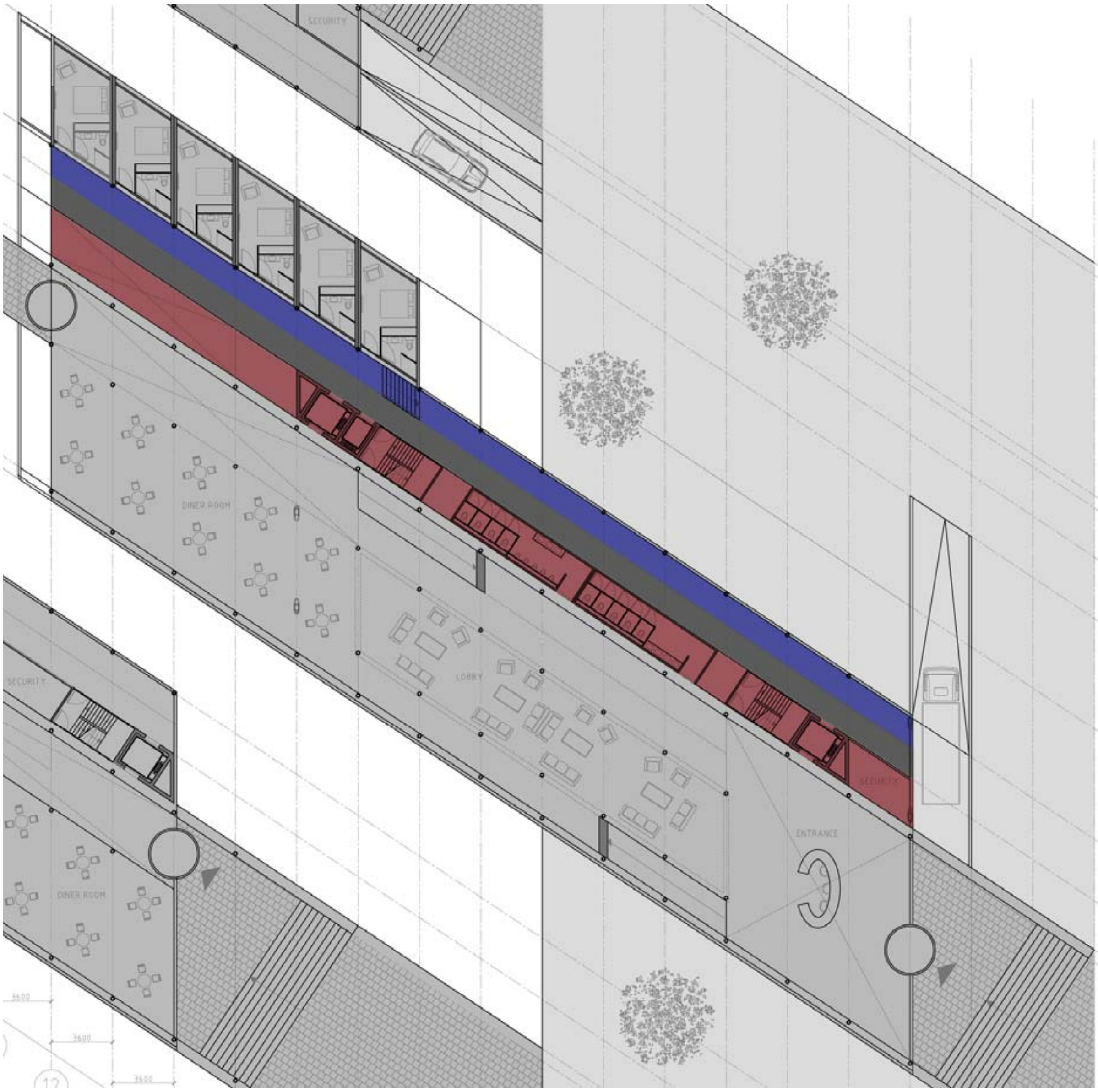


Figure 17: Transition zone

5 Laminated Floor Construction

Design proposal for an innovative floor construction.

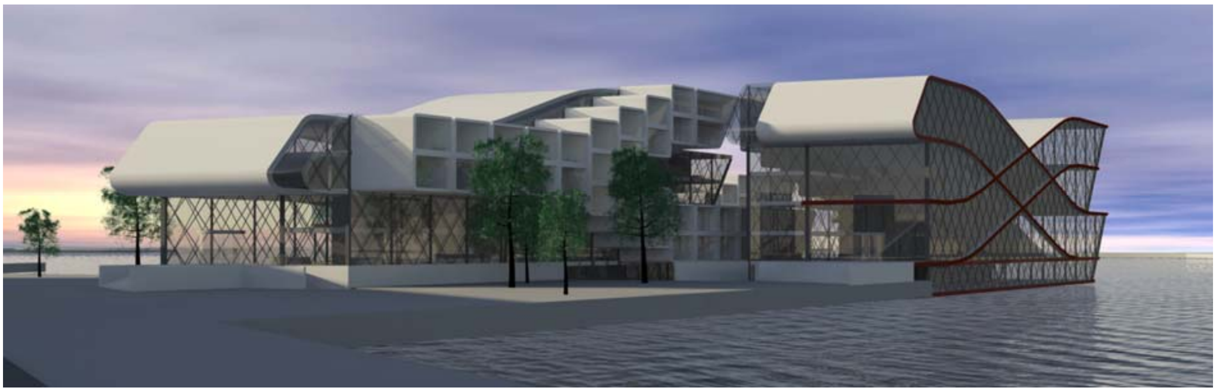


Figure 1: Impression of the design viewed from the bridge crossing the Johan van Hasselt channel.

The research described in the previous chapters about fiber reinforced plastics, forms the foundation for the design. Especially sandwich elements play an important role in this since it are their properties on which the design is based. Besides the use of sandwich elements, modular systems are used which are also based on sandwich structures. In both cases the FRP's are a primary part of the load-carrying system. The rooms are made entirely out of FRP and form modules which can be placed against the structure regarding the demand for rooms. How this works will be explained in chapter 6 of the report, for now the focus will be placed at the construction of the functional strips. In these strips the freedom of form which sandwich elements offer will be exploited in order to shape space and to create constructional zones. In principal these elements are curved into one direction and by that divide the functions over the available space and connects them at the same time. As a result the elevation of the design as well as the section are dominated by the curved lines which meander through the building.

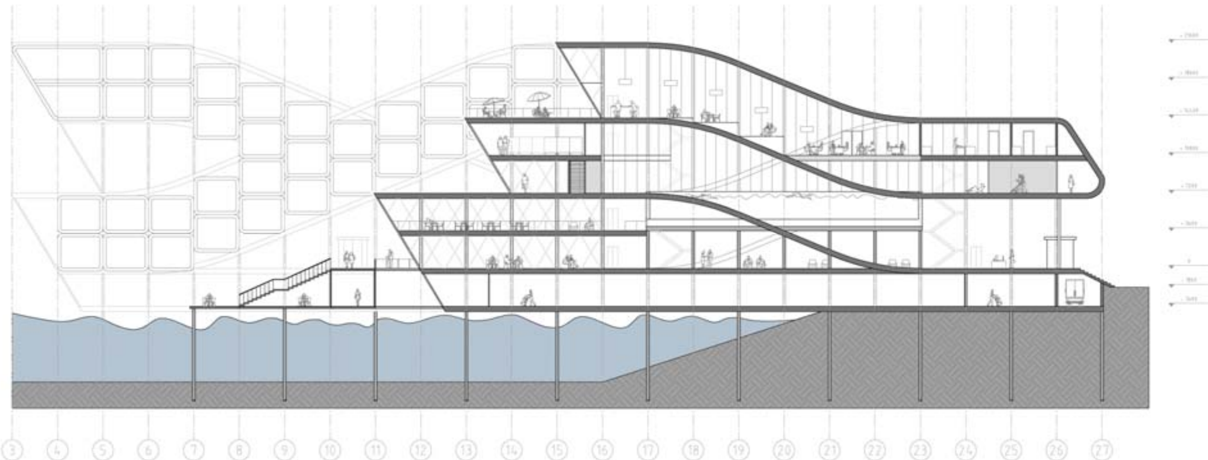


Figure 2: Horizontal section of the building across the functional zones.

5.1 Laminated floor construction

The function floors are all assembled from laminated sandwich elements. Doing so makes it possible to assign different tasks to the different layers. Figure 3 shows an 1/20 section of the building in which the layered floors can be seen. The total amount of layers has been determined at 5, the next paragraph will show calculations out of which this decision can be retrieved. Within this composition the middle three layers will be responsible for the distribution of forces. The outer layers form a protection shield around the constructive core and offer the possibility to apply finishing layers. The centre part consists of a pultruded hollow core FRP element through which pipes and cables can be distributed. This part of the structure contributes the least to the load-carrying function of the floors since the moment of inertia is relatively small in the centre. As a result it becomes optional to have openings in the elements. Besides pipes and cables, this part will also hold the ventilation shafts. In essence one could say these are the climate control layers of the floors.

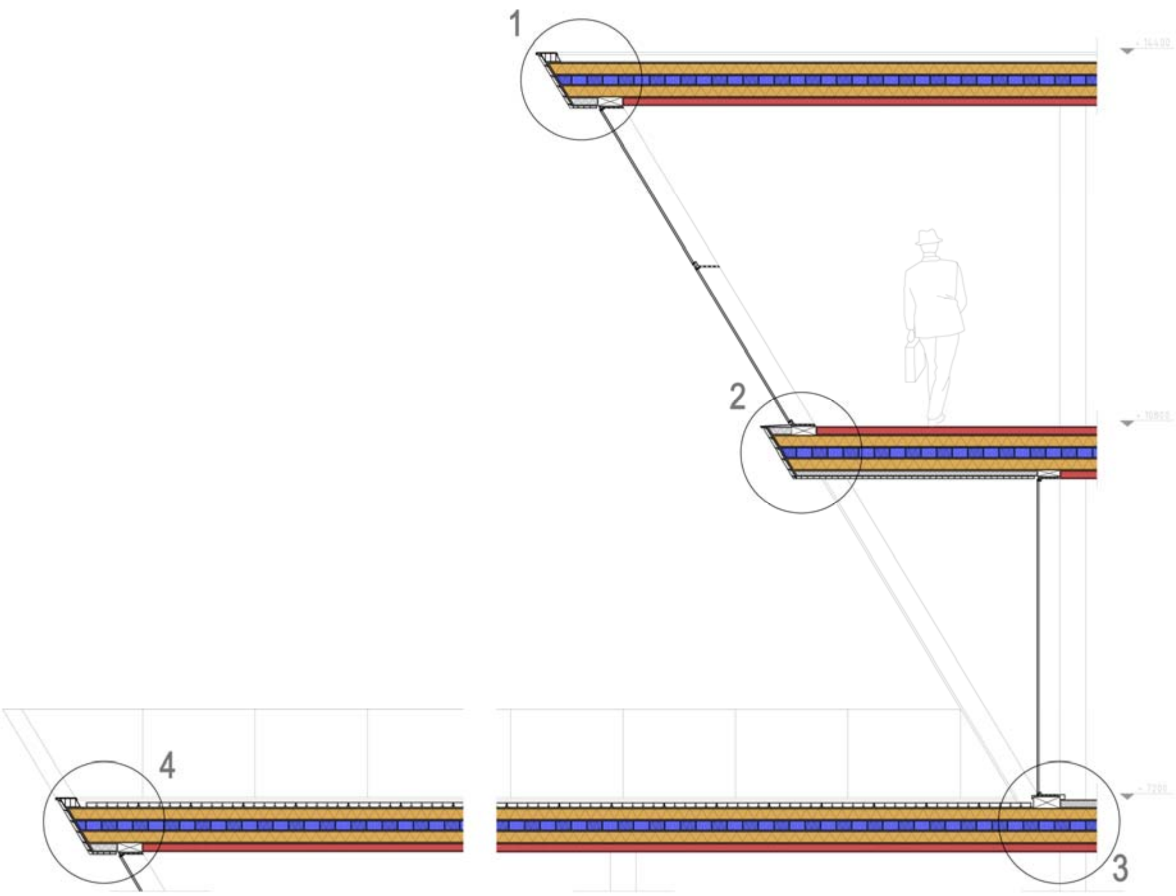


Figure 3: 1/20 section of the floor construction

The orange layers are sandwich elements with a rigid foam core. The core will be made out of a modified phenolic polymer which will transfer the shear between the facing plies. The facing plies itself are a combination of carbon and aramid fibers. This combination ensures that the thermal expansion of the elements will be around zero. The aramid fibers used have a negative thermal expansion coefficient, something which is unique. The carbon fibers have the same thermal expansion coefficient but this time it is positive. Combining the two results in a material which has a thermal expansion coefficient around zero. Doing so makes it possible to make extremely large surfaces without dilatation interruptions.

The outer layers of the floors will also be made from sandwich elements but this time there will be no foam core but instead a honeycomb element is used. These layers are introduced to protect the load-carrying elements against environmental influences from which fire is the most important one. As explained before, the composite layers can be made inflammable with the help of additives but this is not where the problem lies. The heat transmitted from the fire lets the resin melt and as a result the fibers are no longer bounded and co-operating. To prevent something like this from happening, material is positioned in the honeycomb structure which can absorb the heat transmitted by the fire. An example of a material which has the ability to do so is silica. Scientific research has been done after this topic which shows that approaches like this have potential. The idea however is still under developing which makes it difficult to tell whether this will work in a practical situation.

5.2 Calculations

Sandwich constructions are very sensitive when it comes to point loads, which in case of a vertical construction based on columns can be considered a problem. The floors are divided in modular elements which are based on the structural grid. Therefore the dimensions of the floor elements will be 3.6m * 10.8m. This is a relatively large span but due to the use of a construction based on FRP and sandwich elements the thickness of the elements is limited. In order to distribute the stresses to the columns a steel I-beam will be included in the floor elements which prevents point loading of the sandwich construction. Based on this a calculation model has been developed using Excel which by the use of a script generated a list of options for the composition of the floor elements. The thickness of the laminates and the core are a variable in this which means they are calculated from all composite to all core with everything in between. The output only showed the relevant compositions. Figures 4 and 5 show the set-up for the calculations.

HINGED SITUATION

$$w = \frac{5}{384} \cdot \frac{q \cdot l^4}{EI}$$

Bending	w	=	(1/250*l)	300	36,00	
Youngs Modulus	E_FRP polyester woven	=	17200	N/mm2	0,23256	
	E_Foam phenolic	=	4000	N/mm2		
	E_FRP carbon woven	=	68700	N/mm2	0,05822	
	E_FRP aramide isotropic	=	30900	N/mm2	0,12945	
Yield Strength	σ_FRP	=	193	N/mm2		
	σ_Foam	=	2	N/mm2		
Tensile Strength	σ_FRP	=	241	N/mm2		
	σ_Foam	=	4,25	N/mm2		
Length Element	l	=	10800	mm		
Width Element	b	=	1800	mm		
Thickness Glass						
Thickness FRP	t	=	112	mm		
Thickness FRP total	t	=	336	mm		
Thickness Foam	t	=	1	mm		
Thickness Foam total	t	=	3	mm		
Thickness Carbon						
Thickness FRP	t	=	112	mm		
Thickness FRP total	t	=	336	mm		
Thickness Foam	t	=	1	mm		
Thickness Foam total	t	=	3	mm		
Thickness Aramide						
Thickness FRP	t	=	112	mm		
Thickness FRP total	t	=	336	mm		
Thickness Foam	t	=	1	mm		
Thickness Foam total	t	=	3	mm		
Numer of layers	n	=	3			
Glass						
Height layered element	h	=	675	mm		
	z	=	337,5	mm		
Height element	h	=	225	mm		
Carbon						
Height layered element	h	=	675	mm		
	z	=	337,5	mm		
Height element	h	=	225	mm		
Aramide						
Height layered element	h	=	675	mm		
	z	=	337,5	mm		
Height element	h	=	225	mm		

Figure 4: Part 1 of the calculations done on the floor elements

Second Moment of Area	I(xx)_FRP	=	4,61E+10	mm4		
	I(xx)_Foam	=	9,42E+02	mm4		
	I(xx)_Sandwich	=	4,61E+10	mm4		
	I(xx)_Sandwich layered glass	=	4,60E+10	mm4		
	I(xx)_Sandwich layered carbo	=	4,55E+10	mm4		
	I(xx)_Sandwich layered arami	=	4,60E+10	mm4		
	I(xx)_max	=	4,61E+10	mm4		
z_glass	z_1e laag FRP	=	56,5	mm		
	z_2e laag FRP	=	168,5	mm		
	z_2e laag foam	=	225	mm		
	z_3e laag FRP	=	281,5	mm		
z_carbon	z_1e laag FRP	=	56,5	mm		
	z_2e laag FRP	=	168,5	mm		
	z_2e laag foam	=	225	mm		
	z_3e laag FRP	=	281,5	mm		
z_aramide	z_1e laag FRP	=	56,5	mm		
	z_2e laag FRP	=	168,5	mm		
	z_2e laag foam	=	225	mm		
	z_3e laag FRP	=	281,5	mm		
Load Cases	q_glass	=	39,17	N/mm		
	q_carbon	=	36,46	N/mm		
	q_aramide	=	33,19	N/mm		
Weight	FRP polyester glass	=	1800	kg/m3		
	FRP epoxy carbon	=	1610	kg/m3		
	FRP epoxy aramide	=	1380	kg/m3		
	Foam	=	600	kg/m3		
Weight element	FRP polyester glass	=	1209,6	kg/m2		
	FRP epoxy carbon	=	1081,9	kg/m2		
	FRP epoxy aramide	=	927,4	kg/m2		
	Foam glass	=	1,8	kg/m2		
	Foam carbon	=	1,8	kg/m2		
	Foam aramide	=	1,8	kg/m2		
	Sandwich element glass	=	1211,4	kg/m2		
	Sandwich element carbon	=	1083,7	kg/m2		
	Sandwich element aramide	=	929,2	kg/m2		

$$\sigma = \frac{M}{W}$$

$$W = \frac{I}{Z}$$

$$M = \frac{1}{8} \cdot q \cdot l^2$$

$$M = \frac{1}{2} \cdot l \cdot F$$

Load	4550	N				
Temporary load	5	kN/m2				
Safety factor	1,5					
Permanent load glass	11,88	kN/m2				
Permanent load carbon	10,63	kN/m2				
Permanent load aramide	9,12	kN/m2				
Safety factor	1,2					
Total load glass	21,76	kN/m2	1,8	m2	39,17	kN/m
Total load carbon	20,26	kN/m2	1,8	m2	36,46	kN/m
Total load aramide	18,44	kN/m2	1,8	m2	33,19	kN/m

Figure 5: Part 2 of the calculations done on the floor elements

This model calculated three different material combinations all with the same core material:

1 Glass-Polyester
2 Carbon-Epoxy
3 Aramid-Epoxy

Besides different material combinations various compositions have been calculated as well. Laminated sandwich constructions with layers varying from three to five layers have been analyzed in order to make a decision on which combination would be most efficient (figure 6). The reason for using a layered sandwich construction can be found in the failing principle of such a structure. The most common form of failing is the delamination of the composite ply and the foam core. This is followed by rupture of the core itself. Both are the result of fabrication defects which can lead to shear stresses not being distributed properly. Of course stresses being too large on itself can be named as reason as well, however this is very unlikely since in case of a floor application the boundary conditions are based on the usability of the construction and not directly on its material properties. Since FRP materials are extremely strong but in a sense flexible, the yield strength lies far beyond the usability of such an element. In case the core starts to crack there is no turning back which leads to damage and failure of the construction beyond repair. Scientific research, described in Part A of the report, shows the use of a laminated sandwich structure being more controllable than one single element. This is mainly due to the fact that the distance between two FRP plies is reduced and an evenly distribution of FRP over the full height of the element. In theory a sandwich element consisting only of one element would be the lightest and most efficient one in terms of weight and load carrying capacity, however this type of construction is unreliable. Therefore a laminated construction will be used.

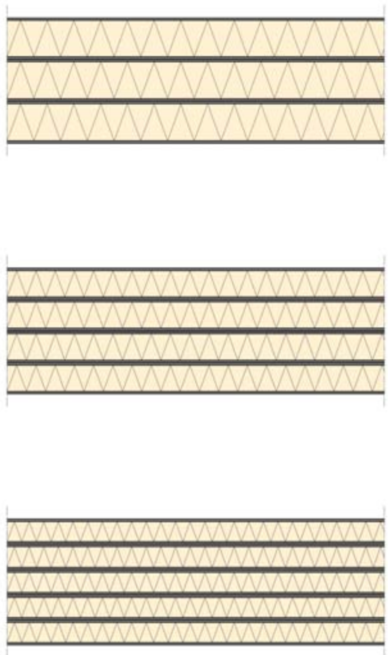


Figure 6: Various sandwich compositions

1		Thickness, mm	Layer, mm	Composite, mm	Deflection, mm	Load, kN/m2	Weight, kg/m2
2	Epoxy Carbon 3	309	103	13	36,49	10,61	264,18
3	Epoxy Carbon 3	300	100	14	36,44	10,62	264,84
4	Epoxy Carbon 3	321	107	12	36,15	10,62	265,32
5	Epoxy Carbon 3	312	104	13	35,83	10,63	265,98
6	Epoxy Carbon 3	333	111	11	36,13	10,64	266,46
7	Epoxy Carbon 3	303	101	14	35,75	10,64	266,64
8	Epoxy Carbon 3	324	108	12	35,52	10,64	267,12
9	Epoxy Carbon 3	294	98	15	35,91	10,65	267,30
10	Epoxy Carbon 3	345	115	10	36,46	10,65	267,60
11	Epoxy Carbon 3	336	112	11	35,52	10,66	268,26
12	Epoxy Carbon 3	348	116	10	35,87	10,67	269,40
13	Epoxy Carbon 3	363	121	9	36,03	10,71	272,34
14	Epoxy Carbon 5	320	64	8	36,20	10,71	272,80
15	Epoxy Carbon 5	305	61	9	36,00	10,72	273,90
16	Epoxy Carbon 5	340	68	7	36,04	10,73	274,70
17	Epoxy Carbon 5	290	58	10	36,35	10,74	275,00
18	Epoxy Carbon 3	381	127	8	36,12	10,76	277,08
19	Epoxy Carbon 3	384	128	8	35,59	10,78	278,88
20	Epoxy Carbon 5	280	56	11	35,99	10,79	279,10
21	Epoxy Carbon 5	365	73	6	35,78	10,79	279,60
22	Epoxy Carbon 5	270	54	12	35,99	10,83	283,20
23	Epoxy Carbon 3	402	134	7	36,28	10,84	283,62
24	Epoxy Carbon 3	405	135	7	35,77	10,86	285,42
25	Epoxy Carbon 5	260	52	13	36,31	10,88	287,30
26	Epoxy Carbon 5	395	79	5	35,76	10,88	287,50
27	Epoxy Carbon 3	429	143	6	36,18	10,96	293,76
28	Epoxy Carbon 5	255	51	14	35,57	10,97	294,40
29	Epoxy Carbon 3	432	144	6	35,70	10,98	295,56
30	Epoxy Carbon 5	430	86	4	36,35	11,01	298,40
31	Epoxy Carbon 5	245	49	15	36,42	11,01	298,50
32	Epoxy Carbon 5	435	87	4	35,57	11,05	301,40
33	Epoxy Carbon 4	360	90	11	39,95	11,09	304,88
34	Epoxy Carbon 4	348	87	12	39,72	11,10	305,76
35	Epoxy Carbon 4	376	94	10	39,75	11,11	306,40
36	Epoxy Carbon 4	336	84	13	39,83	11,11	306,64
37	Epoxy Carbon 3	462	154	5	36,08	11,12	307,50
38	Epoxy Carbon 4	324	81	14	40,25	11,12	307,52
39	Epoxy Carbon 4	392	98	9	40,01	11,12	307,92
40	Epoxy Carbon 3	465	155	5	35,64	11,14	309,30
41	Epoxy Carbon 4	316	79	15	40,00	11,16	310,80
42	Epoxy Carbon 4	412	103	8	40,08	11,17	311,84
43	Epoxy Carbon 4	436	109	7	40,12	11,25	318,16

Figure 7: Calculation results

Figure 7 shows part of the calculation results. Due to the high stiffness of carbon fibers, the top of the lists contains only combinations based on a carbon-epoxy construction. The calculations are all based on standard formulas with the intention to not make the analysis more complex as it is. One of the findings when analyzing the result is the absence of a construction based on four layers in the first thirty results. This can be explained by the fact that in case of an even layered structure, composite layers are positioned in the absolute centre of the element. These parts contribute little to nothing to the stiffness of the construction but they do add weight which makes them less efficient. The decision of which combination to use is partly based on the design concept. A thickness of 500 mm was determined for the floor elements which needs to include everything. Based on this and on the self weight of the elements the decision has been made to use a combination of three layers based on a carbon-epoxy construction. This combination has a thickness little over 300 mm which leaves room to add additional layers which can include building physical aspects and the finishing of the elements. A combination of carbon and aramid fibers can be produced as stiff as the carbon fibers on it self would be. This does not change anything in the composition or the construction height of the elements.

5.3 Construction details

Figure 8 shows one of the details connecting the floor elements with the facade on a continuous floor slab. On the outside there will be no fifth layer which is used on the inside for the finishing. Instead this space is used to apply pultruded planks underneath which water can be drained. By doing so the envisioned thickness of the floors is remained on the inside as well as on the outside. The facade will be based on a combination of pultruded profiles rigidly connected to the glass panes.
How the floor elements are build and how the construction and the facade will cooperate will be explained with the help of a comic (figure 9).

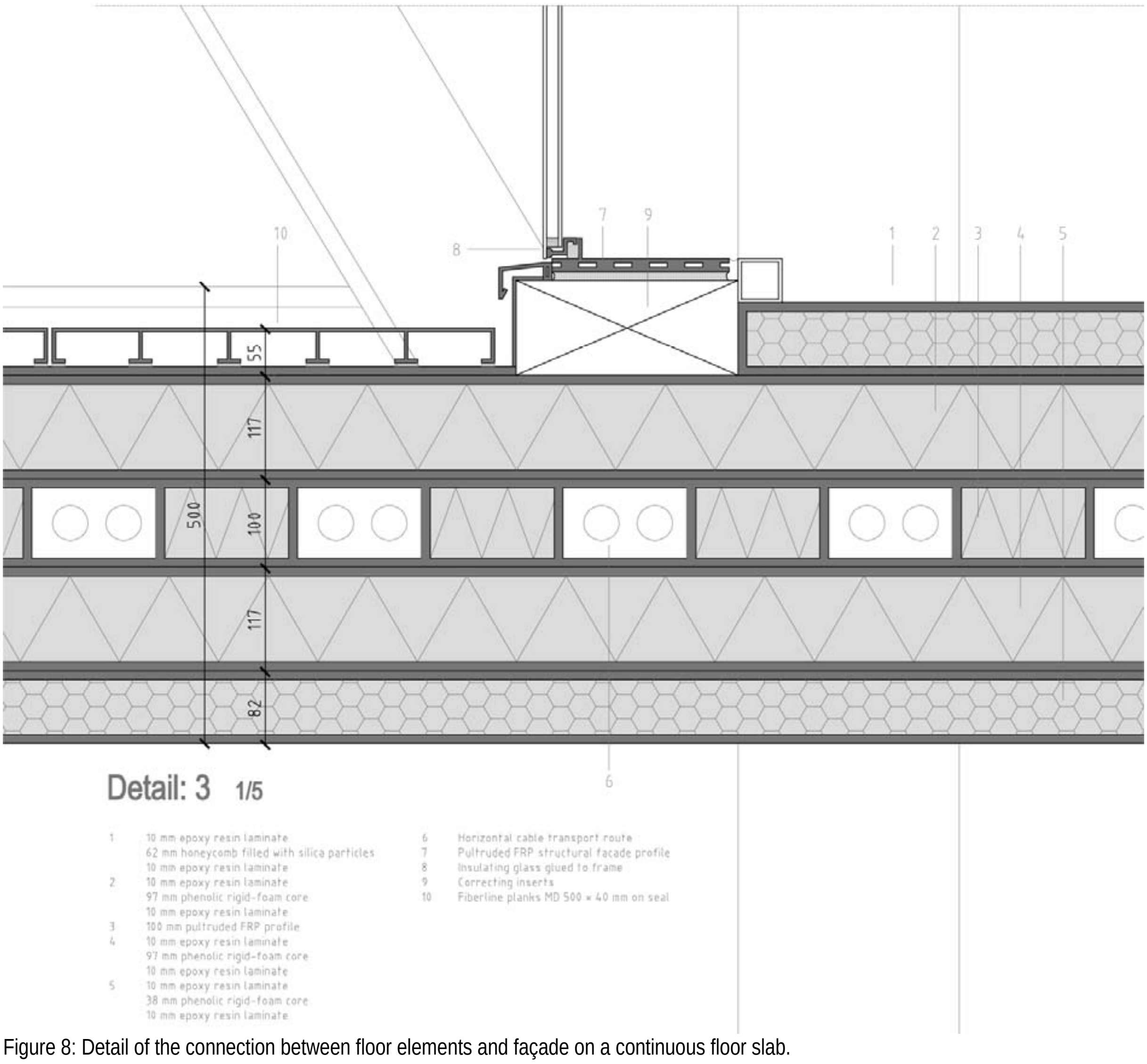


Figure 8: Detail of the connection between floor elements and façade on a continuous floor slab.

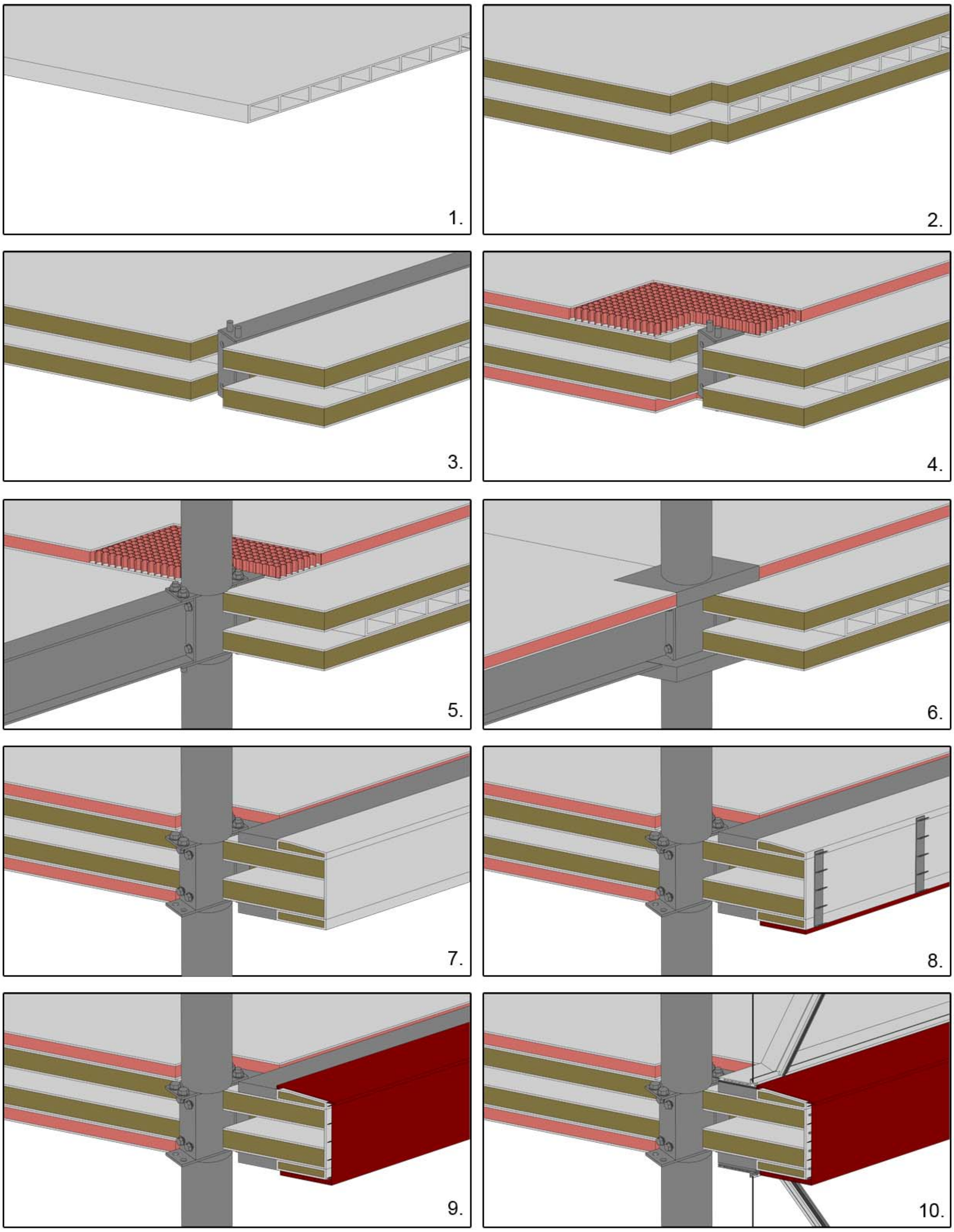


Figure 9: Assembling the floors and finishing

1 The floor elements will be preassembled starting with the hollow core in which cables and ventilation shafts can be placed.

2 On both sides of the hollow element sandwich panels will be attached. These parts are displaced according to the hollow part which forms the connection between various floor elements.

3 To prevent point loading, steel I-beams are included which will be responsible for the evenly distribution of forces along the elements. On the other side of the steel beams there will be the same composition as on the inside. This is possible due to the good thermal conductivity properties of both core and ply materials.

4 Finally the honeycomb based sandwich elements are applied on top and bottom of the elements. The floor elements are now completed and can be transported to the building site.
5 On site they will be connected to the columns with the help of a connection unit. With this unit the floor elements as well as the vertical construction will be connected to one each other. The elements will be connected by bolts.
6 The connection is covered with a special element which hides the connection between the steel elements. This element can be removed if needed.
7 Now the finishing and preparations for the connection of the façade can be made. Adjusting elements are applied even as a sandwich based finishing on the edge of the floor elements.
8 Mounting elements for the floor finishing are applied.
9 The final finishing of the floors is attached in the form of a translucent element behind which lighting can be placed in order to preserve the shape and appearance of the building at night as well.
10 Modular façade elements are placed between the floors. How they will look and function on a technical level will be explored in the second part of the graduation project described in Part C of this report.

5.4 Conclusion

The proposed laminated sandwich construction for the floor elements is highly experimental. This is mainly the result of the contradictions when it comes to the functioning of a sandwich element. In theory the distance between the two facing plies must be as big as possible to generate a large moment of inertia which makes the element stiff. On the other hand are the shear stresses which need to be transported from the one facing ply to the other trough the foam core. In order to do this properly the core needs to be as small as possible. This process cannot be fully understood at this moment. In various scientific studies which have been reviewed there comes no unambiguous solution to mind. As a result of this it becomes almost impossible to verify if the proposed construction will function as envisioned. When it comes to the design, assumptions have been made on how the construction might function in the future. Scientific studies show solutions for the posed problems, however the results in theory and practice do not always agree with each other. Therefore it is impossible at the moment to develop a reliable calculation model for constructions like this. However when looking to the findings in experimental studies this problem is likely to be solved in the near future.

6 Construction of the Rooms

The rooms of the hotel are fully prefabricated modular elements which can be connected to the construction of the transition zone. The amount of rooms present can be determined by the prosperity of the hotel. Along the transition zone rooms can be mounted. In the design proposal the rooms answer the curved movements of the floors however it is possible to fill up the entire transition zone with rooms. The transition zone itself has an important structural role to play as well. This chapter gives insight in the function of the construction and the idea behind the rooms from a structural point of view.

6.1 Construction principle hotel

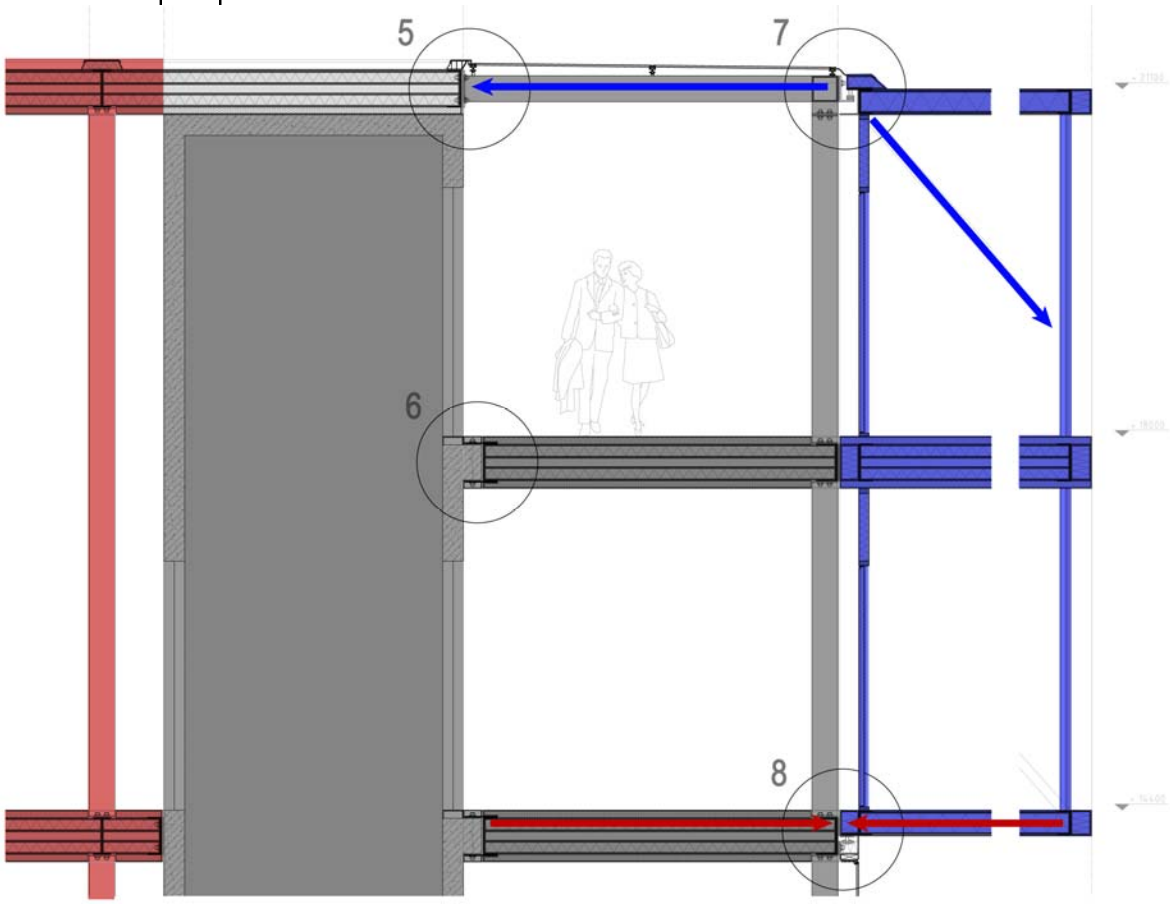


Figure 1: 1/20 section transition zone and rooms

Figure 1 shows a section of the transition zone with on the left the curved floor elements and on the right the modular rooms. The curved floors have their own vertical steel column construction which will be connected to the concrete core. They do so since the core is not as long as the building itself and therefore not always present. Due to their shape a direct connection with the core elements is difficult as well. The right part of the transition zone has to transfer the loads from the rooms to the core. These floor elements are also built with sandwich modules with a similar height as the curved elements have. Due to this, the floors are over dimensioned which leaves room for piping and draining systems being transported from and to the rooms. Steel profiles will be included to transfer the compression stresses coming from the rooms.
The rooms itself will consist of a two storey high sandwich construction reinforced with steel profiles. The arrows in figure 1 show the flow of forces in the construction of the rooms and the transition zone. One particular important part of the construction will be the diagonal steel profile in the walls of the rooms. The rooms come as a duo in order to decrease the stresses in the construction. How the rooms will be mounted can be seen in the next paragraph.

Figure 2: Schiecentrale, Rotterdam

6.2 Construction details rooms

The rooms will literally be hung from the transition zone. A reference project in which similar modules are mounted to the façade will be the 'Schiecentrale' in the city of Rotterdam (figure 2). How this connection will look like can be seen in figure 3 on the next page. Both top and bottom details are shown. To the transition zone steel adjustable elements are mounted from which the rooms can be hung. A flexible connection between the façade of the transition zone and the rooms is made in order to seal the building.

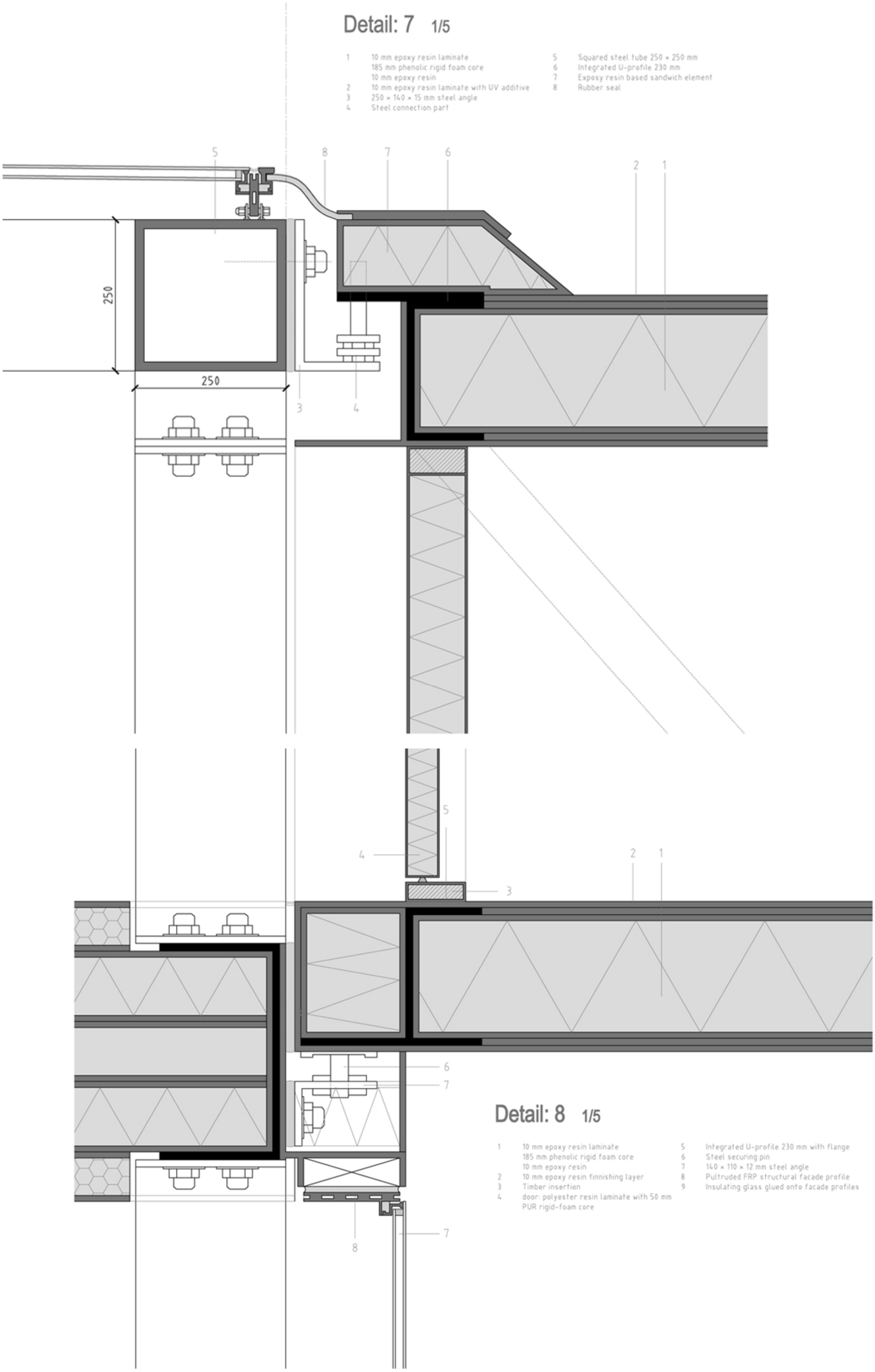


Figure 3: Top and bottom detail Construction rooms

PART C

Composite Façade Design

Building Technology

Dual Graduation Track

PART C

1 Starting position design & Research question

This chapter describes the starting position of the building technology part of this dual graduation track. In order to have a structured design process, the architectural concept and the research question are explained as well as the approach which has been used. Together these paragraphs form the basis for this project. The architectural concept of the building as well as the building itself are described in Part B of this report. This parts main focus lies on the design of the façade from a technological point of view.

1.1 Starting position design

The expression of the building is determined by the curvature of the floor elements which are pushed through the façade (figure 1). The façade itself is almost 100% transparent and placed between the floor elements. As a result of this, difficult locations arise due to the curvatures. No functions other than separating the inside from the outside and offering a view outside have been implemented in the façade so far. In the current design the façade consists of diamond shaped elements who do not take any notice of the curved lines which run through. At first sight this might not seem to be a problem because the profiles used in the façade are extremely slender which makes them almost invisible. When taking a closer look at the places where the floor elements cross each other, it becomes clear that there are problematic places which ask for a design solution instead of a technical solution. The front façades are all similarly shaped in an orthogonal way, which makes that they have less problems fitting in. In a way one could say that the current design shows the envisioned design concept, but has not yet taken a proper form.

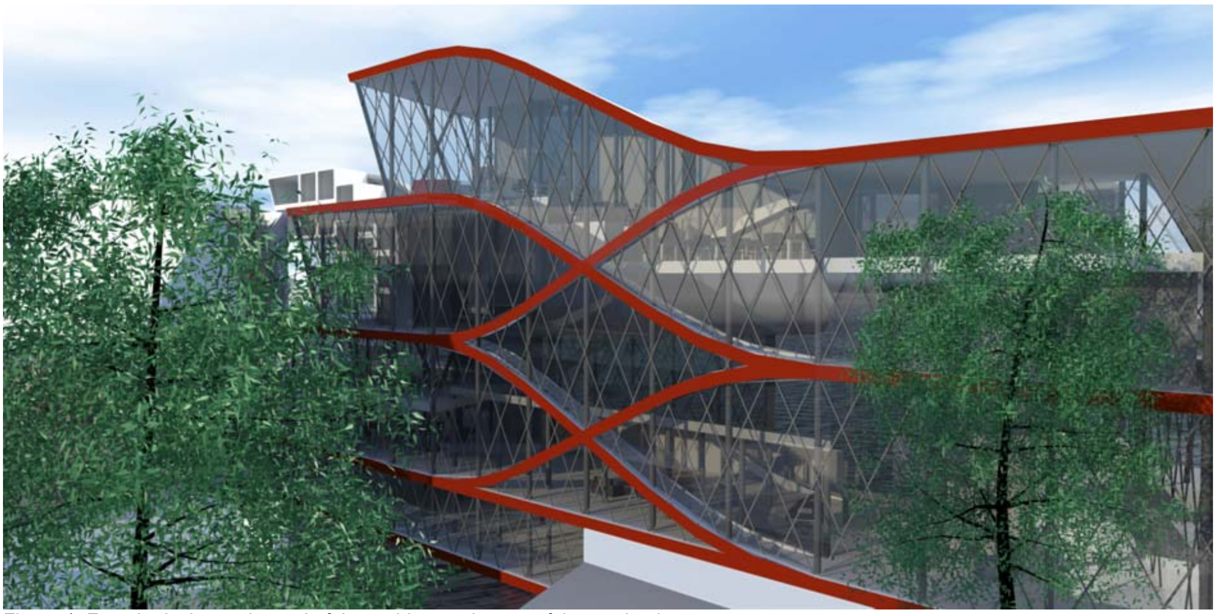


Figure 1: Façade design at the end of the architectural stage of the graduation process

1.2 Research question

Composites have been the starting point for the architectural design of a hotel. The whole architectural concept is based on the free form possibilities composites have to offer, which in case of the hotel are represented by the construction of the floors. In this part the façade will be explored into depth from both the architectonical and technological perspective. The technological research will be used to guide the design. Composites represented by fiber reinforced polymers (FRP) are the starting point for this research and design project. The main research question of this trackwill be:

How can an innovative FRP based façade support and enrich the architectural design?

The envisioned architectural concept of floors shaping functions and being represented in the façade has to be guarded at all times. The façade has to accentuate this design concept which in a way makes that the floors are the most important elements of the façades and the actual façade has to fill the spaces in between. This however does not mean that the façade is to be a dull and emotionless part of the design in order to make the curved floor lines look more interesting, the contrary has to be the goal.

1.3 Approach

It might be clear by now that special interest will go out to the development of a façade based on the possibilities FRP's have to offer. The properties of this specific group of materials have been explained in depth in Part A of this report so they are not

to be explained in this part. However this background knowledge has influenced the design and the decision making during the process. Knowing the possibilities of FRP, the first step in designing a façade has to be the determination on what a façade should be and the functions it should fulfill. Besides that, knowledge has to be gained about the development of FRP in façades with a link to the architectural as well as the technological expression. Parallel to this stands the question of how a façade based on FRP could be built and produced and what consequences this might have for the design. Producing and combining elements are part of this question.
Forgetting about the technical options, a design research was done after the façade layout and the question how this could enrich the architectonical concept of the hotel. After taking a realistic look to the research done so far, the design and the engineering are combined to become a smart and practical design. The final step will be the implementation of the façade in the already present design of an hotel and take notice of the changes in expression and experience of the building as a whole.

2 Façade functions & design

What exactly is a façade? What functions could and/or should one fulfill? These questions will be answered in this chapter. The main goal of this will be to set the boundary conditions for the technical design. In theory everything is possible but however not always desirable. Determining the conditions the design should meet make the process as efficient as possible.

2.1 Definition of a façade

The façade forms a protective layer around a building, influencing both the internal and external appearance. Functions applied to the façade are becoming more and more important when it comes to the functioning of a building as a whole. Especially the influence they exercise on the internal space asks for careful decision taking in order to guarantee proper functioning of the building. All these functions integrated into the building skin generate a certain complexity which can only be unraveled when all functions are reviewed as an integral part of the design. There are three questions which are vitally important:

1. Function: What is the practical purpose of the building/the building skin?
2. Construction: What are the elements/components of the building/the building skin and how are these elements assembled into a whole?
3. Form: What does the building/the building skin look like?

These categories are related and need to be treated as such in order to achieve the desired result. In terms of comfort it could be stated that functional properties are more important than structural, aesthetical or ecological aspects. On the other hand they are directly related and influence each other in such a way that they need to be equally reviewed in the total building design. The building skin itself is the most dominant system of all building systems and not only in terms of design. A number of vital functions are fulfilled by the skin and it is also a principal factor in the energy consumption of a building. When talking about the building skin, we more specifically talk about the façade and the roof of a building. Despite their different positions, their functions are very similar and the difference between the two can be hard to determine.

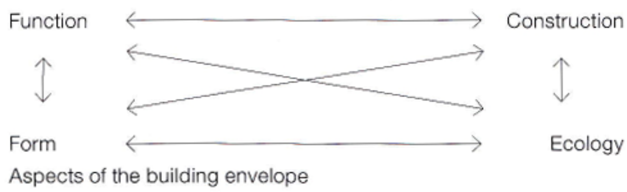


Figure 1: Aspects of the building envelope *(source: in DETAIL: Building Skins)*

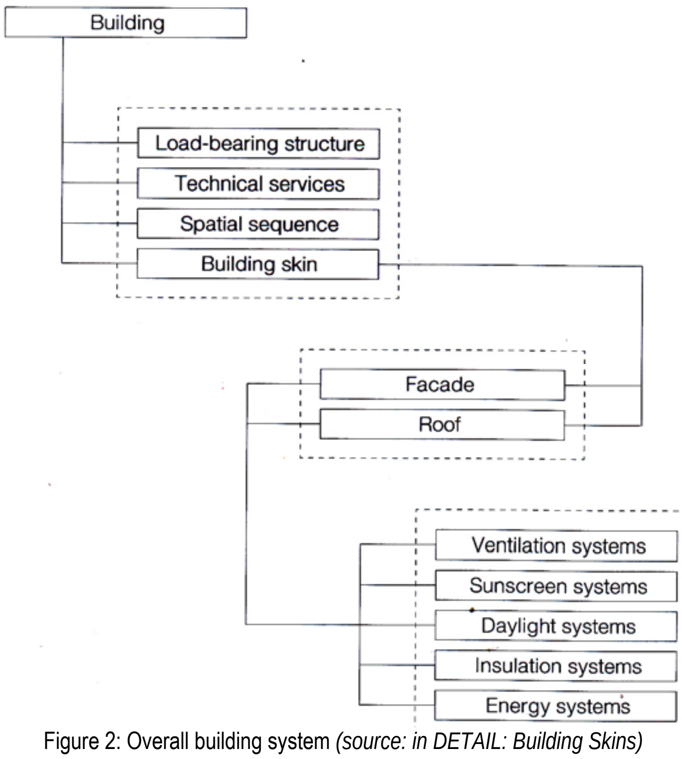


Figure 2: Overall building system *(source: in DETAIL: Building Skins)*

The building skin needs to regulate the conditions on the outside in order to provide a comfortable interior climate. The term comfortable is relatively vague and generally based on personal experience. However comfort is the basis on which specifications are based for walls and roofs. In order to do this in such a way that not only one individual user of the building finds themselves comfortable but as much users as possible do, parameters are connected to the term comfort in order to create something which can be measured and controlled.

2.2 Functions of a façade

Figure 3 illustrates the variety of functions which a façade needs to fulfill in order to work properly. In principle it will be up to the designer to determine which functions are integrated and which ones are left out. Some of the functions can be taken over by the building cores or other parts of the building. However this could be considered a step back in terms of energy control since this in almost all cases means functions are regulated in a mechanical way far from the location they actually take place, like ventilating. Nevertheless there are several other factors which need to be considered besides the energy consumption of a building which might lead to different conclusions. These requirements when determined can bring forward an archetype of the façade desired which on itself can become the basis of the design. Figure 4 shows a procedure for determining boundary conditions and requirements.

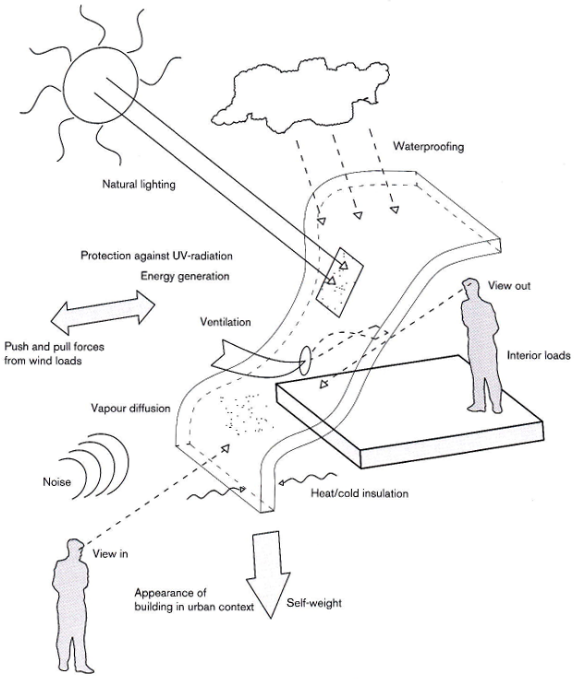


Figure 3: Facade functions *(source: Facades: principles of Construction)*

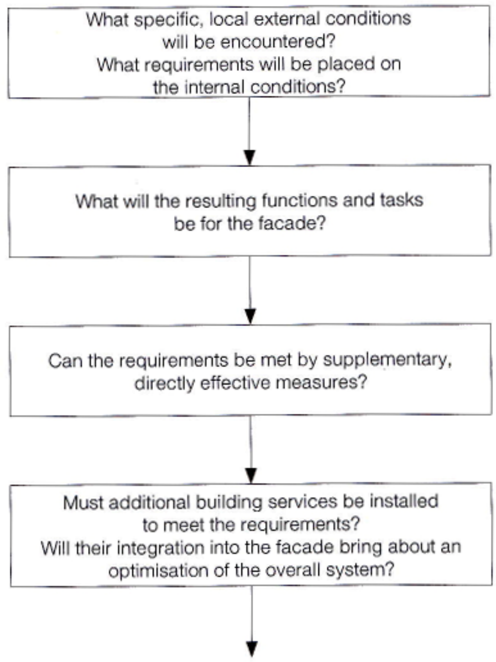


Figure 4: Determining boundary conditions *(source: Façade construction manual)*

2.3 Functions present/envisioned

Figure 5 shows what functions are present in the façade at the beginning of this track. The façade at this point is not much more than the fill between the floor elements. In an architectural concept this indeed might be the case however as described earlier, the façade is much more than this. The system embedded at this stage of the design is limited to a daylight system with virtually no control over it.

The envisioned functions of this façade are shown in figure 6. With the exception of one, all functions shown are desired in the new façade. The exception here will be the generation of energy within the façade. Nowadays this is a hot topic, however since this research will focus on the material in combination with construction, this is a topic one could do without in order to stay in control over the project.

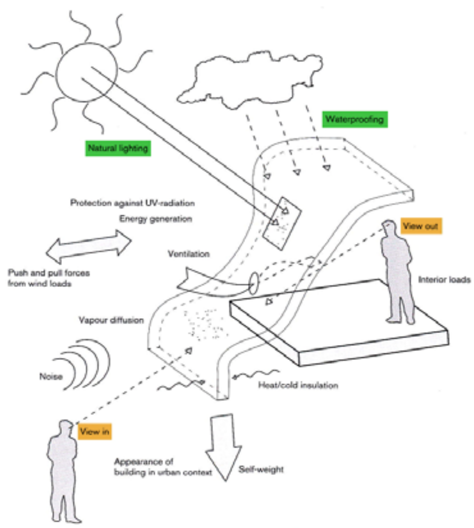


Figure 5: Facade functions present

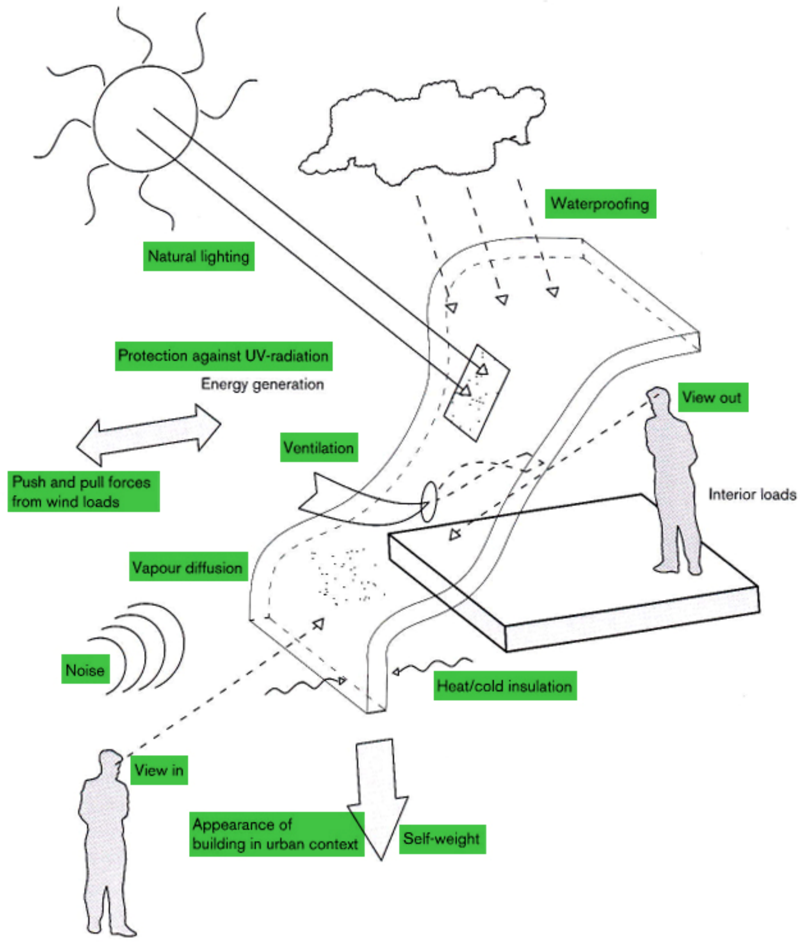


Figure 6: Facade functions envisioned

2.4 Conclusion

The various aspects of the building envelope and in this case the façade, need to be considered very carefully in order to come up with a design which fits all requirements. Besides trying to implement all possible functions in the façade one should also consider the consequences of doing so. Functions which are left out of the façade design need to be fulfilled by the construction or other parts of the building. The opposite might also be true, however the contribution and the complexity of such a shift in functions should be taken into account to avoid losing the main focus of this project.

Deplazes A., et. al., *Constructing Architecture, materials processes structures,* (Basel, 2008)

Herzog, Krippner, Lang, *Façade Construction Manual,* (Basel, 2004)

Knaack U., Klein T., et. al., *Facades: Principles of Construction,* (Basel, 2007)

Schittich C., *In DETAIL: Building Skins,* (Basel, 2006)

3 Development FRP in facades

A brief history of the development of FRP in façades is required in order to understand the possibilities with the material in practice. What does the material mean for the expression of the building and what technical progress in relation with conventional materials can be distinguished? The last part of this chapter will describe several projects from different periods with the intention to visualize the developments with FRP.

3.1 Development of FRP architecture

FRP has been used as a façade material since the 1950s. Initially plastics were only used for furniture and small precise objects but due to the development and use of new production processes it became possible to produce complete buildings. The use of glass fiber reinforced moulded parts are the main reason for this step forward in the use of plastics and especially FRP's as a building material. The development of FRP dates from the 1940s but it took until the late 50s before a building made completely out of FRP was produced. During that period polyester resin in combination with the industrial scale production of glass fibers was discovered as a potential building material. The Second World War turned out to be a hold back on the one hand and a catalyst on the other. During the war almost all production capacity was invested in the production of military material. During this period production processes were optimized and new applications were introduced, like the self-supporting radio domes made out of FRP, one of the first structures which has actually been build. After the war these production capacities were available for non-military uses once again.[1] Besides the over capacity, FRP and other materials were also used to compensate for the lack of conventional building materials available after the war. The first residential building made of plastics was built in 1956 in France. The building consisted of flat and curved GRP sandwich panels with GRP stiffening ribs. Figure 1 shows a mobile hotel cabin dating from the same year which gives an indication of the new building material.

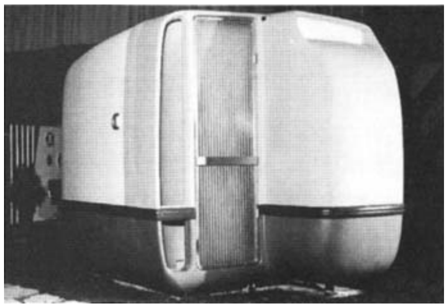
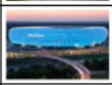


Figure 1: GRP hotel cabin *(source: Plastics in architecture and construction)*

3.2 Application of FRP, the early years

The introduction of FRP sandwich panels with a PUR core made it possible to create lightweight and rigid elements which were suited for self supported building skins. In the early days of building with plastics as well as nowadays, production costs are proportionally high. Therefore architects and researchers are always looking for ways to make the process as cost efficient as possible. The first façades made out of FRP date from the late 1950s and the early 1960s. These were actually complete buildings with a construction and a skin based on plastics. Figure 2 shows a list of buildings which have a plastic building skin, not all of them are made out of composites. The projects are sorted by year of completion which as a result gives an overview of the evolution of the plastic building skin. As can be seen in the figure, there is a gap between the early 1970s and the late 1990s. This gap is the result of the way people looked at the material. As can be seen the first plastic buildings are all FRP based self supporting single storey houses. These houses were all designed for mass production, however in most cases only the prototype was ever build. Nevertheless these buildings showed the expression of plastic architecture and the language which has come along with it. The design possibilities of the new material became known to the general public. The curved building elements are not only applied to give the buildings a futuristic expression, but also because they increase the stiffness of the material, this however is only a part of the truth. The most efficient way of carrying loads is when only normal forces are present in the supporting structure, hence the curved elements which makes the flow of forces more efficient. This principle holds for every material but it lies not in the nature of every material to take such shapes, something which comes naturally to plastics. On the one hand people were inspired by the design and shapes of the new plastic houses but on the other hand they were not yet ready to give up there traditional way of living. A difficulty on the side of the architects was placed in the question: how to create a mass production house with a custom expression. In the early 1970s not a single house was taken into mass production. Various reasons can be listed for this such as the oil crisis which led to a considerable rise in the price of plastics and the fact that the new plastic houses were as expensive as a traditional house but smaller. Besides moral and financial problems, there were also technical issues with the build houses like mould, delamination etc. The poor fire behavior of the material is something that needs to be taken into account as well. The sum of all this led to the end of the experimental era in which the basic starting points of building with plastics and especially FRP were discovered.

[1] Knippers J., Cremers J., et al, *Construction Manual for Polymers + Membranes,* (Munich, 2011)

Project			Image	Appearance of building in urban context	Energy generation	Energy storage	Interior loads	Insulation (heat/cold)	Load-bearing	Natural lighting	Noise	Self-weight	UV protection	Vapor diffusion	Ventilation	View in	View out	Waterproofing	Wind loads		*Composite*
House of the Future	design: location: completion:	Richard Hamilton & Marvin Goody California, USA 1957		X				X	X	X	X	X	X	X		X	X	X	X		X
Bulle Six Coques	design: location: completion:	Jean Maneval Nantes, France 1967		X				X	X	X	X	X	X	X		X	X	X	X		X
FG 2000	design: location: completion:	Wolfgang Feierbach Altenstadt, Germany 1968		X				X	X	X	X	X	X	X	X	X	X	X	X		X
Futuro	design: location: completion:	Matti Suuronen different locations worldwide 1968		X				X	X	X	X	X	X	X		X	X	X	X		X
Zip-Up House	design: location: completion:	Richard Rogers - 1969		X				X	X	X	X	X	X	X	X	X	X	X	X		X
Venturo	design: location: completion:	Matti Suuronen Helsinki, Finland 1971		X				X	X	X	X	X		X	X	X	X	X	X		X
Idee Workstation	design: location: completion:	Klein Dytham architecture Tokyo, Japan 1996								X		X	X	X		X	X		X		
BMW Bubble	design: location: completion:	Bernhard Franken, ABB Frankfurt, Berlin, Germany 1999		X						X		X		X		X	X	X	X		
Hotel Burj al Arab	design: location: completion:	Atkins, Epsom Dubai, United Arab Emirates 1999		X				X				X	X	X				X	X		
Eden Project	design: location: completion:	Nicholas Grimshaw & Partners Cornwall, United Kingdom 2001		X				X		X		X		X		X	X	X	X		
National Space Centre	design: location: completion:	Grimshaw Leicester, United Kingdom 2001		X				X		X		X		X		X	X	X	X		
Polymer Engineering Centre	design: location: completion:	Cox Architects & Planners Melbourne, Autralia 2001		X				X		X	X	X	X	X				X	X		X
Terminal V	design: location: completion:	Hugo Dworzak Laurerach, Austria 2002		X				X			X	X	X	X				X	X		X
Information Pavilion	design: location: completion:	Mario Cucinella Bologna, Italy 2003		X						X		X				X	X				
Kunsthaus Graz	design: location: completion:	Peter Cook / Colin Fournier Graz, Austria 2003		X				X		X	X	X	X	X				X	X		
Laban Creekside	design: location: completion:	Herzog & de Meuron London, United Kingdom 2003		X						X		X	X					X	X		
Allianz Arena	design: location: completion:	Herzog & de Meuron Munich, Germany 2005		X				X		X		X	X	X				X	X		
Private House	design: location: completion:	Pfeifer Roser Kuhn Müllheim, Germany 2005			X		X	X		X		X	X	X	X			X	X		
Badajoz Congress Centre	design: location: completion:	SelgassCano Badajoz, Spain 2006		X								X			X	X	X				X

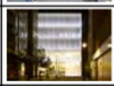
Project				Appearance of building in urban context	Energy generation	Energy storage	Interior loads	Insulation (heat/cold)	Load-bearing	Natural lighting	Noise	Self-weight	UV protection	Vapor diffusion	Ventilation	View in	View out	Waterproofing	Wind loads		Composite
Fiberline Factory	design: location: completion:	KHR Arkitekter Middelfart, Denmark 2006		X				X	X	X	X	X	X	X		X	X	X	X		X
Private House	design: location: completion:	Takeshi Hosaka Minamituru-gunn, Japan 2006						X			X	X	X	X				X	X		X
Loftcube	design: location: completion:	Studio Aisslinger Munich, Germany 2007		X				X	X	X	X	X	X	X	X		X	X	X		X
Reiss Headquarters	design: location: completion:	Squire and Partners London, United Kingdom 2007		X						X		X				X	X		X		
Tea House	design: location: completion:	Kengo Kuma & Associates Frankfurt am Main, Germany 2007		X					X	X		X		X				X	X		
Chanel Mobile Art Pavilion	design: location: completion:	Zaha Hadid Architects Hong Kong, Tokyo, etc 2008		X				X		X	X	X	X	X				X	X		X
Aero House	design: location: completion:	Richard Horden, Wieland Schmidt various 2009		X				X	X	X	X	X	X	X		X	X	X	X		X
Dornier Museum	design: location: completion:	Allmann Sattler Wappner Architekten Friedrichshafen, Germany 2009		X				X		X	X	X	X	X		X	X	X	X		
In Holland	design: location: completion:	Rietveld Architecten Delft, Netherlands 2009		X				X	X	X	X	X		X		X	X	X	X		X
Office Pavilion	design: location: completion:	Selgas Cano Madrid, Spain 2009		X				X	X	X		X	X	X	X	X	X	X	X		X
The Walbrook	design: location: completion:	Foster + Partners London, United Kingdom 2009		X			X			X		X	X			X	X		X		X
Stedelijk Museum	design: location: completion:	Benthem & Crouwel Architects Amsterdam, Netherlands 2011		X				X			X	X	X	X				X	X		X

Figure 2: Evolution of the plastic building skin

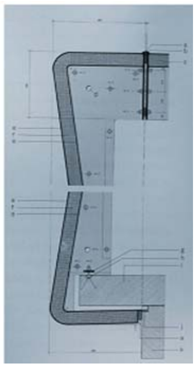
3.3 Application of FRP, nowadays

It took until the late 1990s before the search for plastic applications in buildings continued. At that point several new production methods are improved which allows an even greater freedom for the designer. No longer are complete buildings made out of plastics but only specific parts. The façade is one of these parts. However, during this period plastics are not used in a constructional way. This is the result of the safety regulations belonging to the technical properties of the material. With a few exceptions this is still the case at this very moment. As a result of the extensive production options, unique elements are made only to be used in a single project. The result of this is that its no longer the futuristic expression of a building which reminds of the use of plastic but the unique shapes and applications for which plastic is used. Besides FRP there are also a great variety of other plastics which can be and are used in building skins. All have their own expression and in most cases their own function.
Due to resent developments in the field of material science, FRP as a constructional façade material is starting to become optional. Besides the conventional materials used for façade constructions like wood, steel and aluminum. FRP will contribute to this list in its own way; with its own design and technical possibilities which will result in a contemporary expression. Besides this the use of FRP also benefits building with prefab elements.

3.4 Reference projects

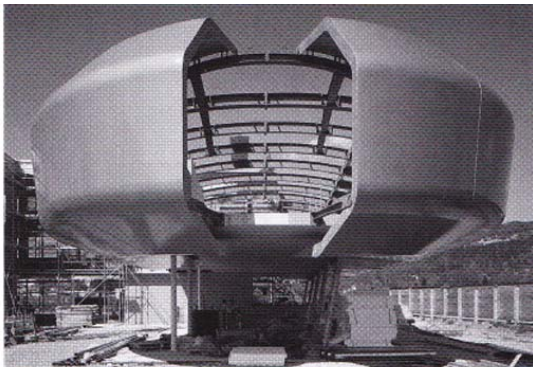
Four reference projects have been selected and are shown on the following pages. Each project shows a façade entirely or partly based on FRP's. Besides an overview of the building a detail of the construction is shown. The selected buildings each represent a period in the development of FRP in architecture.





Architect: Wolfgang Feirerbach
Building: FG 2000
Year: 1968
Location: Altenstadt, Germany
Source: Plastics in Architecture and Construction

FG 2000 is a prefabricated detached house conceived and built in a contractor's workshop. It is an example of a modular construction using plastics. The individual elements are sandwich elements with 4-6 mm thick FRP layers on each side of a 60 mm thick rigid PUR foam core. The plastic upper storey of the FG 2000 can be erected within one day without the need for heavy lifting machinery. This building dates from the time that only small buildings could be made. The fact that only the upper storey is made out of FRP shows the fact that the technical knowledge on how to optimize this material for construction was not gained yet. However the prefabricated modules and the assembly method are very innovative for 1968. Also the use of FRP as façade and self-supporting structure at the same time is typical and innovative. The buildings, mostly houses, dating from this time all have the same principle. The outer walls are slightly curved, which is not only done out of aesthetical considerations but mainly out of technical considerations. The fibers used in the composite are now subjected to bending stresses instead of only normal stresses parallel to the fibers. This would have resulted in the matrix carrying the loads since the fibers are unable to carry loads in that direction with only a layer thickness of a couple of millimeters. Buckling of the fiber structure is something to be avoided at all times.

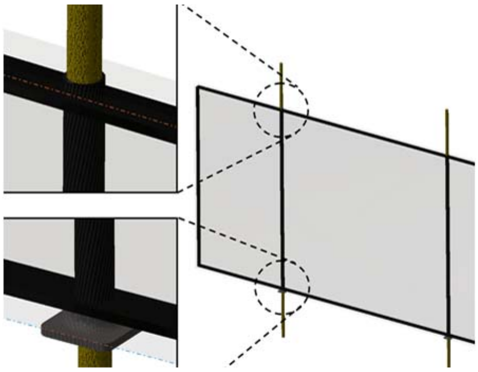
Architect: Hugo Dworzak
Building: Terminal V
Year: 2002
Location: Laurerach, Austria
Source: Plastics in Architecture and Construction

This project dates from the time FRP's and other plastics were about to be used for specific parts of the building and the façade only. No longer was the entire façade including construction made of composites due to the limitations of the material. In this case FRP is used to create a shell around a steel structure which in itself is not very innovative however in this case that was not the intention. Here FRP is mainly used to create a virtual experience for clients who visited the company. The expression of the building is determined by this and also evokes a feeling of plastics being used due to the smoothness of the surface and the shape of the elements. Only three different modules are used to generate this shape. All elements have a width no wider than 2.5 meters for transportation reasons. The shape of the building required that the modules were produced by hand. In case a much larger amount of elements was needed the elements could have been produced with the use of compression moulds. However this is a very expensive production method due to a costly mould which only becomes profitable if large quantities are required.

Architect: Foster + Partners
Building: The Walbrook
Year: 2009
Location: London, United Kingdom
Source: Construction Manual for Polymers + Membranes

This office building has a façade with an area of 14 000 m^2 which is filled with FRP sun shading elements. This is the first building in which FRP is used on such a scale. The result of this is that more expensive production methods became profitable which resulted in small tolerances and a minimalistic finish of the construction. The moulds for the 4000 louvers were made out of CNC milled PUR foam. The metallic paint gives the impression that the elements are made from steel but more importantly this reflects the light into the interior. Depending on time of year and time of day, the direct sunlight is screened of. The geometry of the elements was developed digitally by the use of a parameterized 3D model. Without this model it was virtually impossible to handle the large amount of different shapes. The size of the building made the use of FRP profitable. As mentioned before, the production methods are expensive but necessary to generate the amount of elements in an acceptable amount of time. The appearance of the building is highly determined by the use of FRP even when only used for one function of the façade. This period of using FRP characterizes itself by using the material in a way suitable to its properties.

Architect: Rietveld Architecten
Building: InHolland
Year: 2009
Location: Delft, Netherlands
Source: factsheetcomposietgevel.pdf

Another project in which the use of FRP determines on a high level the appearance of the building is the InHolland building in Delft. However the FRP is hardly visible, nevertheless it is used for the construction of the façade. This is a highly innovative façade which is shown by the comparison between the theoretical design and the realized facade. This curtain wall façade has a construction of specially developed glass/Kevlar tension cables which theoretically should run within the glass element, delivering a perfectly flat façade on both sides with a thickness of only 45 mm and a height of 13 meters. However due to the deflection of the façade, something encountered during the design period, the cables are mounted onto the glass frame instead of being positioned between the glass panels. None of the parties involved in this project was found willing to take the responsibility for the possible failure of the construction. Nevertheless an impressive façade was build in which FRP plays the lead part. This façade became possible due to resent developments in the field of producing altered fiber structures which could improve the composite material for very specific purposes. The façade design shows the options one has not only to develop FRP in architecture but also to reinvent conventional building methods.

3.5 Conclusion

The development of FRP in architecture has led to a point on which no longer complete structures and façades are made out of composites but only specific parts of the façade. By doing so the scale on which the material can be used went from small houses to large office buildings. The variety of functions which can be represented by FRP materials show that this material is far from being developed completely. In the design the material is intended to be used for the *construction* of a façade which is also a new field on this scale. However the search for a combination of functions represented by FRP should continue.

Cobbers A., Jahn O., *Prefab Houses,* (Köln, 2010)

Engelsmann S., Spalding V., Peter S., *Plastics in architecture and Construction,* (Basel, 2010)

Herzog, Krippner, Lang, *Façade Construction Manual,* (Basel, 2004)

Knippers J., Cremers J., et al, *Construction Manual for Polymers + Membranes,* (Munich, 2011)

Schittich C., *In DETAIL: Building Skins,* (Basel, 2006)

http://www.inholland.nl/NR/rdonlyres/8589260B-7E26-42F0-9D29-1C04A9D622CA/0/Factsheetcomposietgevel.pdf

4 Prefabrication – Modular - Unitized

Due to the high production costs of FRP materials and the difficult connection methods, preassembly and the use of reference systems is something this material benefits from. This chapter gives insight on the different definitions and shows the system used in the architectonic design. Also the intentions according to the production of the façade, yet to be developed, are explained.

4.1 Prefabrication

The façade is an assembly of individual parts since it usually cannot be produced in one single piece. The design as well as the designer determine to which degree a façade is split up. This separation, or scale can be listed as below:

- system
- subsystem
- component
- element
- material

When working with FRP, prefabrication is something a designer should consider very seriously. The type of connection chosen determines for a large part if prefabrication is necessary or optional. In general one can state that a connection with adhesives needs to be made in a controlled environment. This is something one rarely finds on a building site, hence these types of connections should be made in a factory or in a similar environment. Bolted connections can be made on site as well as in a factory since they are less dependent on a controlled environment. Besides the choosing of a connection type, there are other factors which might be considered advanvantegous when it comes to prefabrication. Working with preassembled parts generally means speeding up the building process, less weather dependent, decrease of manual labor on site and better quality control.

4.2 Modular system

Besides prefabrication of façade parts, working with FRP also tends to benefit from the presence of a modular system. A modular system is a way of dimensional coordination by the use of modules. Generally this dimensional system has its origin in the construction of a building, however this is not always the case. Production restrictions, transportation, weight, etc., are all aspects which can influence the dimensional system used in a building. Every building has a dimensional system but it is not in every building that this dimensional system is used in the form of a modular system. This dimensional coordination serves to establish rules for the sizes of components on which to base the planning, production and erection[2]. In case of FRP the use of a modular system can be profitable since the production costs of elements are high and often manual labor is required which also means an increase of cost.

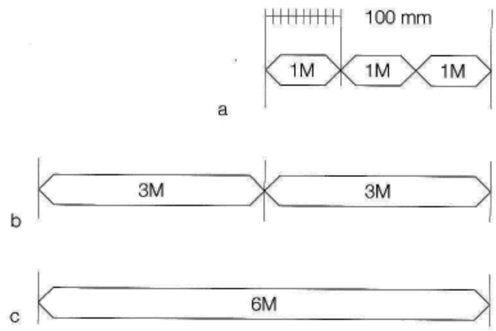


Figure 1: Dimensional coordination *(source: Façade Construction Manual)*

Reference system

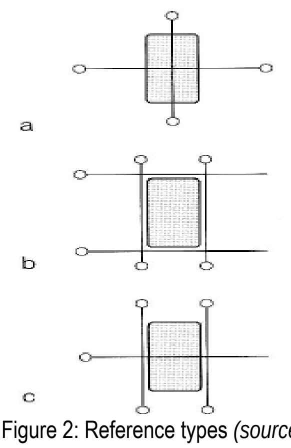


Figure 2: Reference types *(source: Façade Construction Manual)*

When decided that a modular system will be used, a reference system is required to determine the position and relation of the modular elements. Three types of references are optional: planes, lines or points. In essence this results in a grid on which the complete design or parts of it can be based. The grid lines are based on the modular dimensioning system explained before. In principle there are two ways one can relate elements to a modular grid:

- axial controlling lines (figure 2 – a)
- face controlling lines (figure 2 – b)

Axial controlling lines determine the position of an element, face controlling lines determine position as well as dimension. A combination of these two principles is also possible (figure 2 – c). In this case the position of an element is determined in one dimension and its size is

[2] Herzog, Krippner, Lang, *Façade Construction Manual,* (Basel, 2004)

determined in the second dimension. Besides these three types of modular grid systems, one can also distinguish a separation in primary and secondary grid systems. In most cases the primary grid is similar to the structural grid in which case the secondary grid in most cases is similar to the planning grid. Figure 3 shows the various ways these two grid types can be combined. At corners these systems and other boundary conditions are likely to cross each other (figure 4).

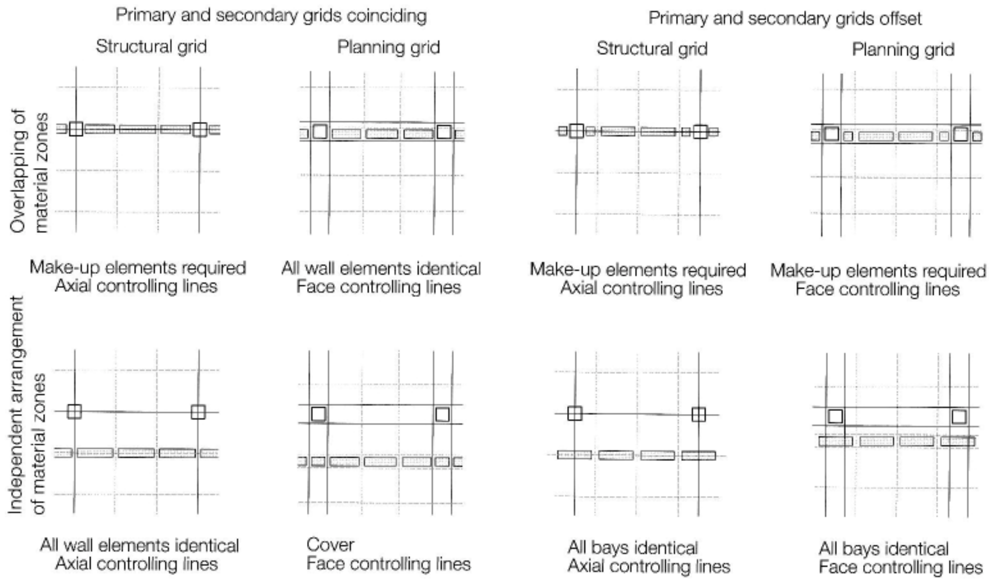


Figure 3: Primary and secondary grids *(source: Façade Construction Manual)*

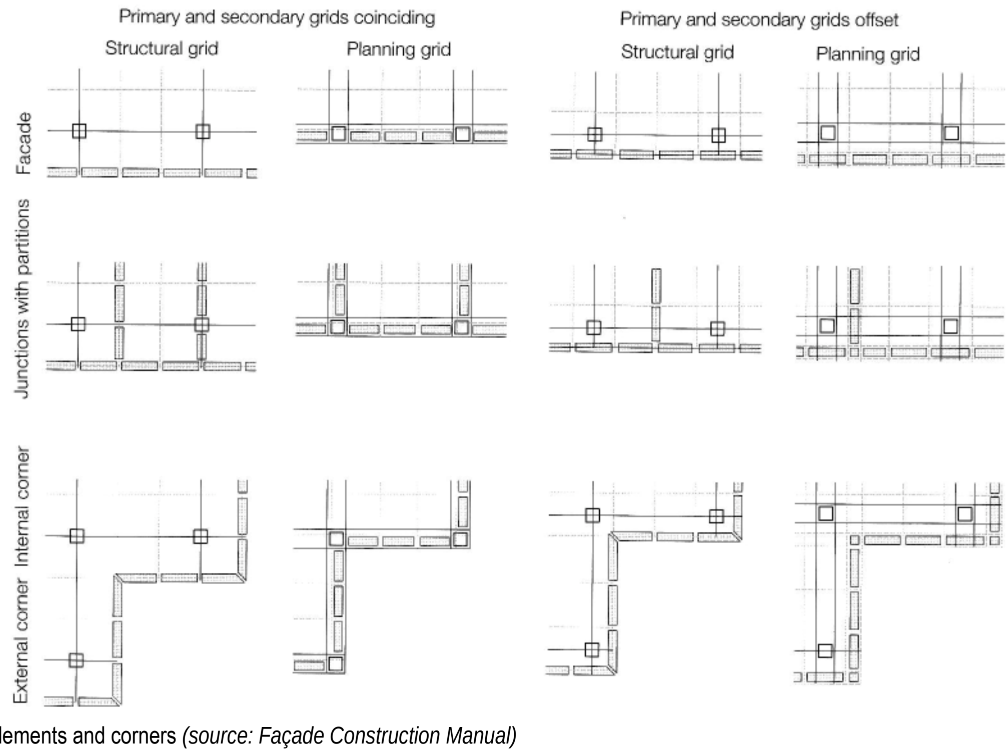


Figure 4: Elements and corners *(source: Façade Construction Manual)*

The position of the façade depends on the type of modular grid chosen. The appearance of the façade is largely determined by this. In the Façade Construction Manual five positions are distinguished (figure 5):

1 in front of the columns
2 on the front face of the columns
3 between the columns
4 on the rear face of the columns
5 behind the columns

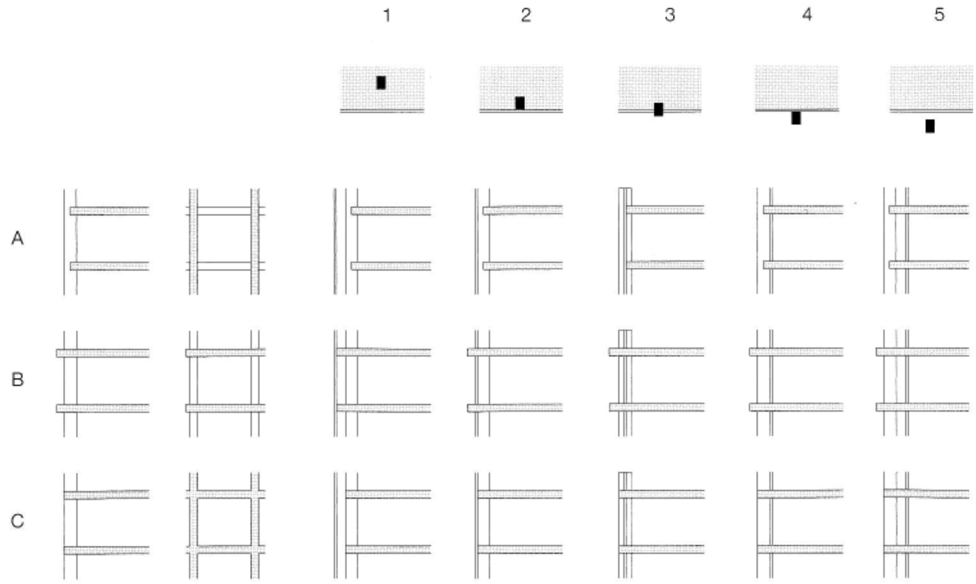


Figure 5: Relation between façade and load bearing structure *(source: Façade Construction Manual)*

4.3 Unitized system[3]

Combining prefabrication and a modular grid system gives a so called unitized system. When it comes to façade designs a unitized system almost only is used in curtain wall systems. A unitized system usually has the same width for all the modules and has the height of one storey. The main application of this type of system are office buildings since they have a façade which in most cases is highly repetitive. Large elements can be produced within this system. However, as a result of the prefabrication the modules need to be transported and mounted as well which generally means that different types of loading will be applied. In the design process one should take these issues into account in order to prevent damage during transport or while mounting the modules. It is fairly common to take extra care of the water drainage of the modules. Since the modules are placed at once there is an increased chance of water and air leakage. This partly is the result of the adjustment options which need to be included when placing large modules at once. Also production tolerances are a cause of physical defects.

It becomes clear that there are various topics which ask for extra attention and careful consideration when using a unitized system. However there are advantages as well: shortening the building process, high quality control, low labor costs, independent of weather circumstances and a reduction of the production costs. Due to the circumstances in which FRP is produced in combination with the connection possibilities, unitized systems are very well suited for usage in combination with this material. As mentioned before, the production costs are in most cases very high and they are to be reduced in case a unitized system is to be used. Appendix A shows examples of unitized and modular façade systems which already are available on the market.

4.4 Grid system architectonic design

The hotel design is based on a structural grid which is shown in figure 6. The floor plan is based in one direction on a grid of 3.6 meters, this part of the grid is positioned perpendicular to the façade. However due to the urban environment an angle has been introduced which offsets the façade surface, leaving openings between the column with a width of 4.3 meters. In the other direction only the distance from the inside part of the column till the end of the floors has been determined. The façade is supposed to be situated within that area which means that it is placed between the floors (figure 6, left) instead of being mounted against them which is far more common. This is the result of the architectural concept. The space left between the floors comes down to 6.7 meters which ideally will be span at once. However the design of the façade should be based on a grid of 7.2 meters since it should give the space between the curved floors a uniform appearance. Figure 7 shows the façade distribution at the end of the architectural part. The elements to be developed should be uniform and be positioned between the red lines in order to create the envisioned appearance of the building. The final design which is about the form finding should be found within the boundaries of the construction; columns and curved floor slabs.

[3] http://www.thifaso.com/unitized_structural.html

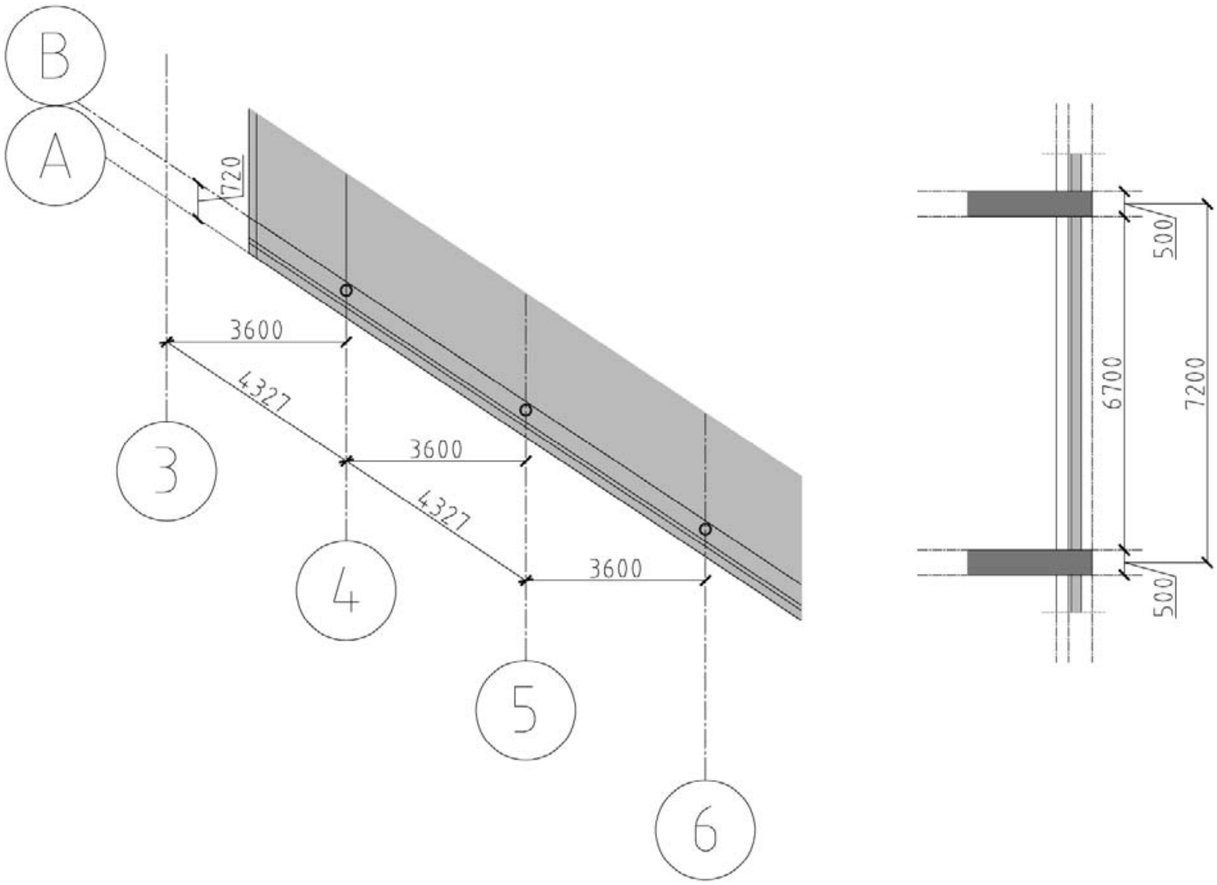


Figure 6: left – floor plan grid, right – vertical grid

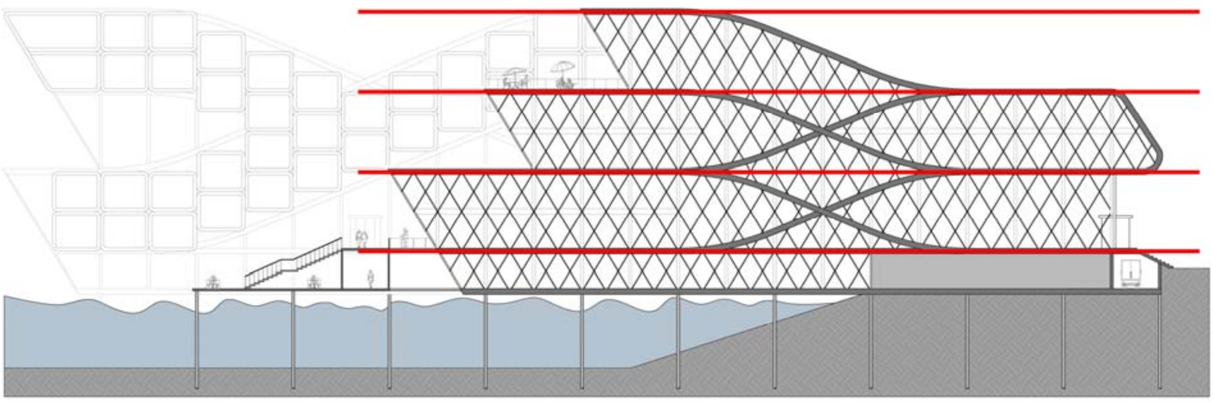


Figure 7: reference lines shown on the façade presented at p4 Architecture

4.5 Conclusion

Grid systems have been reviewed and are used in the architectural design. Within this reference system research should be done after the most suitable distribution of elements. Besides that the design should focus on the prefabrication of elements which logically has consequences for the technical detailing of the façade. The grid has no sacred status, however deviation of the grid should be considered seriously since the intention of the reference grid is to offer grip on the design as well as structuring it.

Herzog, Krippner, Lang, *Façade Construction Manual,* (Basel, 2004)

http://www.thifaso.com/unitized_structural.html

5 Type of construction

The use of FRP as a façade element with a load bearing capacity, tends to be one of the most promising developments. Due to the high strength to weight ratio, good thermal insulation properties, insensitivity for water and other environmental influences, this material has the ability to become a competitor to the more traditional building materials like wood, concrete and steel. When talking about FRP in a constructional position there are two main principles: pultruded profiles and sandwich elements. Both have their own advantages and disadvantages, and ask for a specific design approach. Based on the design concept and the arguments explained below a decision between the two construction concepts will be made.

5.1 Construction

In terms of construction sandwich elements can be the most efficient but on the other hand pultruded profiles deliver the most slender construction. The principle of the sandwich element has been explained before but in a short recap it comes down to the following: The outer fibers of a profile are the ones which are exposed the most to tension and compression, the material in-between contributes little to nothing to the stiffness of the element, hence it can be replaced by a more lighter material and by doing so reducing the total weight of the structure. Besides the constructional advantages, most core materials also improve the thermal and acoustical insulating properties of an element. The sandwich elements have a high strength to weight ratio due to the applied core material.
Pultruded profiles on the other hand do not make use of a core material. For FRP profiles to become efficient construction members of the façade, collaboration with other materials is required. In case of GFRP it is glass with which an extremely efficient and innovative composite construction can be made. FRP profiles with a high amount of glass fibers have a similar thermal expansion coefficient of that of glass. Traditionally glass and window framing are separate elements both with their own thermal expansion possibilities. In the early years of building with glass one believed that the material was not strong enough to be a construction material. However there are some exceptions, the greenhouses. Cast iron and glass are the two building materials which were used to make a greenhouse. Below the Crystal Palace in London which was the larges glass building of the 19th century designed to house the great exhibition of 1851.

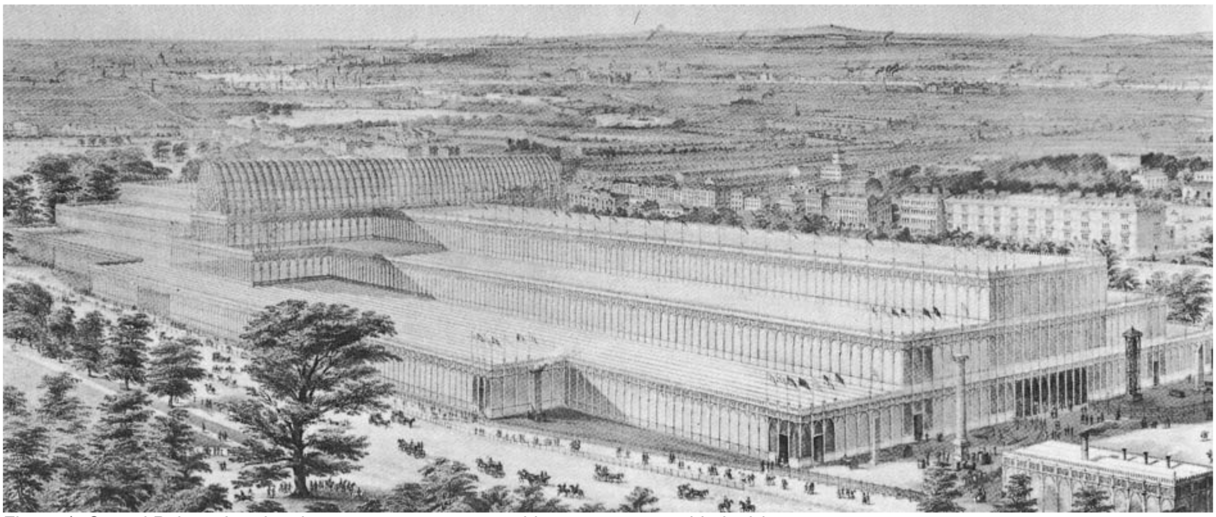


Figure 1: Crystal Palace, London *(source: De Westerse Architectuur; een geschiedenis)*

The designers and builders of constructions like this did not fully understand the role that the glass panels played in it. The cast iron construction was strong enough to carry the weight but it was not stable enough to transfer the shear loads. This was done by the glass elements. The iron and the glass were connected by putty(stopverf, nl) which allowed both materials to expand separately but was strong enough to transfer loads from one material to the next. At the moment it became clear that due to dehydration the putty would lose its cohesive power, this specific building method became unattainable. However the principle of these buildings is the same as that of FRP only in this case both materials have the same thermal expansion coefficient and the applied adhesive is of a higher standard. The two materials can be connected with a stiff adhesive which need to be applied in a thin layer. The complex constructions which result from this bonding can make use of slim framing members because the inherent stiffness within the plane of the glass can be fully activated. In a construction like this the glass takes care of the compressive stresses and the FRP profiles take care of the tensile stresses. This principle is called composite action. Due to the low thermal conductivity of the FRP profiles, a thermal break becomes unnecessary.
Both construction made out of sandwich elements and construction made out of pultruded profiles are innovative and efficient in their own way. Besides differences in constructional behavior there are also differences in form which in some cases narrow down the application fields.

5.2 Form – Production

Both types, profiles and sandwich elements have their own production methods. These methods are named here because they determine which forms can and can't be made. Figure 2 shows part of the façade of the Fiberline Factory. The left part of the figure shows a section of the profile which explains the functioning of the construction. These profiles are pultruded. Pultrusion is a continuous process which means that a uniform profile section will be derived from this process. Inserts and openings are difficult if not impossible to make. Only straight elements can be pultruded which in most cases will mean an orthogonal design. Profiles with a shape like the one in figure 2 can also be produced by casting however the stiffness and overall quality of these elements cannot be compared to that of a pultruded profile. In case a die with a small curvature is used, curved profiles can be produced however they will have the same curvature along the profile. The production cost of a die like this are extremely high and are only profitable in case of very large batch sizes. The exact functioning of the pultrusion process will be explained in chapter 6 of the report.

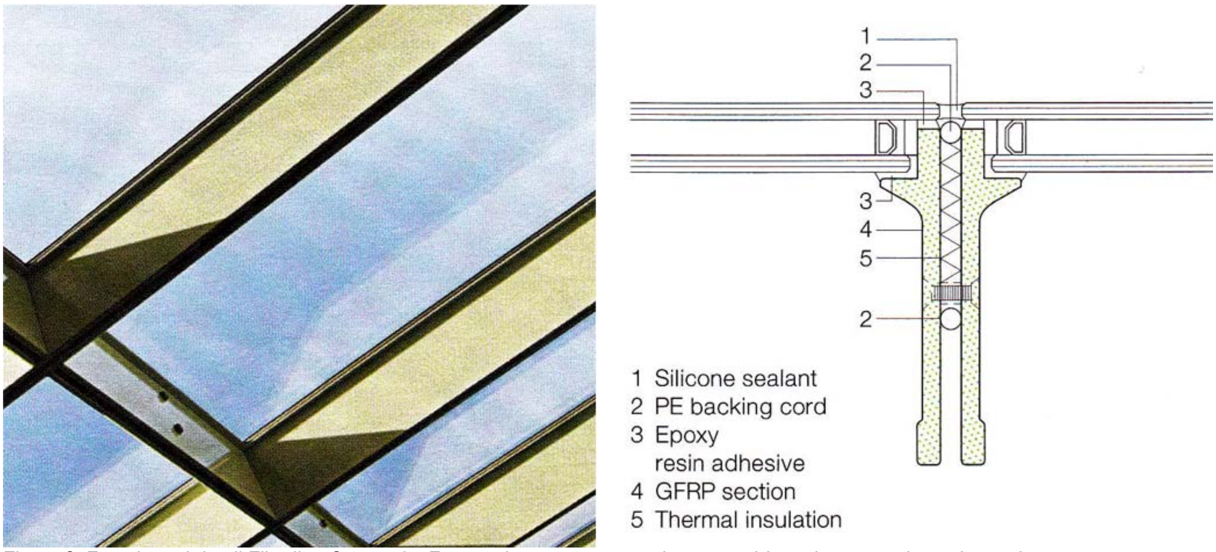


Figure 2: Façade and detail Fiberline Composite Factory *(source: Construction manual for polymers and membranes)*

The production of a sandwich element can also be done by pultrusion but this is a bit unusual and is only done when relatively small elements and a high batch size are required. In most other cases manual labor is required to produce the elements. This increases the production costs but in the same time it also increases the production options. Almost every shape can be made with as much openings and inserts as one requires. This is the complete opposite of the pultruded profiles. This process also requires a mould but in most cases the core element is used for this which means a reduction of the production cost. Depending on the size, required quality and batch size one can decide if it is enough to use only the mould or that a vacuum system is required. When larger batch sizes are required compression moulds become within reach. When it comes to façade design this will however probably never be the case.


Figure 3: Building X - Zwolle

Figure 3 show a facade build entirely out of sandwich elements. The building is 24 meters high and the façade consist of several elements with a height of 12 meters which are stacked on top of each other.

5.3 Specific applications

A façade made with pultruded profiles will differ in a great way from one made out of sandwich element especially when it comes to the visual part. Profiles can be extremely slender especially when considering the fact that the glass carries loads as well. The freedom of form can be considered limited when using this type of elements for the load bearing part of a façade. Sandwich elements on the other hand provide the designer with a great freedom if it comes to form and size, even 3D parts are optional. Besides that these elements offer the possibility for being used on the inside and on the outside at the same time as a result of the environmental insensitivity of the FRP and the good thermal insulating properties of the core material. As a result of this the sandwich elements can be used as a constructional part, finishing and insulation layer at the same time. Almost seamless facades can be made using the right combination of fibers.

At all times it is preferred to prefabricate the elements and thereby construct modules which can be mounted on side. This is mainly due to the fabrication circumstances which are required to produce a reliable product, which can only be achieved in a controlled environment like the factory. Both types offer great possibilities as a load bearing façade element and they do this each in their own way.

5.4 Façade Design

Chapter 9, about the design process will explain the different concepts and variants made with both construction methods. However it soon became clear that a construction with sandwich elements would not result in the transparent façade envisioned in the design concept. Hence, during the process the decision has been taken to continue the search for a façade concept in which profiles are used as construction parts in order to keep the façade as transparent and slender as possible. Due to the research done in the architectural part of this project this decision could partly be foreseen. However both principles are tested at a visual level. The process and the exact functioning of the structural principle as well as the possible connection options will be explained in coming chapters.

5.5 Conclusion

Decisions about what type of construction is to be used are based on research done during this part of the project as well as the architectural part of the project and in combination with the architectural concept. Besides considerations from the technical point of view there is also a personal preference for a design with profiles. This comes forth from the architectural design being based on an experimental way of using sandwich structures. A large amount of knowledge has been gained on their behalf. In order to broaden my knowledge about FRP materials, the ins and outs of profiles in a structural position tends to be more interesting. Slender profiles are unlikely to disturb the image of the curved floor slabs which contributes to the design concept of the façade.

Knippers J., Cremers J., et al, *Construction Manual for Polymers + Membranes,* (Munich, 2011)

Watson D., *De Westerse Architectuur; een geschiedenis,* (Nijmegen, 2001)

6 Production process

In this chapter the most common process for the production of FRP profiles, pultrusion will be explained in order to gain insight in the options and limitations that come with it. Doing so also sets boundary conditions for the design as a result of the possibilities within the process. This holds for both the architectural and the technical elaboration.

6.1 Pultrusion

Non circular composite profiles are most often made with the pultrusion process. Pultrusion is somehow similar to the more common extrusion process used for example to make aluminum profiles. The main difference is in the fact that an extrusion profile is pushed through a forming die, and a pultrusion profile is pulled through a forming die. Other processes used for the production of profiles are circular winding, in case of circular profiles and there is also the possibility of casting the profiles. The latter production process is only done with small batch sizes and can only be used for none structural applications due to the low strength as a result of the chopped fibers being used instead of continuous strings of fiber. As might be clear by now, the pultrusion process is a continuous process which, more than is the case with extrusion, depends on this continuity. Figure 1 shows examples of pultruded profiles, the wide variety of options become clear at once.

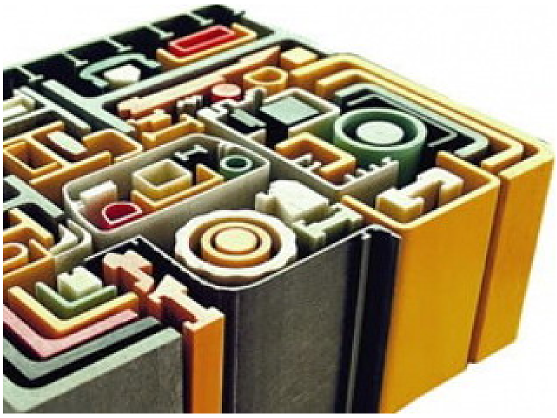


Figure 1: Semi finished product produced by pultrusion *(source:www.expermaterial.com)*

6.2 Process step by step

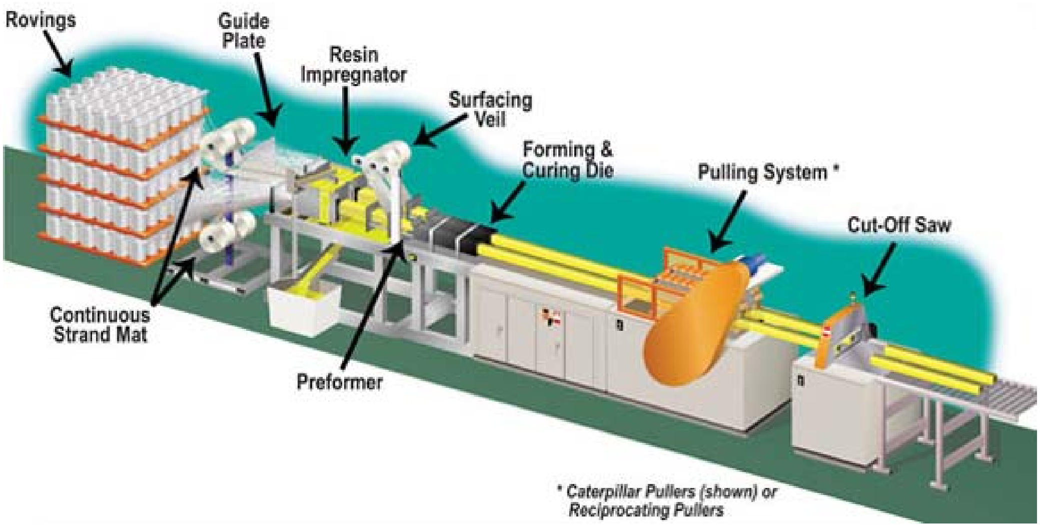


Figure 2: Schematic visualization of the pultrusion process *(source:www.strongwell.com)*

Figure 2 shows the composition of the pultrusion process. It all starts with the roving rolls, these are responsible for continuously feeding the process with fiber strings. Besides strings it is very common to use strand mats to reinforce the outer parts of the profile. If only strings of fiber are used, the profiles will be unable to handle shear stresses since the matrix being used is unable to do so (see Part A of the report).

The strings of fibers and the mats are roughly organized according to the desired shape with the help of guidance plates. This alignment of the fibers is important in order to avoid failure of the process as a result of fibers breaking, bad quality and other problems.

Once ordered properly, the fibers are pulled through a bath filled with resin material. The most commonly used combination is that of a polyester matrix in combination with glass fibers. This is followed by an epoxy matrix in combination with carbon fibers. Other combinations with different types of matrix material and different types of fibers are also possible but are usually only applied in case special requirements need to be met. A fiber content of 70% can be achieved with this process which results in a higher young's modulus compared to manual lay-up processes.

When leaving the resin impregnator, excess resin material is removed and the impregnated fibers are pulled through a heated die with the desired profile shape. The heat is necessary in order to activate the curing process of the matrix material. At the moment the profiles leave the die they are fully cured and need to be cooled down before entering the pulling system.

This has to be done, otherwise the fibers are not enough supported by the matrix material and therefore only depending on themselves which will result in failing of the fibers. When cooled down enough the pulling machine gets its grip on the profile and pulls the profile through. It is here were the concept of the process becomes entirely clear, the fibers form the continuous part of the process. Since one single fiber cannot handle pushing forces but only pulling forces the process is based on pulling the cured profiles and thereby the continuous fibers through the process. How unusual this might sound: the process starts at the end. After the profiles leave the pulling system they are given the desired dimensions by cutting them of. The pultruded profiles should be supported during the entire process and in order to guarantee optimal properties the pultruded profiles require post curing. Figure 3 shows images of the different parts of the process. Left the fibers entering the process and right the resin batch and the forming die.

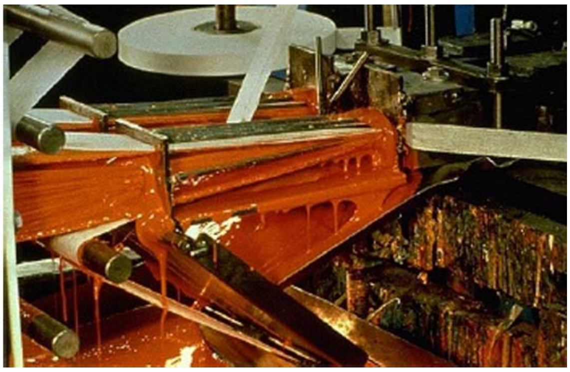


Figure 3: Left – fibers entering the process, Right – resin bath and forming die *(source :pultrusion process composite manufacturing)*

6.3 Options

The wall thickness of pultruded profiles generally lies between 0.5 and 100 mm. The maximum overall dimension are 650 – 1250 mm. Due to the continuous process it is impossible to include inserts in the profiles. Since the use of inserts is commonly used method of connecting various FRP elements, other connection types are to be used which will be described in a separate chapter. Openings are also impossible to include during the process. If openings are really necessary one should make them in the finished product. Keeping in mind that by doing so the fiber structure will be damaged which in most cases is likely to affect the mechanical properties of the element.

In a pultruded part sharp corners are to be avoided since they disrupt the distribution of stresses present. Using a proper radius will increase the stress distribution. When looking at pultruded profiles for example the ones from figure 1 illustrates this fact, there are only curved corners to be seen.

Pultrusion is a low pressure process which leads to the fact that the surface of the pultruded elements always will have fiber texture. In high pressure production processes it is possible to apply as much resin material as needed to give elements smooth surfaces on all sides.

As can be seen in figure 3, color pigments can be applied to the matrix which allows the designer to give a profile every color one can think of.

6.4 Advantages

One of the biggest advantages of the pultrusion process is the elimination of manual interference which guarantees a continuous quality of the product. The dies used in the process are expensive as is the set-up of the different parts, which makes this process profitable when producing over 1000 meters of the same profile. However at that point this is the process with raw material cost between 80-90% of the total production costs, which rules out almost all other production methods. These are the main advantages of the process however when considering the material properties as well the potential of the combination process-material becomes clear. These material properties are described extensively in Part A of the report.

6.5 Disadvantages

- Only continuous and straight cross sections can be produced. Since recently, slightly curved profiles are an option as well. However they require a longer and curved die which increases the production costs exponentially.

- High-tolerance parts cannot be produced.

- Thin wall sections cannot be produced

- Fiber angles on pultruded parts are limited to 0^{o} which makes the use of bidirectional woven sheets necessary for the transport of shear forces.

- Shrinkage, 2 – 3 %

6.6 Conclusion

Knowing the limitations and options of the production process which is used to produce FRP elements has its influence on the design and more specifically the detailing. This is not to be considered a restriction but more as a boundary condition which can be used to structure the design process.

Harper A., *Modern Plastics Handbook,* (USA, 2000)

CES EduPack 2011

http://www.scribd.com/doc/13777193/pultrusion-process-composite-manufacturing

http://www.expertmaterial.com/ppp.htm

http://www.strongwell.com/pultrusion/

7 Technical functioning of the facade

The construction of the façade will be based on the collaboration of FRP and glass as one construction. Chapter 5 gave a brief description of this principle; in this chapter practical projects are analyzed in order to gain more insight in this type of construction. Also assumptions will be made about how to calculate a construction like this. All will be based on real life projects.

7.1 Technical principle[4],[5]

FRP profiles reinforced with a high glass fiber content, tend to have a similar thermal expansion coefficient to that of glass in the longitudinal direction. Since the matrix material is significantly less stiff, this does not influence the thermal expansion enough to change this material property. As a result, the two materials can be bonded together using a stiff adhesive which need to be applied in a relative thin layer. This collaboration between materials in a constructional way is called composite action. Note that this has nothing to do with the fact that a composite material is used, a new composite will be made in a way. When used in a façade, the glass will take care of present shear forces and prevents the FRP profile from buckling. The FRP profile on the other hand takes care of the bending forces by reinforcing the glass panels. However the glass panel itself handles bending forces as well due to the stiff connection. This is the innovative aspect of this construction type, the glass has a constructive role to play, something which is fairly unique in architecture. The result of this construction method are very slim framing members. Theoretically, if only wind loads perpendicular the plane of the façade are applied, the glass will carry the compressive forces and the FRP profile the tensile forces. In practice there are however other forces applied to the façade as well like the shear forces explained before.

Due to the low thermal conductivity of FRP a thermal break between the two materials becomes unnecessary. In practice this probably will still be seen as a cold bridge. The insensitivity for water vapor makes that this should not be a problem.

The bonding of the elements should be done in a controlled environment to guarantee a rigid connection with no weak spots. This results almost directly in the use of prefabricated modules since the building site is not particularly a controlled environment. This type of construction is still under development and only one actual project has been realized so far, the Fiberline Factory (figure 1). Various projects have been exposed at glass exhibitions in Germany, they will be discussed in the next paragraph.

As is always the case with something new, clients become suspicious which does not speed up the development process. But more importantly there are no building regulations for this type of construction so far which makes it practically impossible to implement a construction like this in an actual building. The reason Fiberline has been able to do so lays in the fact that they are the manufacturing company of FRP materials which made it more easy for them to take the responsibility for the proper functioning of the façade. Experimental studies imply that these type of constructions are well-suited for tall storey buildings. Not only are they much simpler when it comes to their structure compared to other curtain wall systems, they are also easier and more economically to erect. The options will be shown with the help of several reference projects in the next part.

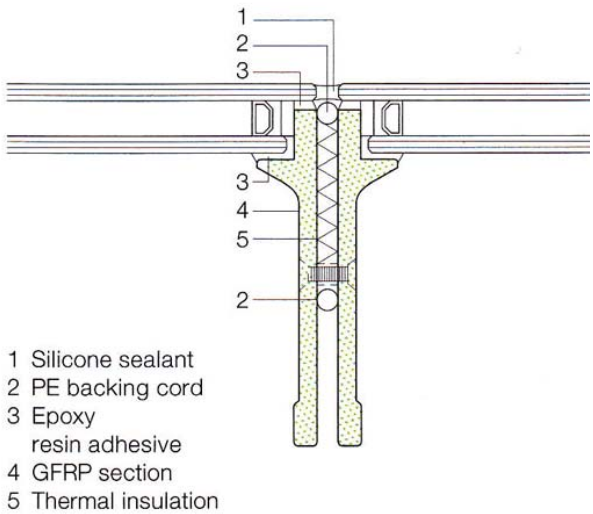


Figure 1: Fiberline Factory façade and detail *(source :Construction Manual for Polymers + Membranes)*

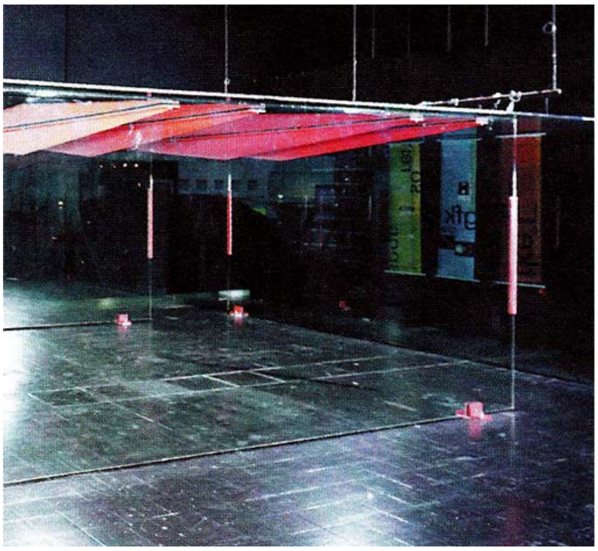
[4] Knippers J., Cremers J., et al, *Construction Manual for Polymers + Membranes,* (Munich, 2011)

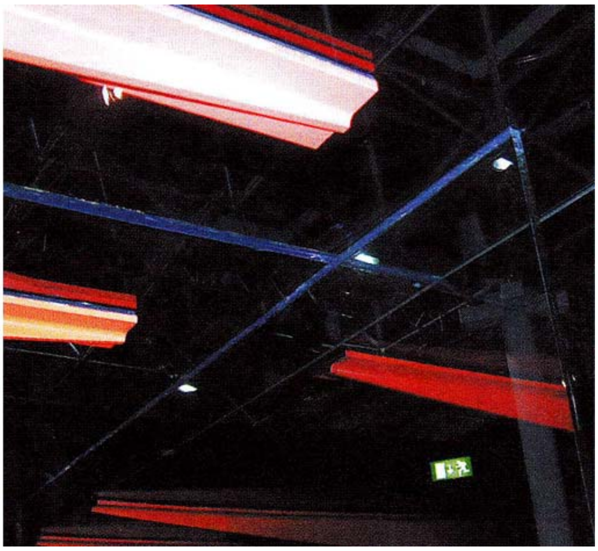
[5] Engelsmann S., Spalding V., Peter S., *Plastics in architecture and Construction,* (Basel, 2010)

7.2 Reference Projects

Architect: ITKE
Building: GRP-glass table
Year: 2002
Location: Düsseldorf, glasstec
Source: www.itke.uni-stuttgart.de

This table was exposed at the Glasstec exhibition of 2002 in Düsseldorf. The construction of this table consists of a 5 millimeter thick FRP laminate which was made with hand lamination. Due to its shape the FRP section is able to carry the weight of the 4m spanning table. The composite action between the glass and the FRP contributes to this as well, it finishes the constructional triangle of the table. The connection between the two materials was made with a two compound silicon adhesive. Special interest is placed in the fact that due to the high glass fiber content and the small thickness of the laminate, the FRP becomes translucent. Lights have been placed in the hollow part of the table to increase the expression of the design.





Architect: ITKE
Building: GRP-glass pavilion
Year: 2002
Location: Düsseldorf, glasstec
Source: Plastics in Architecture and Construction

This glass pavilion was also part of the Glasstec exhibition of 2002 in Düsseldorf. Glass sheets are used for the walls as well as the roof of the pavilion. The contribution of FRP can be found in the roof construction. The glass sheets span a 5.5 m gap which cannot be done with only a thin sheet of glass. Pultruded FRP I-beams are sawn in half and are glued to the glass panel as reinforcement. The principle of composite action is the same as mentioned before. The most extraordinary part of the pavilion are the FRP profiles which end 25 cm before the supporting walls. This illustrates the fact that the FRP is used as a reinforcement and not as a supporting construction. The tapered shape of the FRP profiles contributes to this as well, the highest stresses are found in the middle of the span, hence the construction has the most height on that specific location.

Architect: Knippers J.
Building: GRP-glass facade
Year: 2005
Location: Munich, BAU Munich
Source: www.fiberline.com

This façade system has been developed by the university of Stuttgart under the leadership of Dr. J. Knippers, Professor of Engineering in collaboration with manufacturer Fiberline Composites A/S. The façade was exposed at the BAU Munich of 2005. The façade has a height of over 8 meters which is possible due to the composite action between FRP and glass elements. This system has been developed and tested for over several years according to Knippers. The façade is part of an architectural proposal for a new sports and culture centre in Copenhagen.

7.3 How to calculate

Since there are no calculation models available for calculating FRP-glass structures, assumptions have to be made about how to do so. The façade of the Fiberline Factory has been used as a reference for this, since this is the only actual build design. Figure 2 shows part of the façade in which FRP and glass have joined their forces. Based on images the dimensions of the elements used are assumed. With the help of Excel a calculation model has been made which at first has been used to determine the dimensions of the profiles used in the façade of Fiberline Factory. Then images are used to verify the results. It may be clear that the calculation model is strictly hypothetical, however this is as close as it gets to the reality for now. The façade part and modules of the graduation design are based on this, which makes this a highly experimental part of the design.

Figure 2: Fiberline Factory façade *(source: www.fiberline.com)*

The calculation model is shown in figure 5 on the next page. Material properties have been derived from CES EduPack 2011. Applied loads are extracted from the Bouwkunde Tabellenboek [6]. The assumption was made that normal double glazing was used with the dimensions: 7.2m x 1.2m.
In order to calculate a construction like this a section based on one material has to enter the model. However at this stage we have two materials with two different sections: glass and FRP. In part A of the report a method for transforming these two materials into one has been explained. The conclusion from this explanation came down to the following:

$n = E_1 / E_2$

In this formula the dimensionless number n is called the transformation factor. It indicates that the cross section, having a width *b* on for example the FRP part, must be decreased in width to $b_2 = nb$ in the region where the FRP is being transformed into glass. Doing so delivers a cross section entirely made out of glass. The other way around is also possible. The result of this transformation simplifies the calculation considerably since basic calculation formulas can be used (also shown in figure 5). In part A this method has been used with success to approach the research data of an experimental research after laminated sandwich structures. Figure 5 shows that the initial thickness of the profile, estimated at 20 mm, is reduced to 8.24 mm after applying the transformation factor. For sake of the calculation, the FRP profile is now a glass profile.

Figure 3 show the calculation results. Based on the rule of thumb that the façade is allowed to bend no more than 1/200 of its span, a deformation (w) of 36 mm is the limit. The results show values for as well FRP as for glass. This is due to the fact that the outer fibers of this composition in relation with center of gravity are located in the FRP profile. The stresses which normally would be calculated are the ones found in the outer fibers of the FRP profile, which in this case comes down to a stress of 98,96 N/mm^2. This is well in reach of the maximum limit of FRP which comes down to 193 N/mm^2. However this exceeds the maximum limit of glass; 38 N/mm^2. When taking a closer look at the actual center of the combined materials one finds that the center of gravity is leaning towards the outer fibers of the glass panels. This could be as expected since their area is multiple times that of the modified FRP profile.

Total height element:
4 + 8 + 4 + 230 = 246 mm, Middle point is positioned at: 246 / 2 = 123 mm

Calculated from the side of the FRP profile, the centre of gravity is located at 217,73 mm from the edge. Which means that the distance from the outer fibers of the glass panels to the centre of gravity, a distance of 28,27 mm can be found. When entering this in the formula the results show that the stresses in the glass panels wont exceed 12,85 N/mm^2. Which lays within the limit of the material properties.

Bending and Stresses

					FRP		Glass	
	I	w	kg/m	M	W	σ	W	σ
FRP pultruded + glass	3,26E+07	3,61E+01	33,18	14836608	1,50E+05	98,96	1,15E+06	12,85

	Width	Height
FRP profile	20	230

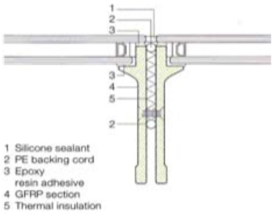
Figure 3: Calculation results

The calculation results show that the profiles used in the Fiberline Factory should approximately have the following dimensions: 230 x 20 mm. Looking at figure 4 supports this assumption which for this project means that the calculation model can be considered valid.

Figure 4: Fiberline Façade seen from the inside *(source: www.fiberline.com)*

[6] Bone A.H.L.G., Kemps T.N.W.G., et. al., *Bouwkunde Tabellenboek,* (Groningen/Houten, 2007)

FIBERLINE GLASS FACADE



Bending	w	=	36	200
Youngs Modulus	E_FRP pultruded	=	28000	N/mm2
	E_glass	=	68000	N/mm2
	n_composite	=	0,41	
Yield Strength	σ_GRP pultruded	=	193	N/mm2
	σ_glass	=	38	N/mm2
Width Element	b	=	1200	mm
Height Element	h	=	7200	mm
Thickness glass1	t_glass1	=	4	mm
Thickness glass2	t_glass2	=	4	mm
Thickness spacer	t_spacer	=	8	mm
Height FRP	h	=	230	mm
Thickness FRP	t_FRP	=	20	mm
Thickness FRP modi	t_FRP modified	=	8,24	mm
Area	A_glass1	=	4800	mm2
	A_glass2	=	4800	mm2
	A_FRP	=	4600	mm2
	A_FRP modified	=	1894,12	mm2
Centre	z_glass1	=	2	mm
	z_glass2	=	2	mm
	z_FRP	=	115	mm
	z_total	=	217,73	mm
	z_glass-stress	=	28,27	mm
	z_glass1 modified	=	14,27	mm
	z_glass2 modified	=	26,27	mm
	z_FRP	=	102,73	mm
Load Cases	q	=	2,2896	N/mm
Weight	FRP pultruded	=	2100	kg/m3
	Glass	=	2450	kg/m3

$$\sigma = \frac{M}{W}$$

$$W = \frac{I}{Z}$$

$$M = \frac{1}{8} \cdot q \cdot l^2$$

$$I = \frac{1}{12} \cdot b \cdot h^3 + A \cdot z^2$$

$$w = \frac{5}{384} \cdot \frac{q \cdot l^4}{EI}$$

Load		
Temporary load	0,56	kN/m2
Safety factor	1,5	
Permanent load	0,89	kN/m2
Safety factor	1,2	
Total load	1,908	kN/m2
	0,001908	N/mm2

Figure 5: Calculation model FRP-glass structures

7.4 Implementation Façade Design

The façade design of the graduation project is to have a very high level of transparency. This means that almost all insulation should be located in the glass elements. The double glazing used in the Fiberline Factory façade has a U-value which is below standard which means a different type of glass is to be used. Therefore triple glazing will be applied filled with gas which has a much higher U-value. The specifications of the different types of glazing are shown in figure 6, as is the composition.

Type glas	U-waarde
Enkel Glas	5.8 W/m²K
Dubbel glas	2.8 W/m²K
Hoogrendementsglas met lucht	1.4 W/m²K
Hoogrendementsglas met gas	1.1 W/m²K
Driedubbel glas met gas	0.6-1.0 W/m²K

U-waarde	Glas compositie	Spouwdikte	Totale glasdikte
0.6 W/m²K	4mm low-e / 15mm + argon / 4mm / 15mm + argon / 4mm low-e	2 x 15mm	42mm
0.7 W/m²K	4mm low-e / 12mm + argon / 4mm / 12mm + argon / 4mm low-e	2 x 12mm	36mm
0.8 W/m²K	4mm low-e / 10mm + argon / 4mm / 10mm + argon / 4mm low-e	2 x 10mm	32mm
1.0 W/m²K	4mm low-e / 8mm + argon / 4mm / 8mm + argon / 4mm low-e	2 x 8mm	28mm

Figure 6: Glass specifications and composition *(source:* evmglass.com/driedubbel-glas/)

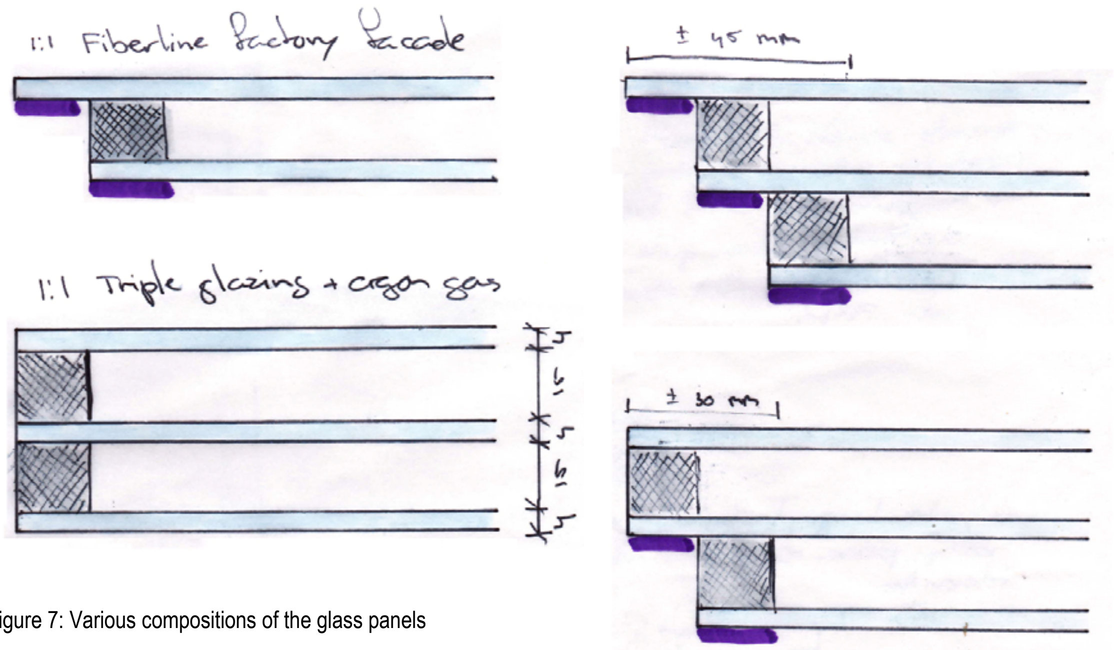


Figure 7: Various compositions of the glass panels

Figure 7 shows various compositions within the used construction type. The contribution of the glass panels to the stiffness of the construction will be the largest in case all panels are connected with the FRP profile. The spacer in the glass is not suitable for this job which means the glass panels need to be positioned gradually. Theoretically this means that in case of triple glazing the FRP profiles could even be more slim than they already were. On the other hand the thermal insulation of the façade could be improved when only two panels are used and a third is used to increase the distance between the inside and the outside face of the façade. This last option will be used in the façade design, also because the width at the level of the connection increases when three panels are to be active in a structural way.

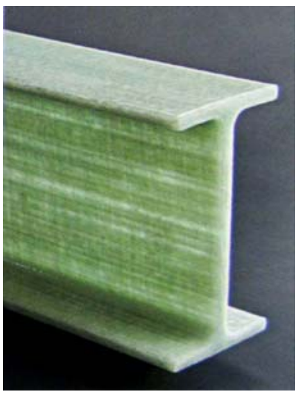


Figure 8: Translucent I-beam
(source: Plastics in Architecture

In order to increase the transparency level of the façade translucent profiles will be used, figure 8 shows an example of this. The greenish color is the result of applied color pigments to the matrix resin. It is possible to give the profile every color one could think of.

7.5 Conclusion

FRP-glass structures are a relatively new construction type in the field of architecture. This results in the absence of valid calculation models as well as other standards with respect to this new construction type. The developed calculation model will be used for the design of the façade knowing that the reliability of the results is questionable. However this should not have to interfere with the development of the façade since this it is not strictly meant to be a mechanical research.

Bone A.H.L.G., Kemps T.N.W.G., et. al., *Bouwkunde Tabellenboek,* (Groningen/Houten, 2007)

Engelsmann S., Spalding V., Peter S., *Plastics in architecture and Construction,* (Basel, 2010)

Knippers J., Cremers J., et al, *Construction Manual for Polymers + Membranes,* (Munich, 2011)

CES EduPack 2011

http://evmglass.com/driedubbel-glas/

http://heartworking2.fiberline.com/print/pages2.asp?id=4754

www.fiberline.com

www.itke.uni-stuttgart.de

8 Connection Techniques

When using semi-finished products the connection between them is most likely to form the most critical point in the structure. In load-bearing structures two types of connection are used: bolted connection and glued connection. Both have their own problems but they have in common that they both can handle limited forces only. Local concentrations of stresses occur at the connection points which can cause failure. The knowledge described in this chapter is likely to be more in depth than required for this project. However it is important to know that every connection made with FRP elements influences its behavior on a high level. The main goal of this part of the report is to give insight in possible problems which might occur and also to show options on how to connect different elements.

8.1 Bolted connection

The biggest advantage of bolted connections is the ability they have to be disassembled when needed and they are also not weather dependent. The forces which can be transferred through the bolts are much lower than the load-bearing capacity of the profiles cross-section. In principle bolt connections are based on shear forces, which is exactly the problem in case of FRP. In general the bolts are working in a perpendicular direction compared to the fibers. In that direction the fibers are able to redistribute the forces which results in a comparatively weak connection. When too much load is applied onto the bolts or they are tightened very fast, the bolts can tear through the material or split the profile. Figure 1 shows the possible failure situations. Around the bolts high stresses can occur since the fibers are ripped apart and the forces have nowhere to go. The location of the holes needs therefore careful planning in order to come up with the best location possible for the bolt connection.

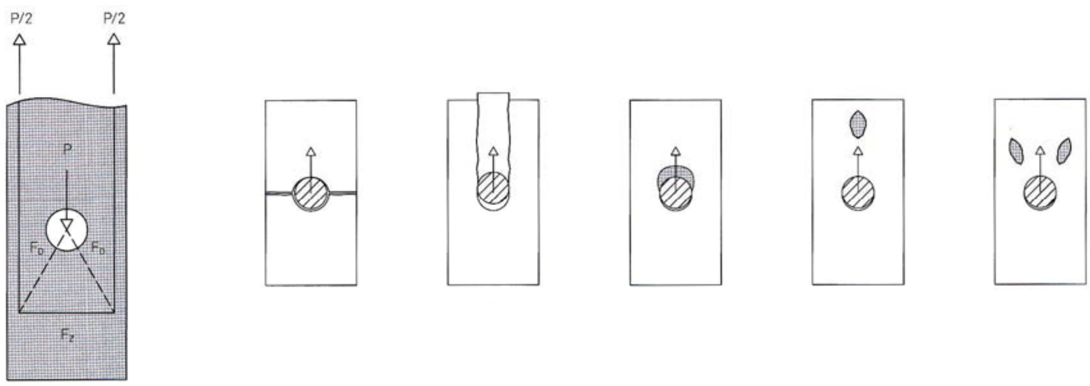


Figure 1: Failure mechanisms in bolted connection *(source: Plastics in architecture and construction)*

In case of pultruded FRP profiles, steel parts are used at places of connecting. These plates distribute the shear forces and make it possible to connect the profiles at every position possible. Steel plates are welded when a connection is needed, this however cannot be done with FRP which result in the use of external elements to make the connection. Figure 2 shows steel corner reinforcement used by the company Fiberline on pultruded profiles. A formula which can be used for calculating the load-carrying capacity of a bolted connection is given below.

Figure 2: Steel plate used for bolted connections *(source: www.fiberline.com)*

$F_R = 2 * (e_1 – (d_0 / 2) * t * f_\tau$

where:
$e_1 \geq 3.5\ d_0$ and $b \geq 4.0\ d_0$

F_R	= Admissible shear force
t	= Thickness of laminate
d_0	= Diameter of hole
e_1	= Edge distance in direction of force
b	= Width of laminate
f_τ	= Admissible shear stress in direction of force (determined in tests or taken from manufacturer’s data)

The admissible shear stress of a pultruded cross-section is approximately 25 N/mm^2

8.2 Glued connections

Glue connections are in almost all situations permanent connections between FRP elements. Gluing is a method of connecting well suited to FRP components which guarantees a load transfer over a certain area. There are three types of failure with glued connections:

- Failure of the glue itself
- Loss of adhesion between the materials
- Failure of the material or delamination of the FRP element

Besides the mechanical properties of the glue it is also the dimensions of the connected components and the internal structure of the components which are critical for the distribution of stresses in the glue connection. In general it is not the glue connection that fails but the adhesion of the individual layers of fibers in the composite. With the following formula the maximum shear force of glue connection can be calculated.

$(\sigma_E / \sigma_R)^2 + (\tau_E / \tau_R)^2 \leq 1$

σ_E = Tensile stress acting perpendicular to adhesive joint

σ_R = Admissible tensile stress perpendicular to adhesive joint

τ_E = Shear stress acting parallel with adhesive joint

τ_R = Admissible shear stress parallel with adhesive joint.

Stresses of approximately σ_R = 1 N/mm^2 and τ_R = 8 N/mm^2 are possible with pultruded sections.

Figure 3 shows examples of how glue connections should and should not look.

Besides the connecting possibilities there are also the working options. These are in number the total opposite of the connections, since almost all conventional tools can be used to work FRP elements.

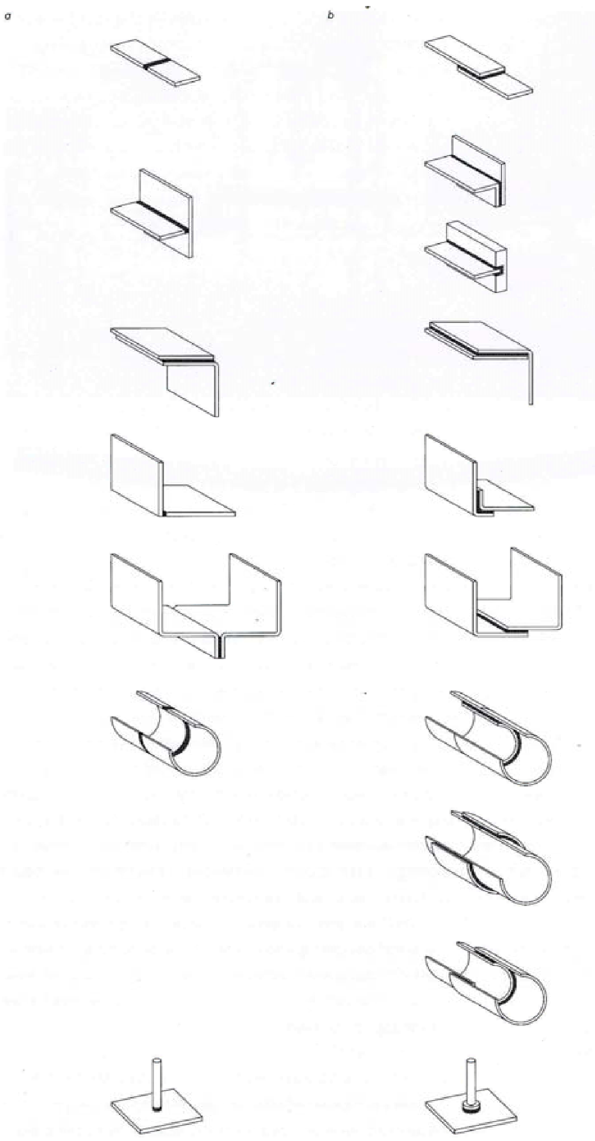


Figure 3: left – unfavorable designs, right – favorable designs
(source: Plastics in architecture and construction)

8.3 Combining connection types/elements

Just as can be done with other materials, combining joining techniques is possible with FRP as well. However one should know that it will always be the more rigid part of the connection which will carry the loads. In case of a glued and bolted connection, it will be the glued part which will carry the loads. Combining connection types therefore is not done for that particular reason. Combined joints in which each type of connection is responsible for the distribution of forces in different directions is an application field which benefits from this connection principle. Combined joints also offer a better guarantee that failure can be prevented. In Germany, glued façade elements more than 8 meters above ground level must be additionally secured with mechanical fasteners.[7]
FRP sections produced by pultrusion are normally available with sizes up to 30 x 30 cm. If larger spans are required, larger profiles are required as well. This can be done by combining separate available cross-sections into one by means of glue and bolt connections. In order to improve the load carrying capacity even further it is also possible to apply CFRP strips on top and bottom of a profile. Some examples of these combined elements are shown in figure 4.

[7] Knippers J., Cremers J., et al, *Construction Manual for Polymers + Membranes,* (Munich, 2011)

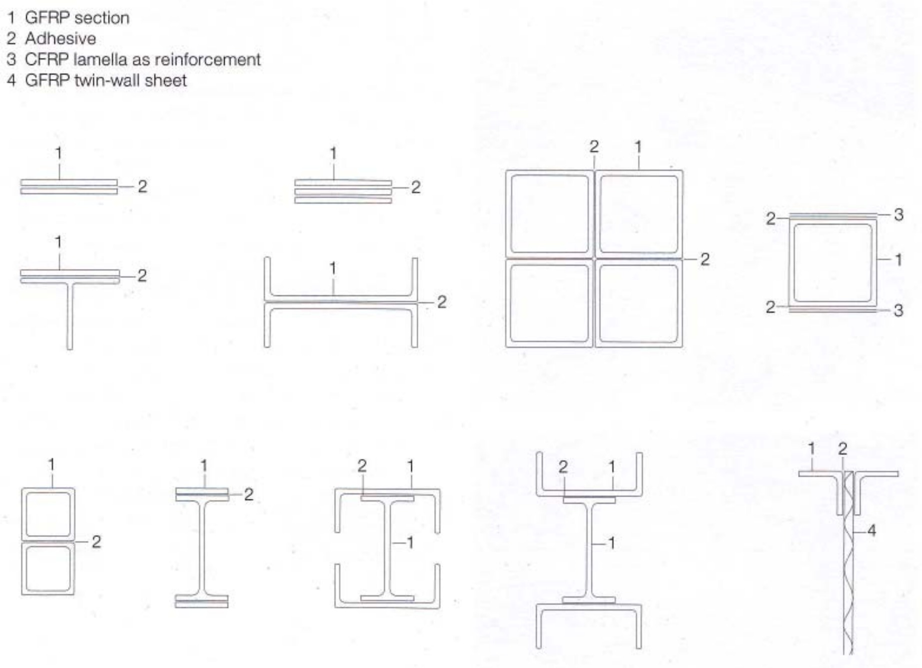


Figure 4: Compound FRP sections *(source: Construction Manual for Polymers + Membranes)*

8.4 Conclusion

Knowing about the connection options should influence the design in such way, that without calculating every joint, realistic assumptions can be made about which type of connection is to be used. This knowledge is to be used when designing the details of the FRP-glass façade .

Engelsmann S., Spalding V., Peter S., *Plastics in architecture and Construction,* (Basel, 2010)

Knippers J., Cremers J., et al, *Construction Manual for Polymers + Membranes,* (Munich, 2011)

9 Design Process

This chapter gives insight in the architectonical design of the façade illustrated with various design concepts. This study has been put into practice parallel with the technical research described in earlier chapters. This means that during the process to be described, not all knowledge about the technical details was present yet. Halfway through the process, at the moment of P3 things began to fall into place, something which is reflected in the results.

9.1 Architectonical starting point

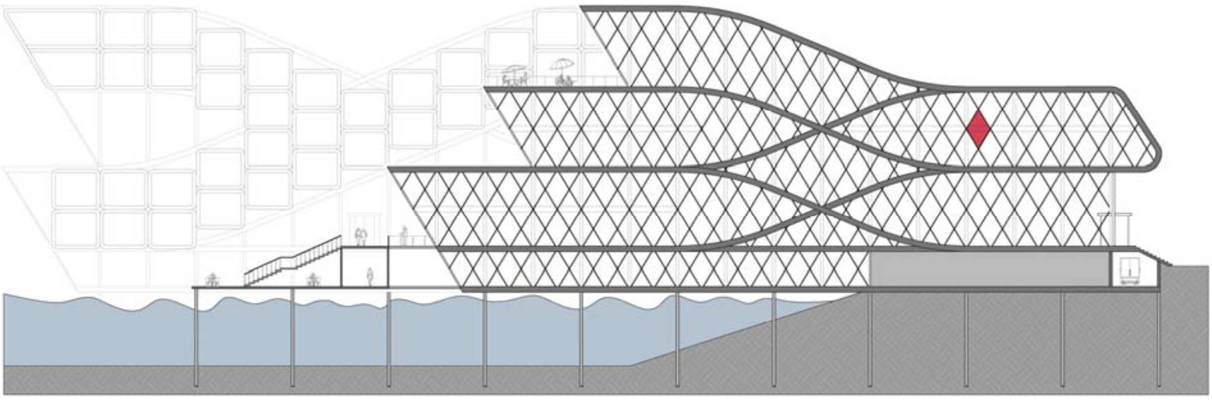


Figure 1: Architectonical starting point at the start of the building technology part

Figure 1 shows the architectonical starting point at the beginning of the building technology part. In red the shape of the envisioned modules is shown.. Figure 2 shows a detailed layout of the layering of the various construction parts. The floor slabs running through the façade is a part of the envisioned architectonical concept who need to be continued during the development of the façade. Due to the direction of the construction parts in this façade design, the floors are not supported at all. The façade takes its own course through which a couple of lines are running. This is not a proper explanation of the design concept. Besides that there are also a great number of locations in which the proposed elements needs change due to the positioning of the façade between the curved floor slabs. In practice this should not be a problem, however the number of different modules needed rises quickly which in itself is not very efficient (figure 3). This combined with the fact that the architectonical concept is not clear enough when applying this façade design asks for a change. The next chapter will explain a few of the various design concepts which have been made during the process. In essence they represent the different techniques and principles thought of.

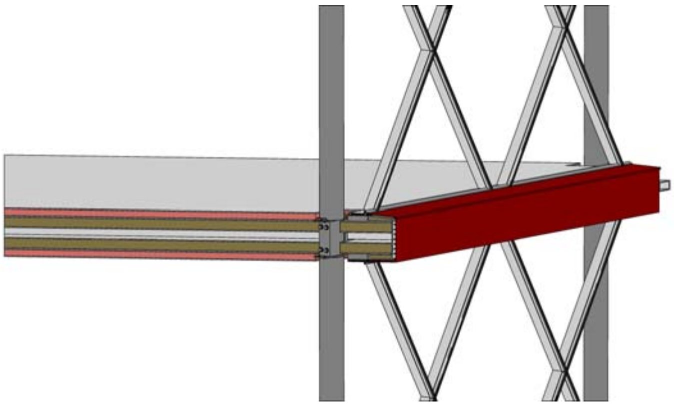


Figure 2: Detailed composition of the facade

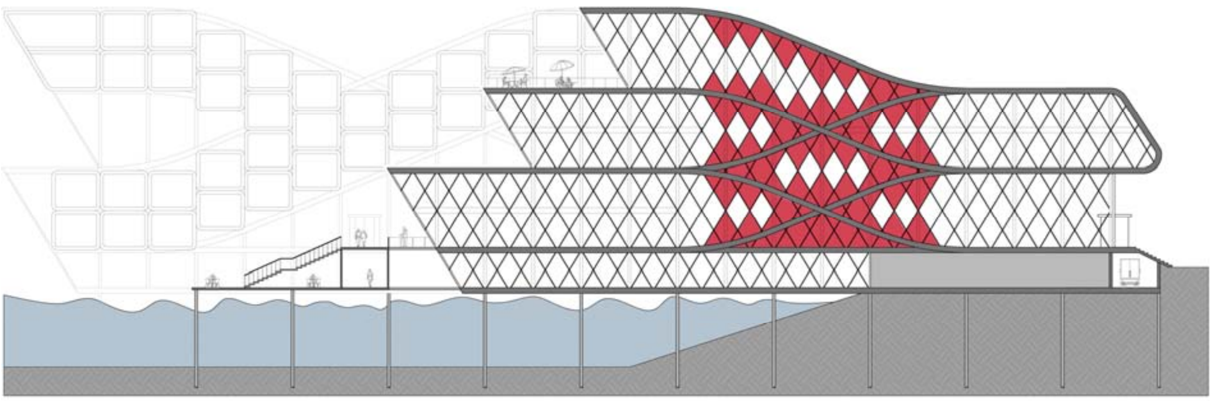


Figure 3: Number of different elements

9.2 Various design studies

Figure 4 is an example of a façade design proposal in which the lines of the floors are used to distribute the construction parts of the façade. In case no horizontal floor slabs would be present this could be a very interesting design. However due to the fact that there are horizontal floor slabs present, the façade is split into three different parts. The result of this is the attention concentrating at the area which has the most movement, the centre. Floor slabs are no longer the most important part of the façade. A uniform distribution of the façade seems to be the key element of the design.

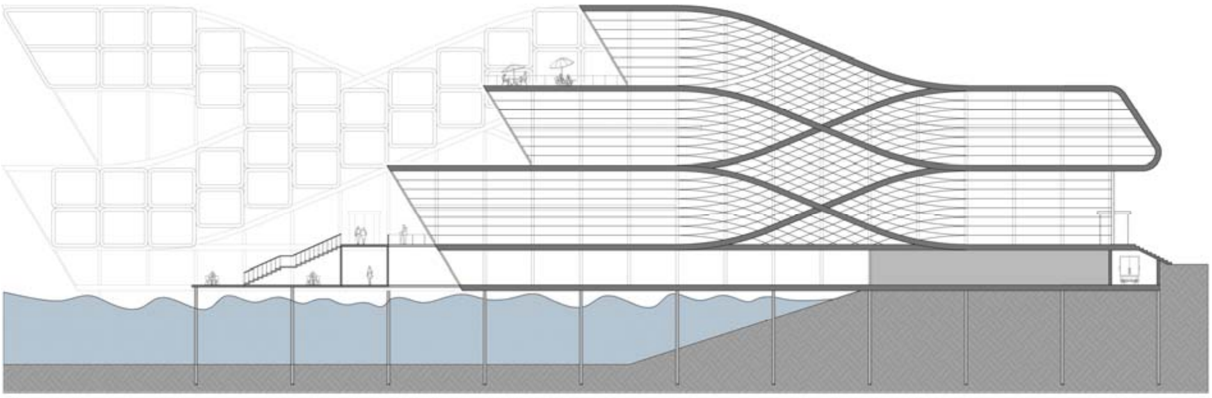


Figure 4: Curvature of the floors being reflected in the facade

Both the façade at the end of the architectural part and the one explained above are based on a FRP-glass structure. This is however not the only innovative way of producing a façade with FRP materials. Sandwich elements can also be used for this purpose. The main advantage of this type of construction is placed in the fact that every shape is possible, something which is certainly not the case for a FRP-glass based structure. However the biggest disadvantage in the use of sandwich elements is the size of the construction. The structural principle of this construction has been explained before and concluding from that a sandwich element which has to span for example from floor to floor will have a structure as wide as the floor slabs. The result of this will be that it is hard to tell which is which and thereby replacing the focus. After a couple of different variants have been made, from which figure 5 is one, the decision has been made on behalf of the technical and structural properties of the structure that this façade is to be build with a FRP-glass structure at the base.

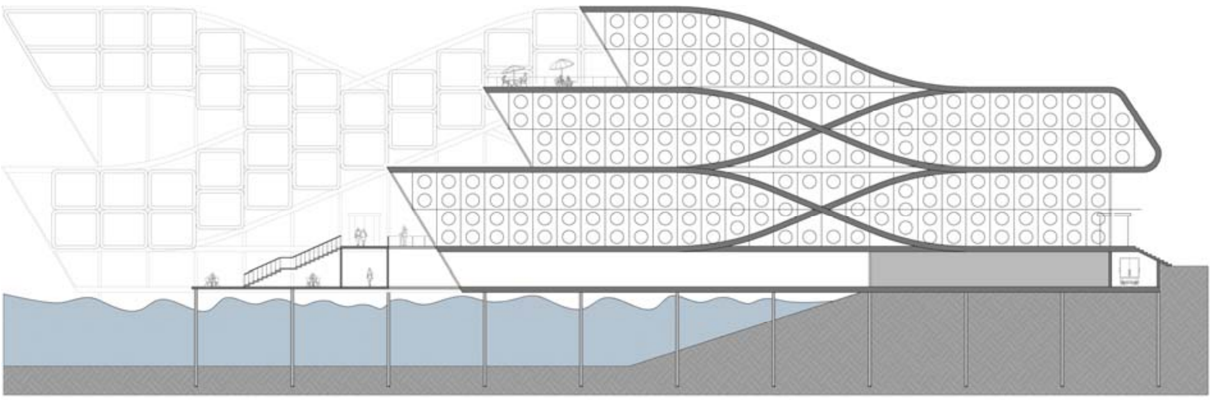


Figure 5: Sandwich elements

The next step taken can be seen in figure 7. The direction of the diamond like shapes has been adjusted to the slope of the floor elements. The result of this is a uniformly distributed design which has no big interference with the lines of the floors. So far this seemed to be the most suitable distribution of the construction. Another important and probably iconic part of the façade is the way sun shading will be applied. Besides the construction lines the façade consists entirely out of glass and is fully on the south orientated. This means a great amount of heat will be generated in the inside which needs to be prevented. Due to the various shapes it will be difficult to work with moving parts, however one innovative idea came to mind. This idea is based on the flexible behavior of FRP which makes is possible to introduce moving parts based on the bending capacity of the material. The principle is shown in figure 6. The result of this will be a dynamic façade which can transfer itself from one shape(figure 7) into the next (figure 8).

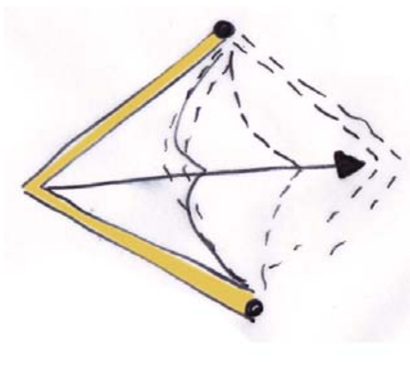


Figure 6: Dynamic element

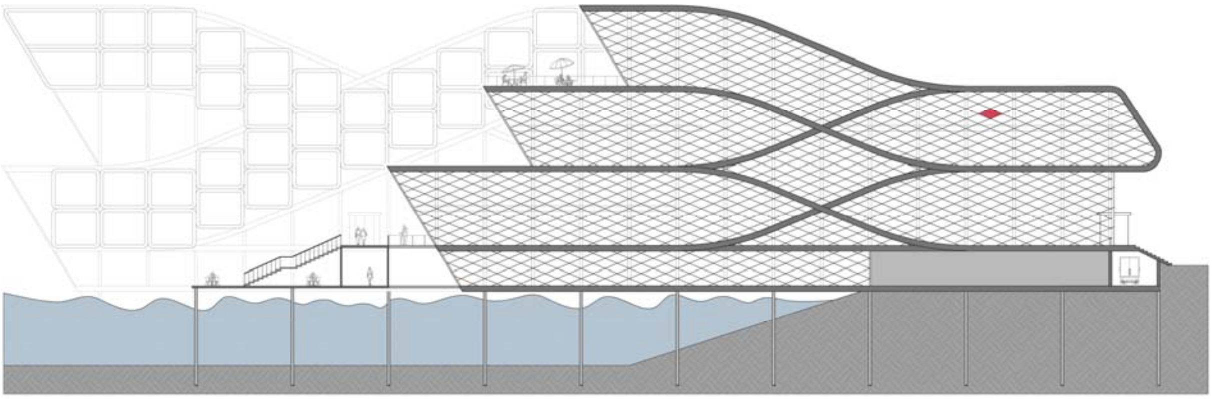


Figure 7: Diamond shape like modules related to the slope of the floors

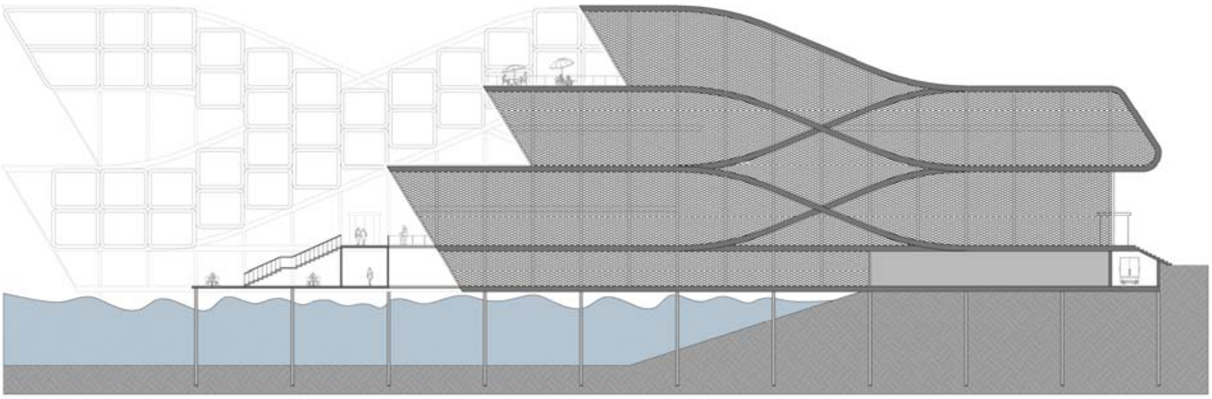


Figure 8: Closing up the façade for sun shading purposes

Figure 9 proves that this concept of sun shading works. The lines of the floors are preserved, something which can be seen best in the image of the exterior in which the façade is closed. Due to the uniform distribution of the elements and the minimal distance between them, all what can be distinguished are the lines of the curved floors. A big disadvantage of this principle is the loss of view towards the outside. Since this façade is south orientated this means the vast majority of time looking outside is not an option. This has great impact on the experience of the different spaces and function of the hotel, this is to be considered a negative development.

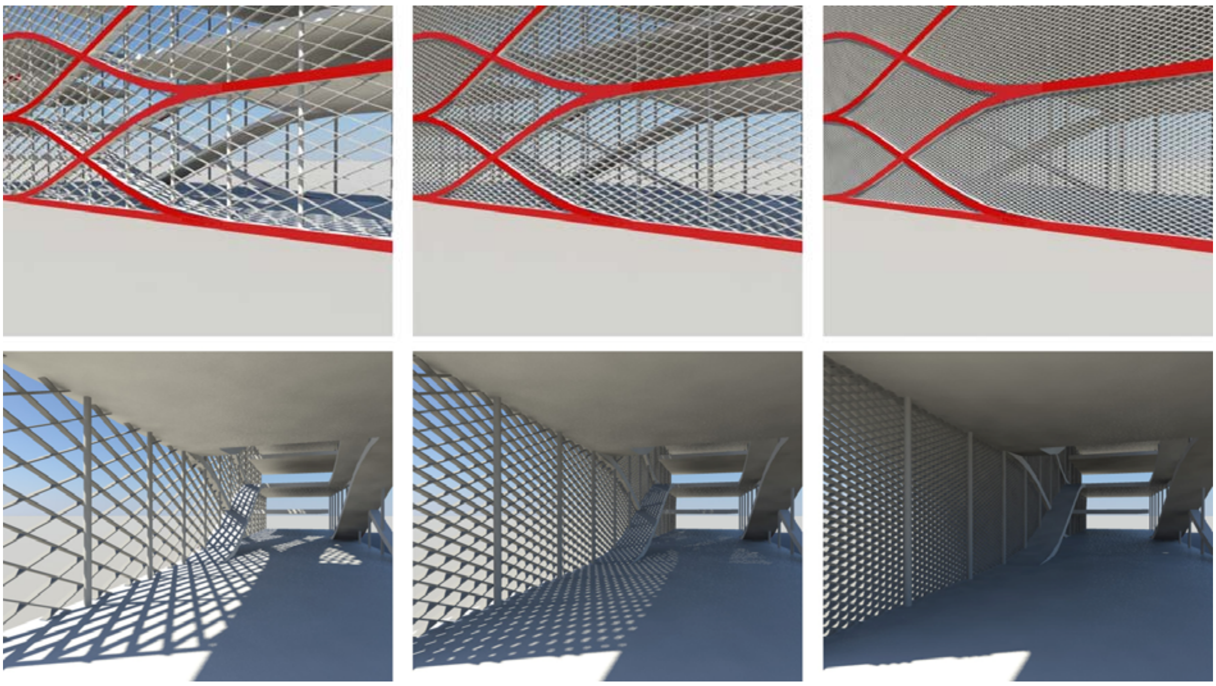
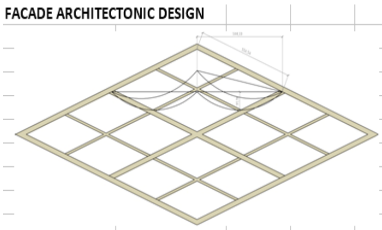


Figure 9: Different stages of the dynamic façade elements, exterior and interior experience

Besides visual objections there are also a great number of technical objections. This construction principle has been calculated from which the results can be seen in figure 10. Even if profiles with a thickness of 3 mm are used, a force of over 25 kg is needed to transform them. This requires large mechanical additions since this forces only hold for one part of the module. Each module has six dynamic parts in order to receive the image envisioned. Considering the fact that at least 8 modules are required to fill the gap between two floors, the amount of mechanis required is very large. These additional elements cannot be situated in the elements themselves since they wont be so slim anymore which means a place in the floor construction needs to be reserved. This itself should be possible however considering the fact that these are to be prefabricated elements complicates things. All of this can be solved, a thing which cannot be changed is the wearing which will occur in the dynamic parts. This and other factors like the rotation points lead to the conclusion that the idea is innovative and very experimental but it also leads to an undesired visual effect on the inside. More importantly, it rises above the plausibility of the design and the known properties of the material.

FACADE ARCHITECTONIC DESIGN



Youngs Modulus	E_FRP pultruded	=	23000	N/mm2
Yield Strength	σ_GRP pultruded	=	193	N/mm2
Width Element	b	=	150	mm
Lenght Element	l	=	508	mm
Thickness FRP	t_FRP	=	3	mm
Area	A_FRP	=	450	mm2
Centre	z_FRP	=	1,5	mm
Weight	FRP pultruded	=	2100	kg/m3

$$\sigma = \frac{M}{W} \qquad W = \frac{I}{Z} \qquad M = \frac{1}{8} \cdot q \cdot l^2 \qquad M = \frac{1}{4} \cdot F \cdot l$$

$$I = \frac{1}{12} \cdot b \cdot h^3 + A \cdot z^2 \qquad w = \frac{5}{384} \cdot \frac{q \cdot l^4}{EI} \qquad w = \frac{1}{48} \cdot \frac{F \cdot l^3}{EI}$$

Bending and Stresses

	I	w	kg/m	M	W	σ	F	kN	kg
FRP-lamel	3,38E+02	91	0,945	32847,08	2,25E+02	146,0	258,64	0,26	26,36

Figure 10: Calculation model dynamic façade module

9.3 Keeping the sun out vs. appearance of the building

As a result of previous developments, research has been done after the movements of the sun during the different stages of the year and the time of day. Figure 11 shows a scheme which illustrates the different angles of the sun which can be expected to be present on a façade orientated on the south. Figure 12 shows a study which has been done in order to determine the dimensions and spacing needed for the elements in order to keep the sun out. It states the obvious that the spacing's become narrower if the dimensions of the profiles are reduced. Relating this to the design, dimensions are chosen on the base of structural requirements. With these dimensions a study has been done after the relationship between the angle and the shape of the elements. The results of this study can be seen in figure 13. When using curved profiles bigger openings can be achieved, this theoretically should lead to a better view towards the outside.

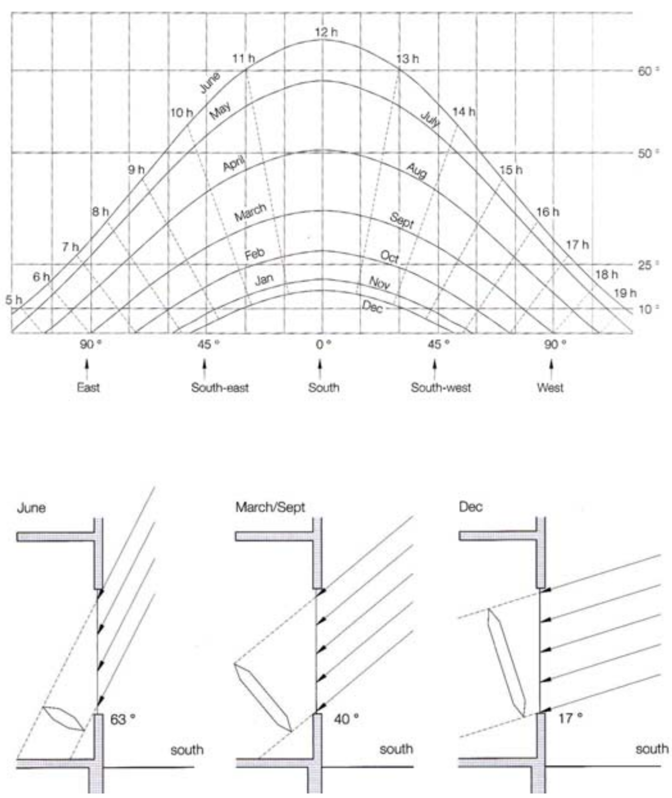


Figure 11: Position of the sun *(source: Façade construction manual)*

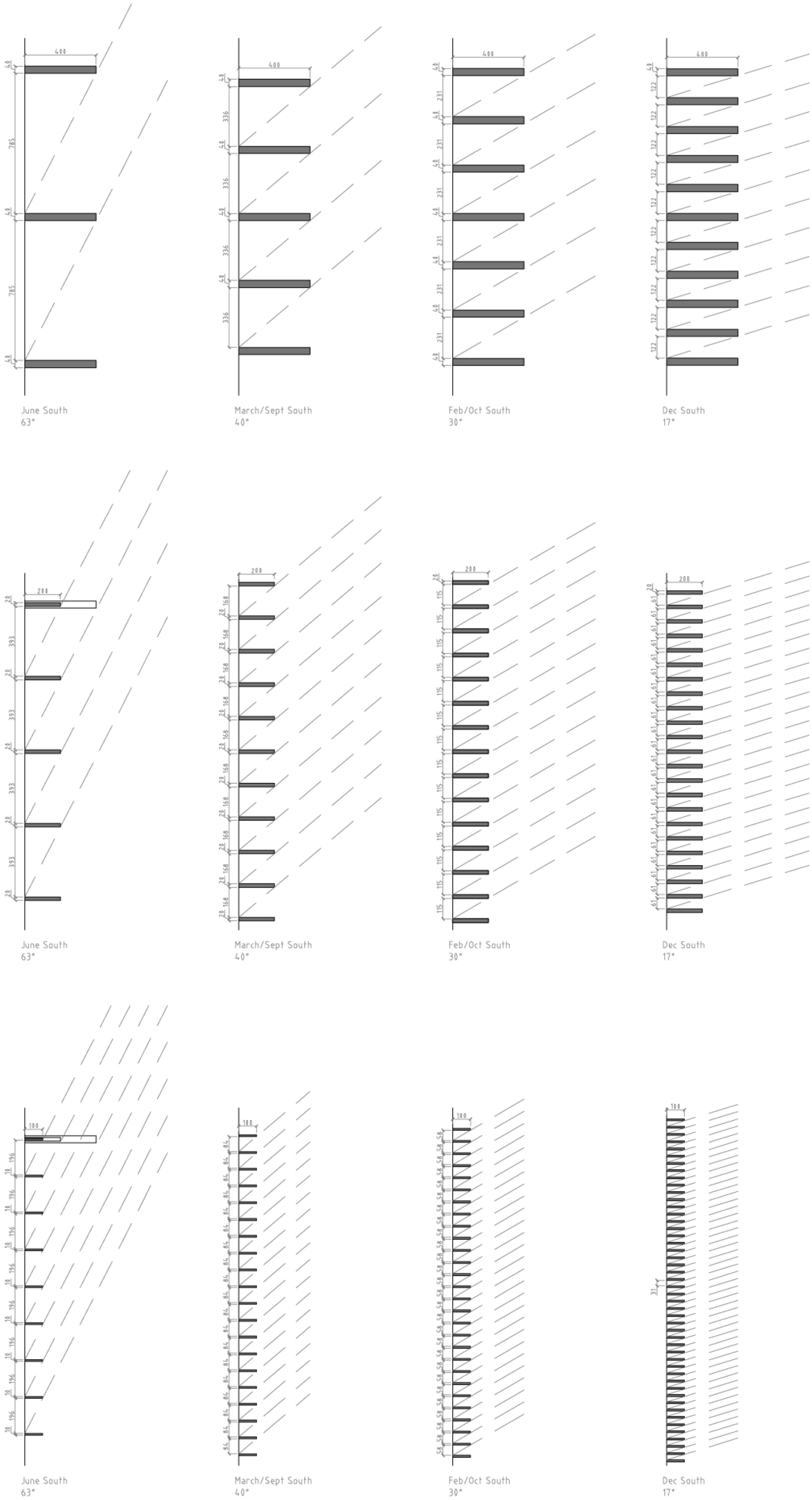


Figure 12: Relationship between spacing and the dimension of the profiles

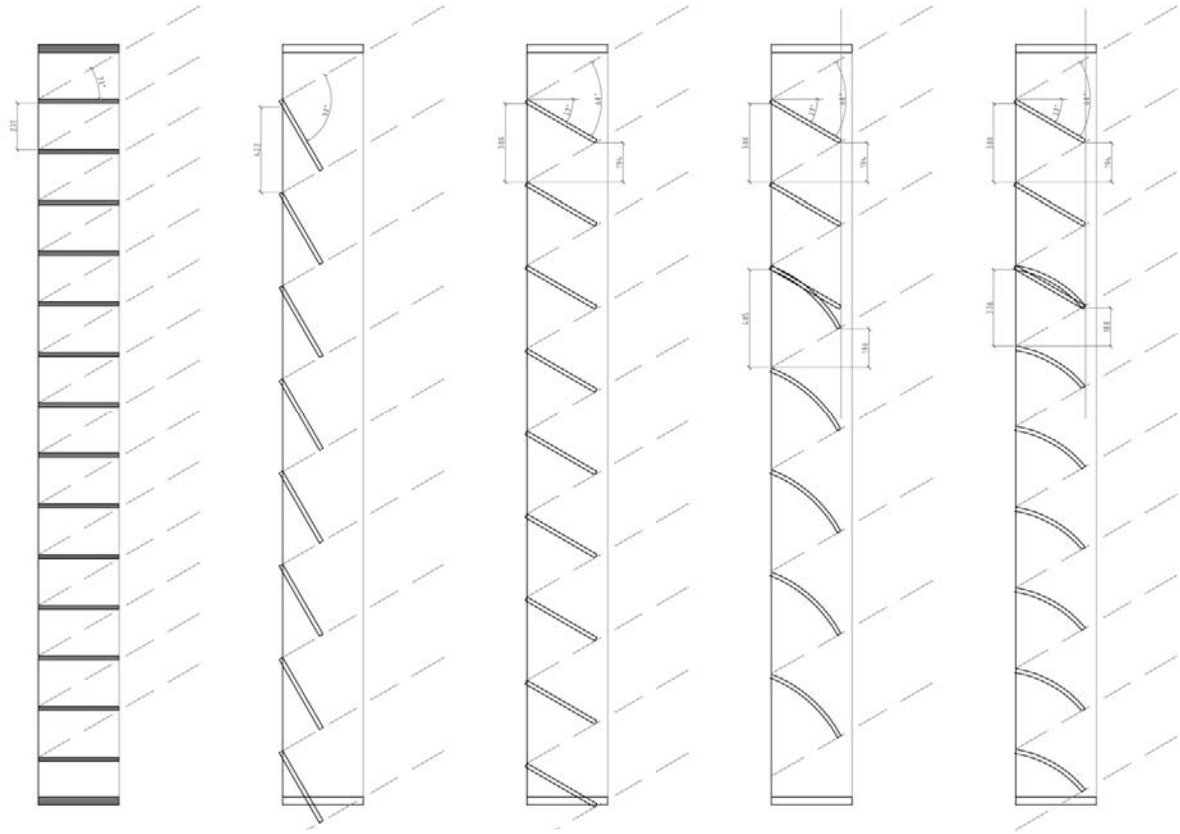


Figure 13: Different shapes, different angles

Small scale models have been made in order to test whether or not this 2-dimensional principle would work in practice. The position of a visitor is likely to change often which means various angles need to be considered, hence models were made. Figure 14 shows two images of these models. From these images it hard to tell which principle has the best results however the right model has slightly curved profiles which do seem to have a larger opening between them. As a result they offer a better view through. Profiles, or louvers with these dimensions are likely to be fixed which means the view through and the appearance/expression of the building are greatly influenced by them. This in itself is not to be considered a negative thing however one must keep in mind the impact of such a decision. The design of the elements and the louvers should therefore be considered carefully. The next part will describe how this research has been translated into a design which was presented at the P3 meeting of the building technology part of this project.

Figure 14: Practical models, testing the angel and shape of the sun shading profiles

9.4 Reflection on P3

Based on the reference grid used for the construction a new shape of the elements was determined. The movement of the building made by the curvature of the floors is continued in the shape of the façade modules. Figure 15 shows this principle completed with the dimensions. The modules are to span from floor to floor in order to spare the FRP profiles from being bound together with bolds which should carry the loads. These point loads are less from favorable since the reinforcement fibers are unable to handles the stresses. In order to stabilize the modules and because the glass panels used are not to be this large, a sub distribution of profiles is necessary. Figure 16 shows the result of all on the expression of the building. In red the shape and size of a module are highlighted. In order to use as much modules with the same size and shape as possible the modules are to be positioned behind the curved lines. The red lines in figure 16 illustrate this principle. This way less different elements are required. When the curved sun shading louvers are applied, the façade will look much more closed (figure 17).

Figure 17 also shows two new look al like floor slabs as a result of the shape and positioning of the modules. The left end of the façade has been cut of in a strange way which sort of a compromise between the actual shape of the elements which is too straight and the previous angel of the façade. When reflecting on this design one might conclude that the architectonical concept has not been implemented as envisioned. Figure 18 confirms this.

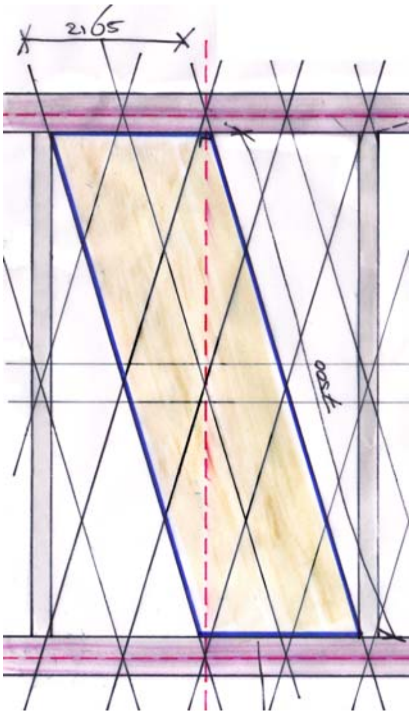


Figure 15: Reference grid and shape module

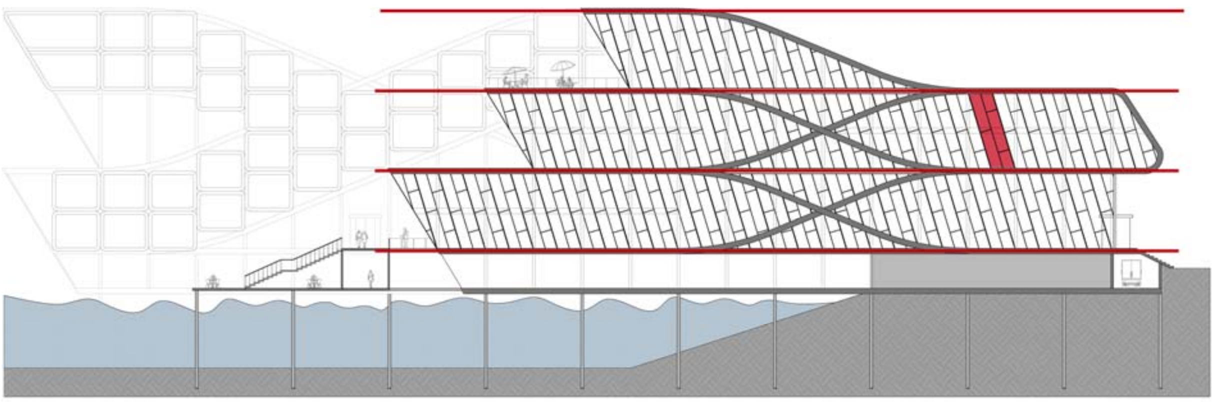


Figure 16: Modules placed between the floors

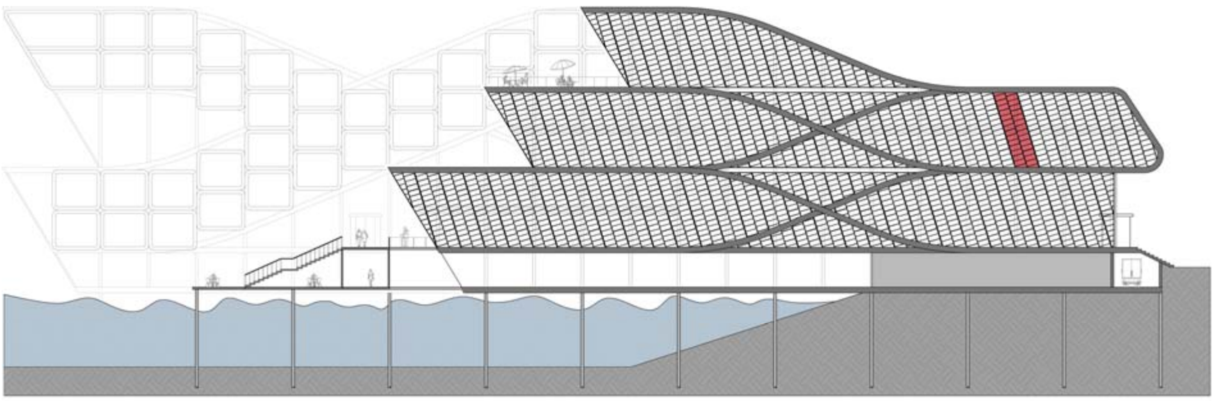


Figure 17: Sun shading louvers applied to the modules

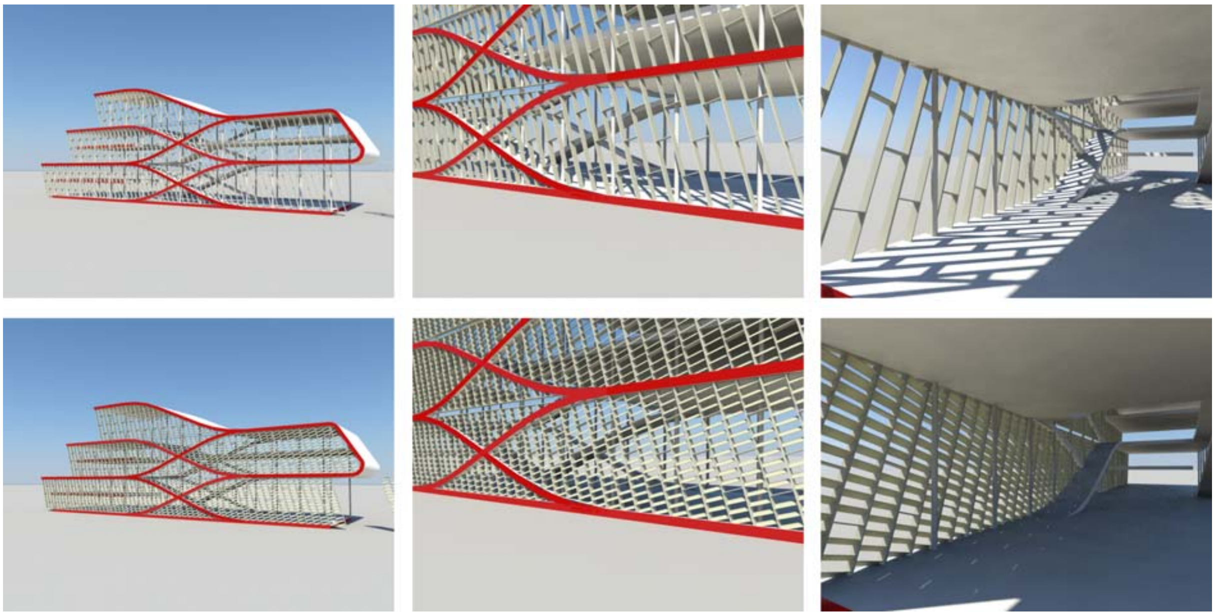


Figure 18: 3D model of the façade modules

Empty modules as well as filled modules are presented in figure 18. On the exterior the distraction of the fake floor lines and the ending on the left side of the façade can be seen clearly. On the inside it becomes clear that looking from a greater distance, the façade is not as transparent as assumed. However the sun shading principle does what it is supposed to do. Figure 19 shows this principle in detail. The FRP elements are positioned on the outside so they will contribute to the sun blockage as well. This is possibly due to the good thermal properties of FRP.
Concluded from this part of the design, the sun shading elements became too much of a present part of the research. It is valuable to have this research done however the design should be based more on the properties and opportunities of FRP rather than only on the sun shading principle. The use of construction on the outside contributes to this idea and needs to be valued.

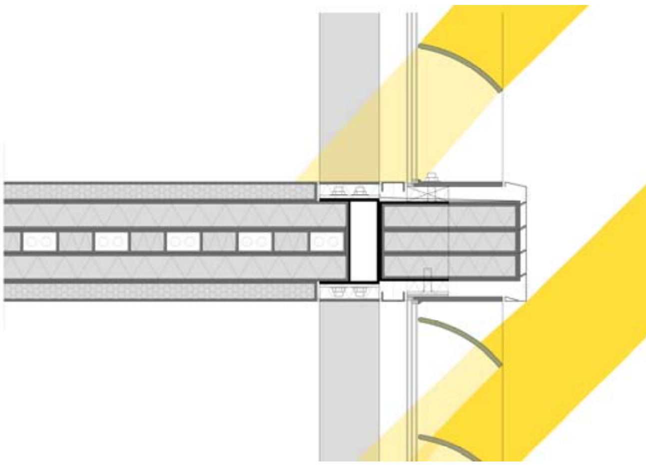


Figure 19: Detail of louvers, FRP construction on the outside

9.5 Preparation for Final Design

Keeping the results from P3 in mind, the process moved on. One major change as a result of a technical decision is the placing of the FRP profiles in vertical straight lines. Besides being water tight, provide sufficient sun shading etc., ventilation is also one of the functions which is to be considered. The idea at this stage of the process is to apply natural ventilation units to the curved floor slabs (figure 20). The chapter which contains an in depth exploration of the technical details will treat this topic also.
Figure 21 shows sketches of alternative façade distributions. The placing of the FRP profiles strictly vertical uses the smallest span between the floors which will result in even more slim profiles. Besides this adding value to the structure, it also fits the architectonical concept of having a uniformly distributed façade with no disturbance of the floor slabs.

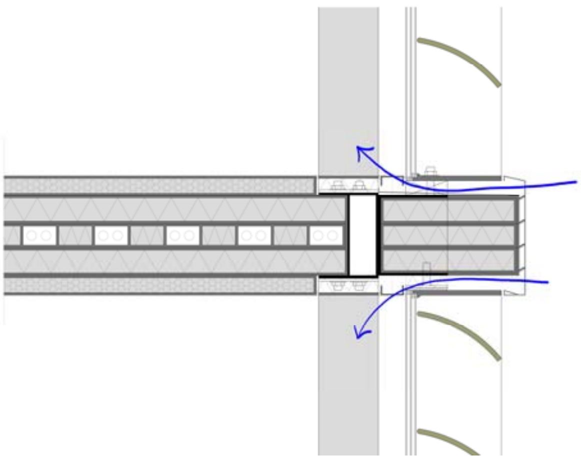


Figure 20: Natural ventilation

Figure 21: Sketches of various façade designs

These façade concepts are based on the use of opaque, translucent and transparent elements as part of the sun shading principle. By doing so the amount of transparent area can be reduced till 50% of its original value. In addition to this, low emission glass is to be used which also can reduce the amount of direct sunlight by 50%. The result of this will be a façade with no moving parts and still being able to provide a view through as well as sun shading. Different distributions of the construction have been researched which led to the design concept shown on the right of figure 21. Figure 22 shows images of a model which is build to clarify the relationships and the applied hierarchy of the different façade elements. Most of the lines which are represented by the floors have a horizontal orientation, as an answer to this the façade structure has a vertical orientation. In turns the strokes of the façade are transparent or not. The none transparent parts are opaque at top and bottom and have a translucent part in between. The niche which is the result of locating the FRP structure on the outside and the glass panels on the inside is here used to structure the different elements in terms of layering. Besides that this is also used to change the appearance of the building. When standing right in front of the façade (left image figure 22), the FRP profiles are hardly visible. The façade is now characterized by the translucent parts which tend to follow the same curvature as the floors. In case one takes a closer look the FRP profiles work like louvers which close up the façade and show practically no more than the red lines belonging to the floors. On the inside the façade is completely flat which increases the experience of the floors bending and curving without being disrupted by additional structures.

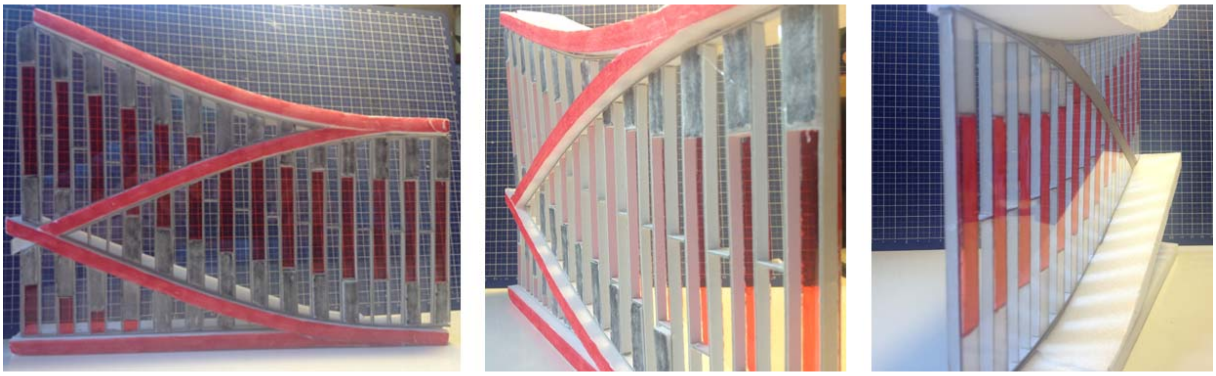


Figure 22: Model of the improved façade modules

9.6 Conclusion/Recommendation

After reviewing the design some adjustments needed to be done. The translucent and opaque parts are to disappear but the distribution of the FRP profiles is to be kept. This will be done to increase the uniform expression of the façade and to make more use of the niche structure explained before which is now held back by the opaque parts. The horizontal FRP parts will be placed back which will result in having vertical lines only. To increase the difference between the curved floors and the façade, the horizontal FRP parts will no longer follow the curved lines. How this is put into practice will be described in the next chapter which will explain the architectonical part of the final façade design.

10 Facade Design

This chapter will describe the architectonical appearance of the façade and thereby of the building. Figure 1 shows the design proposal described in the previous chapter with the opaque and translucent parts of the façade referring to the curved lines of the floors. Due to this non-uniform distribution the focus is placed on the façade elements instead of the lines produced by the floors. By changing the distribution of the façade this can be changed into an image in which the floors are the most important part and the façade is hardly visible in a frontal view.

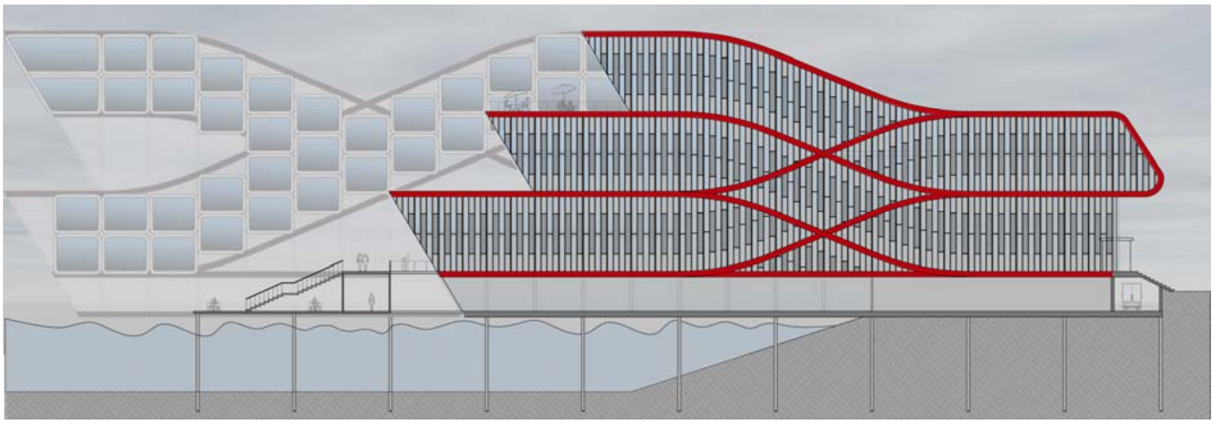


Figure 1: Design vs. research

10.1 Façade design

Figure 2 shows the appearance of the façade as a result of placing the horizontal profiles in a straight line. This results in a calm and structured image in which the floors are the most important element once again. This vertical distribution of the FRP profiles provides the opportunity of parts which can be opened in order to naturally ventilate specific rooms. Earlier designs driven by the idea of using the curved floors for ventilating purposes turned out to be ineffective and extremely difficult to detail given the space required for mounting the façade elements. This will be explained in the next chapter. Directly behind the façade over half of the area can be considered traffic zones which profit very little of parts which can be opened. Therefore these additions to the façade elements will only be done in zones of the façade which include lounge zones like the entrance and the restaurant of the hotel. Due to the vertical positioning of the profiles it becomes less complicated to connect internal walls to the façade which offers the possibility to introduce an enclosed porch at the entrance instead of a turret door which is not always easy to use in case of large groups or with a great amount of luggage. Besides these practical arguments the façade on the front end is no longer disturbed.

The façade in combination with the cantilevering floors are based on a hierarchy in this design. Combining figures 2 and 3 explains what this means. Due to the placing back of the horizontal profiles, only vertical profiles are visible when looking from the side. These vertical elements close the façade entirely and are limited by the floors, thereby accentuating the curvatures. When moving closer and as a result changing the point of view, the façade starts to open up (figure 3), revealing something of the interior of the hotel. Passing by and standing right in front of the façade the FRP profiles are hardly visible. The transparency of the façade and the game played by the curved floors is revealed. The entire design is moving towards the water including the façade only this time it is not so much as the shape which makes this gesture but the various levels and angles from which the façade can be seen.

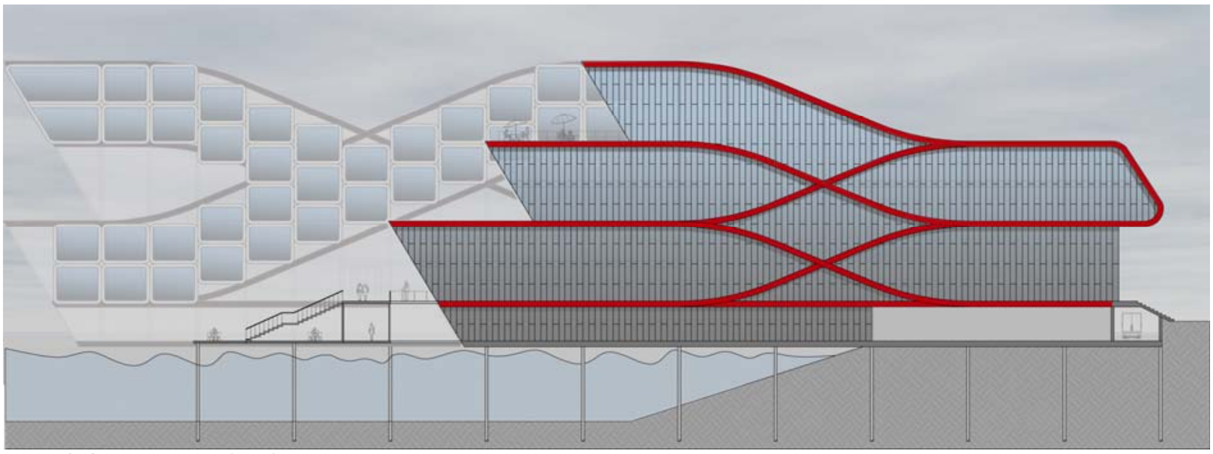


Figure 2: South elevation final façade design

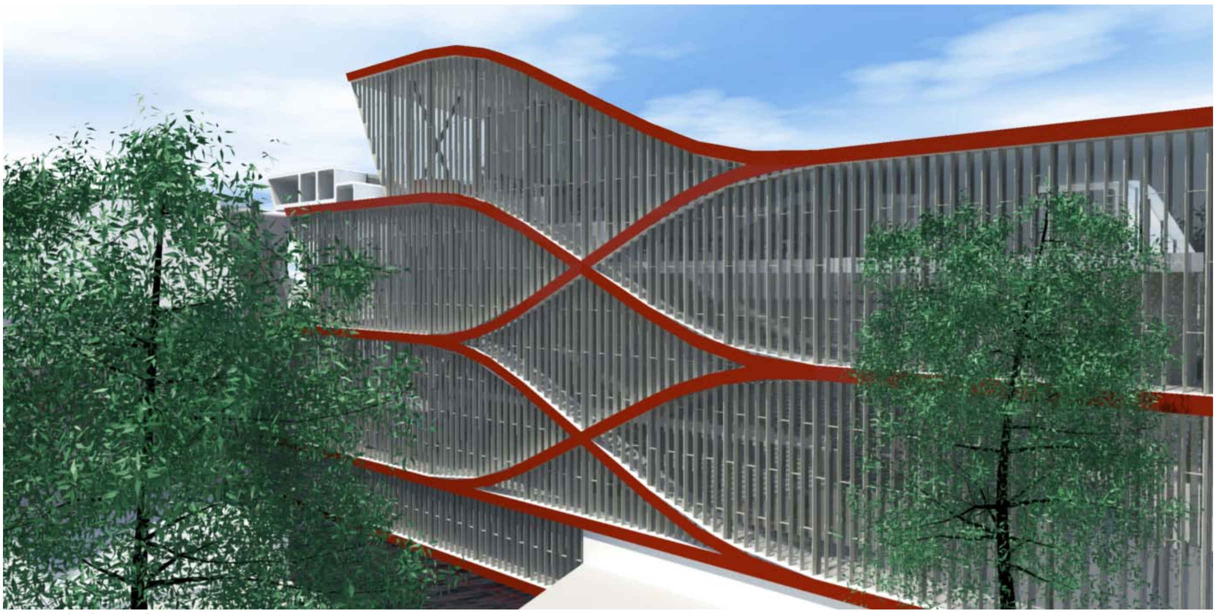


Figure 3: South façade, opening up

10.2 Sun shading

One other particular interesting aspect of this façade design will be the sun shading principle. Due to the vertical positioning of the FRP profiles and the distance between them it becomes possible to use moveable sun shading elements. The FRP profiles will be used for guidance of the screens. The appearance of the building can be changed as a result, something which can be seen in figure 4. Due to the height between floors it is impossible to use only one element. The lines of the floors will be used to divide the sun shading elements. One half will be placed on the outside which will function top down. The other half will be placed on the inside and will function bottom up. The architectonical concept of the various routes through the building will be reflected in the façade by placing the sun shading elements on the outside if directly behind the façade the traffic zone of the visitors can be found. The sun shading elements reflecting the guest route are placed on the inside. Doing so generates depth in the façade and thereby showing the vertical layering of the interior of the building. On the outside the relief of the façade will disappear since the FRP profiles will be used for guidance. How this works in detail will be explained in the next chapter. With this proposition for sun shading elements, not every part of the façade is covered. The parts which are left out contain the entrance and restaurant of the hotel even as cross-sections of the traffic zones. These spaces benefit from this since a view outside is present at all times which increases the experience of the hotel. The technical functioning of this design is explained in the next chapter.

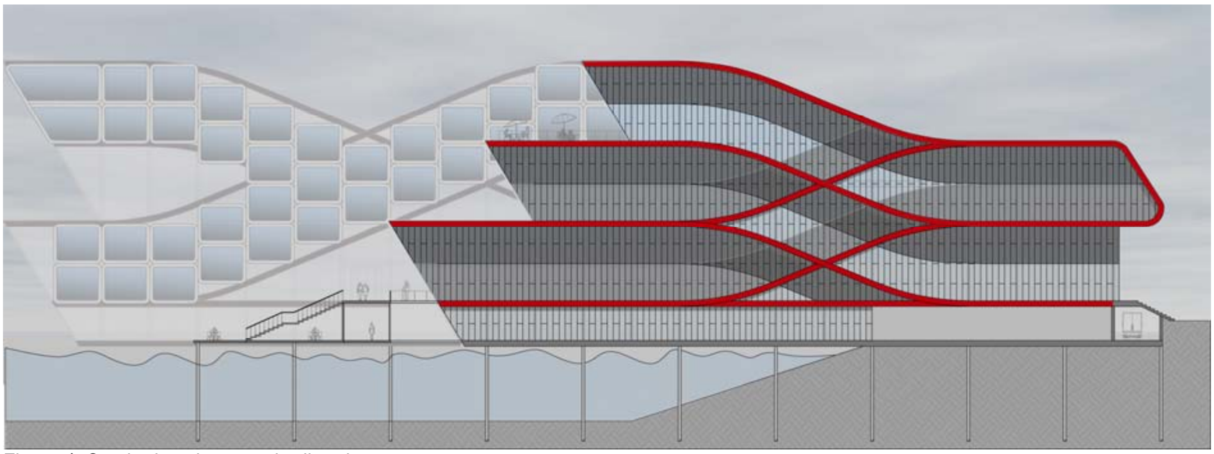


Figure 4: South elevation sun shading down

10.3 North façade

During the design process the main focus has been placed at the south façade since this is the most important façade of the hotel. However due to the use of a structural reference grid the distribution of the façade elements works as well on the north façade as it does on the south façade. The rooms which will be attached to this façade will be based on the same reference grid which means both distributions will coincide at cross sections. Figure 5 shows the north façade including rooms and façade elements. The horizontal parts of the façade are similar in position as the rooms vary in height.

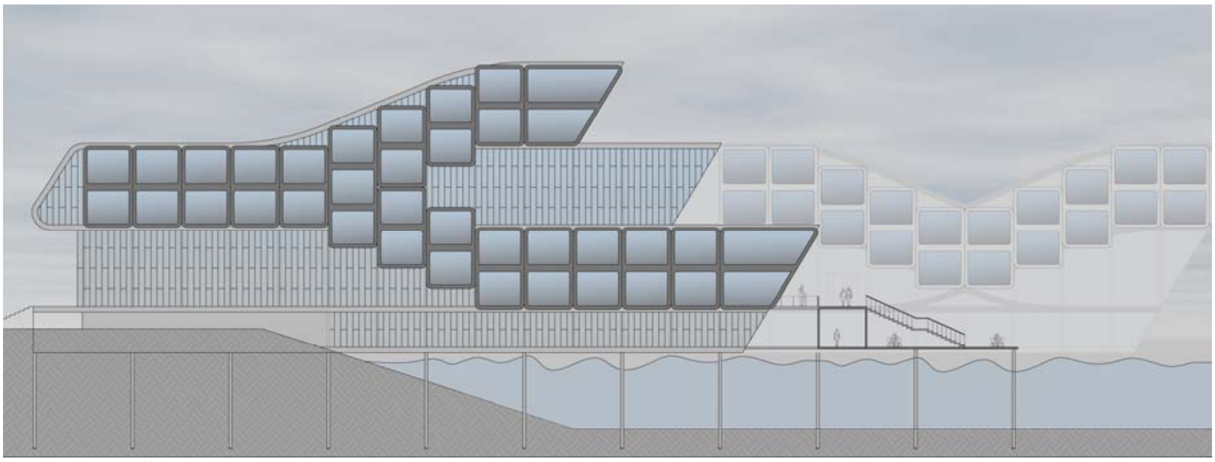


Figure 5: North facade

10.4 East & west facades

In the previous design, the west façade followed the direction of the south façade and thereby fell over. Due to the orthogonal distribution of the façade in this design, the east and west façade can be placed vertical without affecting the appearance of the building. The west façade contains doors on every level which provide access to the various decks. By placing this façade vertical these openings can be integrated in the design. These facades span 3.6 m in most cases which means less construction is required. This results in even more transparent façade elements, thereby stating the difference between the north/south facades and the east/west facades. The orientation and direction of the building visualized in the south façade will continue to exist.

Figure 6: West facade

11 Detailed Design

The technical elaboration of the façade even as decisions made based on technical as well as architectonical grounds, are explained in this part of the report. The distribution of the façade elements as described in the previous chapter will be the starting point for this research and thereby the final design. Since the façade is to be build with prefabricated modules, dimensions of these modules are to be determined.

11.1 Calculating the profiles

Figure 1 shows three obvious elements all based on the structural reference grid and thereby the façade distribution. At first a module was considered with the width of 540 mm which comes down to the left image in figure 1. Two profiles plus glass would be an element, which means there are as much seals required as profiles are present. This is not preferred since the tolerances with this type of façade are small and the glass is the only element separating the inside from the outside. A great amount of seals increases the risk on having problems with the water tightness of the façade. Besides, since the elements are prefabricated and in theory would reduce the building time, they should be as big as possible. However this has consequences for the dimensions of the FRP profiles. All three modules shown in figure 1 have been calculated, they vary in width from 540 mm to 2160 mm. All have a height of 7.2 m which is the distance between two floor slabs. For these calculations the model explained in chapter 7 has been used. Figure 2 shows the calculation and the results. One very important note that must be made in in relation to the calculations is the FRP profiles being based on a deflection of 1/200 * h. This is considered a deflection hardly visible on the inside which is to prevent any suspicion on whether a building is safe. However the material properties of both glass and FRP allow the elements to deflect even further. If only looking at the material properties, the FRP profiles could be even more slender.

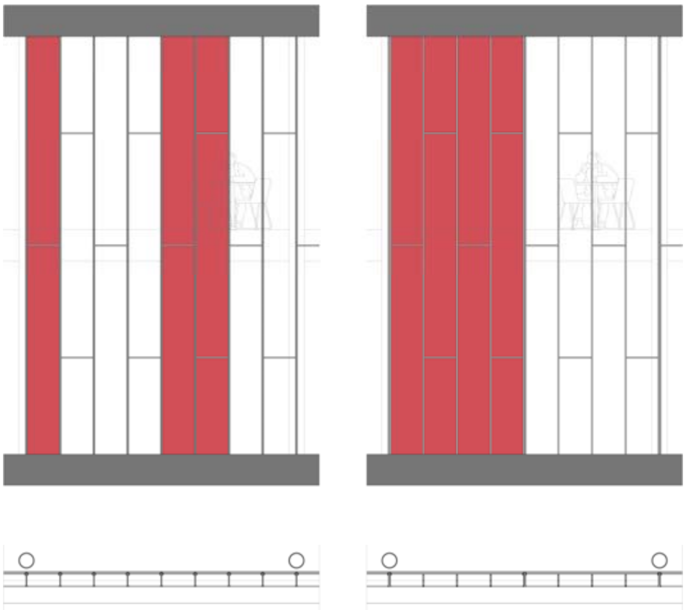
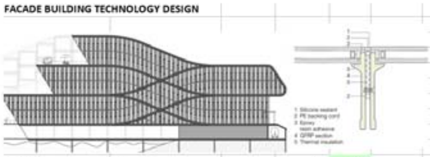


Figure 1: Possible dimensions of the façade modules.

FACADE BUILDING TECHNOLOGY DESIGN



Bending	w	=	36	200
Youngs Modulus	E_FRP pultruded	=	28000	N/mm2
	E_glass	=	68000	N/mm2
	n_composite	=	0,41	
Yield Strength	σ_GRP pultruded	=	193	N/mm2
	σ_glass	=	38	N/mm2
Width Element	b	=	2165	mm
Height Element	h	=	7200	mm
Thickness glass1	t_glass1	=	4	mm
Thickness glass2	t_glass2	=	4	mm
Thickness spacer	t_spacer	=	8	mm
Height FRP	h	=	250	mm
Thickness FRP	t_FRP	=	28	mm
Thickness FRP modi	t_FRP modified	=	11,53	mm
Area	A_glass1	=	8660	mm2
	A_glass2	=	8660	mm2
	A_FRP	=	7000	mm2
	A_FRP modified	=	2882,35	mm2

Centre	z_glass1	=	2	mm
	z_glass2	=	2	mm
	z_FRP	=	125	mm
	z_total	=	239,02	mm
	z_glass-stress	=	26,98	mm
	z_glass1 modified	=	12,98	mm
	z_glass2 modified	=	24,98	mm
	z_FRP	=	114,02	mm
Load Cases	q	=	4,13082	N/mm
Weight	FRP pultruded	=	2100	kg/m3
	Glass	=	2450	kg/m3

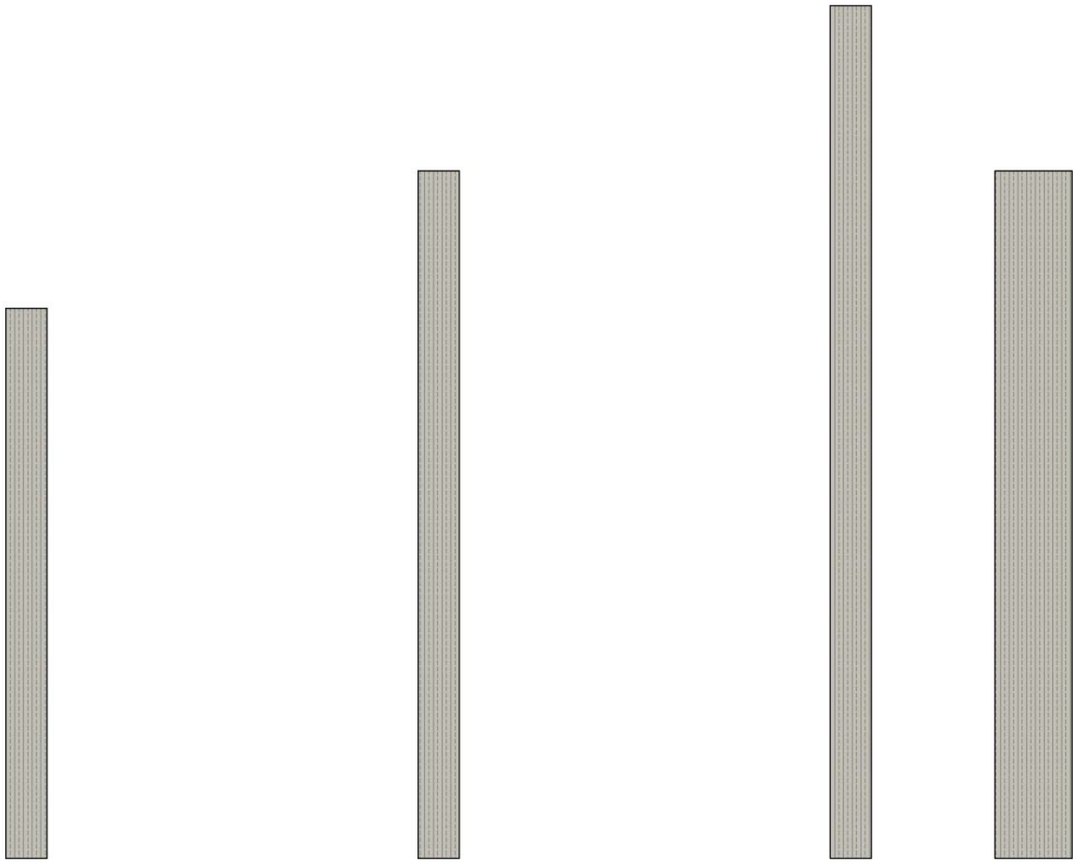
$$\sigma = \frac{M}{W} \qquad W = \frac{I}{Z} \qquad M = \frac{1}{8} \cdot q \cdot l^2$$

$$I = \frac{1}{12} \cdot b \cdot h^3 + A \cdot z^2 \qquad w = \frac{5}{384} \cdot \frac{q \cdot l^4}{EI}$$

Load		
Temporary load	0,56	kN/m2
Safety factor	1,5	
Permanent load	0,89	kN/m2
Safety factor	1,2	
Total load	1,908	kN/m2
	0,001908	N/mm2

Bending and Stresses					FRP		Glass	
	I	w	kg/m	M	W	σ	W	σ
FRP pultruded + glass	5,94E+07	3,58E+01	57,13	2,68E+07	2,48E+05	107,77	2,20E+06	12,16
FRP pultruded	3,65E+07	1,42E+02	14,70	2,68E+07	2,92E+05	91,78		

Figure 2: Calculating the FRP profiles



	b (mm)	h (mm)
Element:	540	7200
FRP profiel:	15	200

	b (mm)	h (mm)
Element:	1080	7200
FRP profiel:	15	250

	b (mm)	h (mm)
Element:	2160	7200
FRP profiel:	15	310
	28	250

Figure 3: FRP profiles dimensions

The results of the calculations can be seen in figure 3. The smallest module is to have a profile with dimensions 15 mm * 200 mm. The largest module will have a profile based on a width of 15 mm, with a depth of 310 mm. Each doubling of the module size adds an extra 50 mm to the depth of the profile. Given the size of the building and the module span, none of these calculated profiles is considered large. Based on the calculations and the fact that the less seals the better, a decision has been made to use the largest elements, keeping the same distribution of profiles as is the case with the smallest profile. The width of the profiles needs to be increased since surface is required in order to bond the glass and FRP properly. This results in a profile with a width of 28 mm and a depth of 250 mm. The calculations are based on profiles on the edges of the module. Profiles in between are considered inactive when it comes to load carrying capacity since they will be connected to the outer glass pane only, however they do contribute which results in profiles 28 mm * 200 mm. They also contribute to the stiffness of the modules during transportation and mounting. The glass panels will have a width of 2.16 m and a height of 7.2 m. These glass dimensions are considered hardly possible due to transportation problems in conventional situations. The reinforcement of the glass by the FRP profiles provides new opportunities when it comes to glass sizes. Profiles on the edge of the module have different dimensions then the ones who divide the surface, this is the result of different contributions to the construction.

Figure 4 shows a section of the façade in which the various modules can be recognized. The distribution of the modules is not only important when in comes to transportation or structural behavior, but also for the proper modeling of the façade. Due to the curvature of the floor elements and the pultruded profiles only being perfectly straight, the lines have to be fragmented. The large radius of the curvature and the small distance between two profiles make this easy. The lower image of figure 4 shows part of the curved façade with sun shading elements. The line made with the sun shading elements consists strictly of straight lines. As one can see, this cannot be seen. The sun shading system itself benefits from this distribution as well. Between two profiles a sun shading element will be placed which is guided by the profiles. The housing of the sun shading parts has to be placed horizontal. This will be done within the depth of the floor elements resulting in a clean image of the façade when the sun shading is up.

Figure 4: 1-20 façade

11.2 Detailing the facade

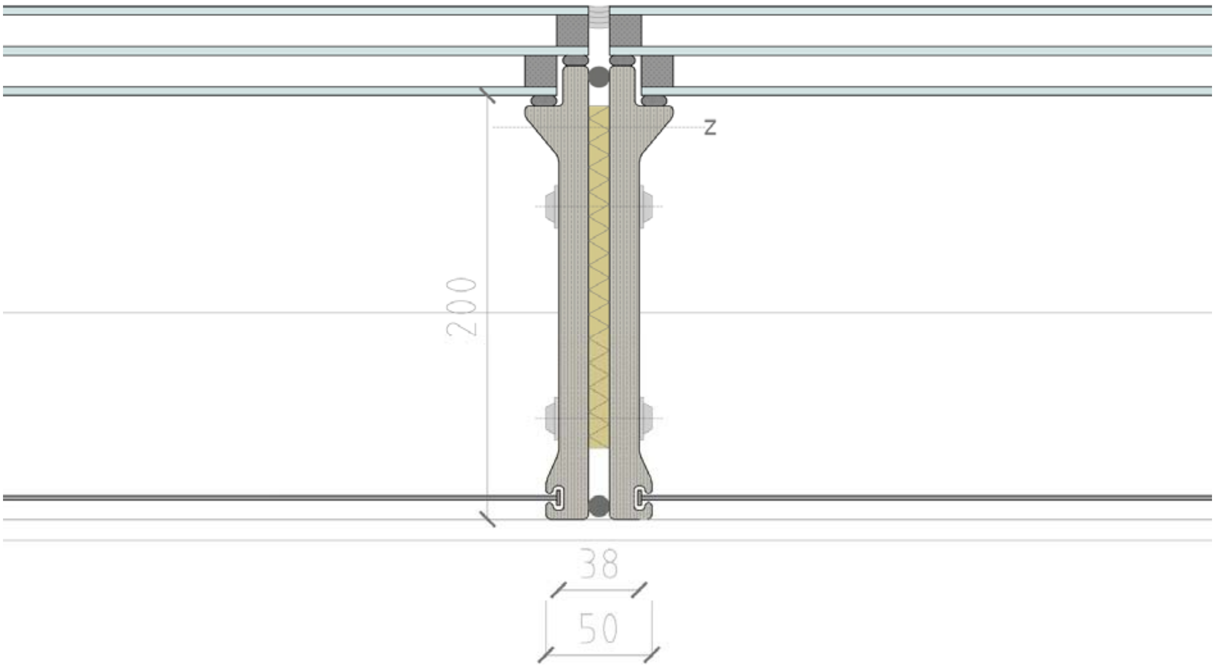


Figure 5: Detail of the profiles used on the vertical edge of the modules

Figure 5 shows the profile used for the vertical edges of the modules. It now becomes clear how the modules will be related to each other. Above the glass panels will be the inside and below the outside. The entire FRP construction will be placed on the outside generating depth and rhythm in the façade. The façade is almost one hundred percent transparent which means the insulating capacity is located in the glass elements. As a result triple glazing will be used from which only two panes will be used for the construction. This provides a buffer zone in which water tightness can be confirmed and it also reduces the dimensions of the FRP profiles at the connection level compared to the situation in which all three panes are structurally active. At the front side of the profiles the shape has been adjusted in such a way, sun shading guidance is provided. The FRP profiles are to be considered more than construction only, due to the integration of elements like sun shading.

The modules will be connected to each other with bolts since there should also be the option of removing one of the modules. Besides this type of connection allows the modules to expand which certainly would not be the case when a glued connection is used. As explained before, a bolt connection damages the fiber structure of the profile. However the holes in the profiles contribute in a negative way to the structural performance, the bolted connection itself is not structural, its task is to hold the façade modules in place.

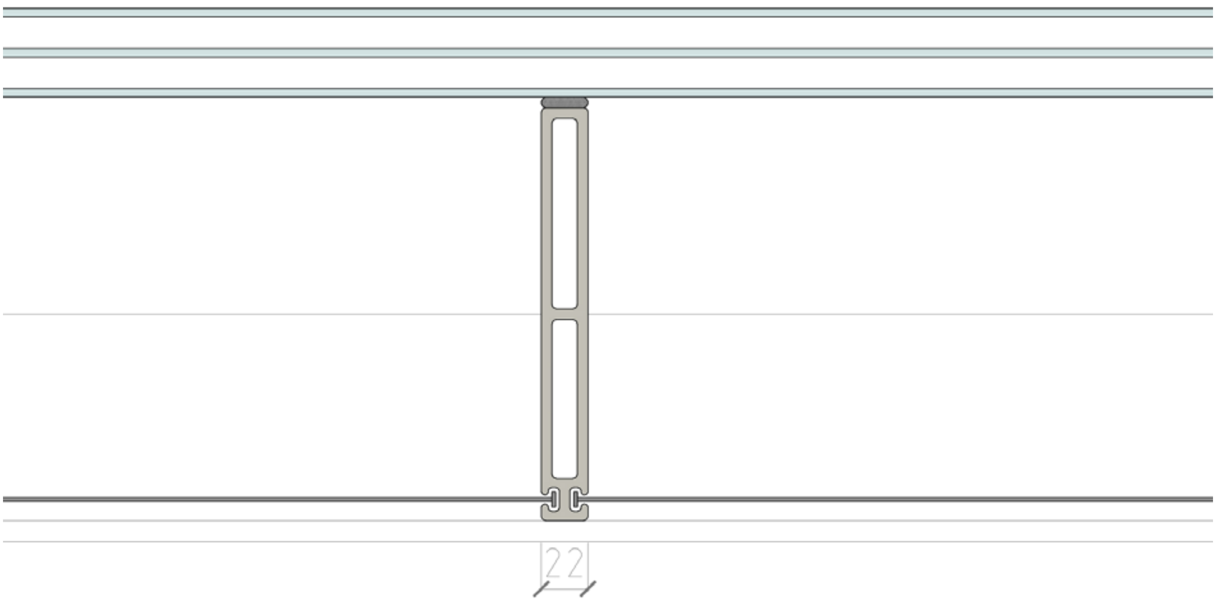


Figure 6: Detail of the profiles used for the distribution of the modules

The profile used for the distribution of the modules and the guidance of the sun shading elements is shown in figure 6. As mentioned before, this profile will be more slender than the ones on the edge of the module. These profiles will only be connected to the outer glass pane thereby not adding unnecessary seals to the building. Besides the vertical FRP profiles there are also horizontal profiles which will be reduced in depth compared to the vertical profiles. These profiles are responsible for the prevention of twisting the modules during transportation and in use as well.

The connection between the different facades will be made using the columns. As a result the lines in the south façade are untouched by the appearance of, in this case, the west façade. The column puts distance between the two which results in the independently functioning of both facades.

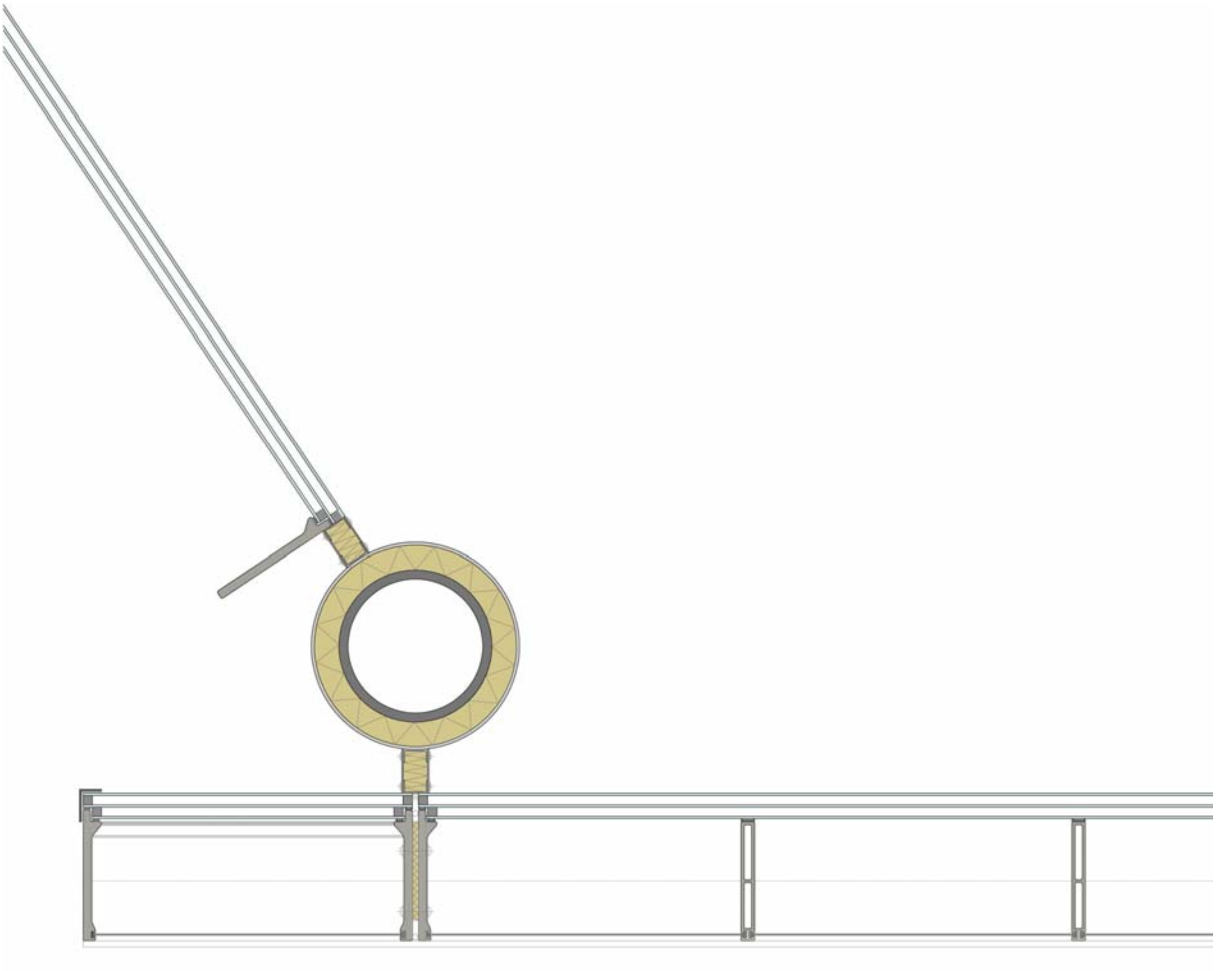


Figure 7: Corner detail

11.3 Connecting floor and facade

The architectonical design showed a façade in which the sandwich floor elements were located on the inside as well on the outside. During the elaboration of the façade it became clear this would be possible in terms of thermal properties however space is required for mounting the façade elements as well as for keeping in mind the lines of the floors being continuous from inside to outside. With the sandwich elements on the outside this would not be possible. Figure 8 shows the connection between façade and floor elements in detail. As can be seen the sandwich elements on the outside are removed thereby offering space for mounting and integrating other parts of the façade like sun shading elements and lighting. The image of the floors running through the façade is preserved by retaining the lines. How all of this will be build is explained in figure 9.

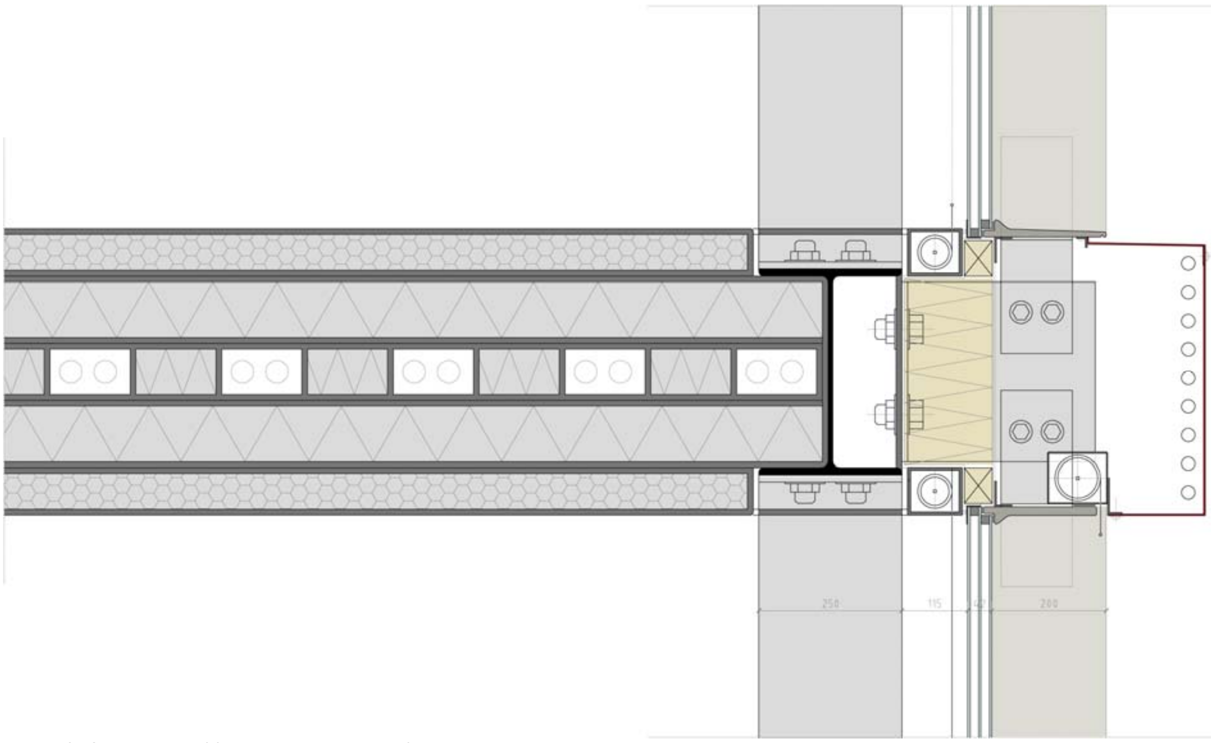


Figure 8: Connection of façade and sandwich floor elements.

1. The layering of the sandwich elements and the included I-beams as explained in Part B of the report but without the sandwich elements on the outside.
2. The I-beam is closed in order to provide connection options for the façade. Steel mounting plates are attached at the level of the columns and in the center between two columns. These mounting plates can be adjusted in all directions so the prefabricated façade modules will fit at all times.
3. Prefabricating the façade modules starting with the glass panes who differ in size due to the connection tot be made with the FRP profiles.
4. FRP profiles are glued to the edges of the glass panes.
5. Dividing vertical and horizontal profiles are attached.
6. At last steel T-profiles are attached on top and bottom of the module trough which the modules will be mounted to the building. These elements are placed between two modules so they are invisible after mounting. The horizontal parts make sure no bolts are required, thereby preserving the load carrying capacity of the profiles. These elements will be used for lifting the modules for transportation and mounting as well.
7. Attaching the modules to the building after which the finishing can be applied.
8. Starting with the sun shading cases. In theory this could be done before mounting the modules to the building, however this will complicate the mounting process leaving little room for movement of the construction worker.
9. Rigid insulating elements are applied which follow the line of the glass which makes this the separation between the inside and the outside. Also mounting strips are attached for the final finishing of the façade.
10. Finally red translucent elements are applied behind which lighting is placed which makes it possible to show the curved lines during day as well as during night. Besides lighting will be placed underneath the FRP profiles. Since they are translucent due to their high glass fiber content they can emit light. This results in an illuminating construction, not to be confused with illuminating the construction. At night the true experience of plastics in the construction will come to life.

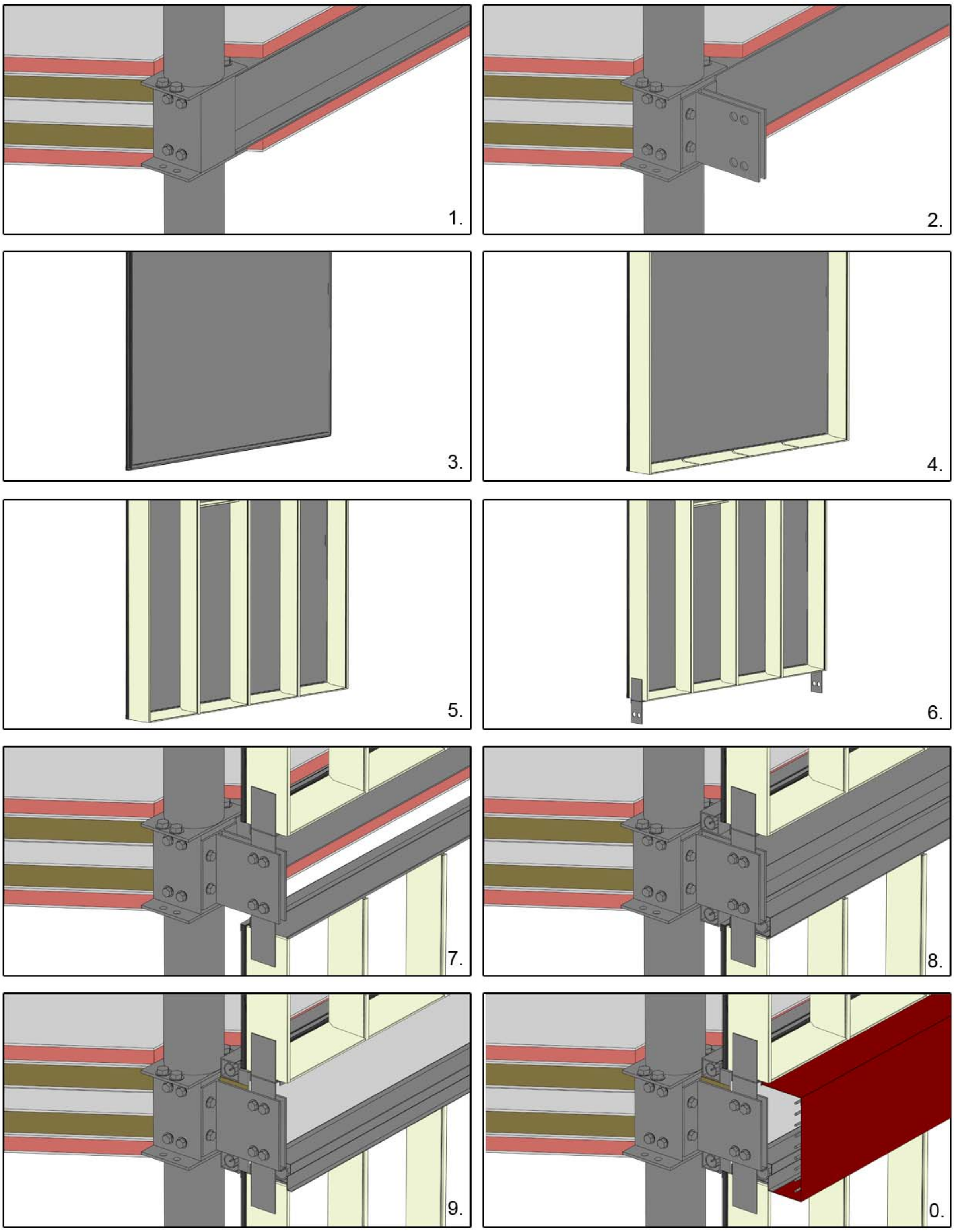


Figure 9: Mounting scheme façade modules

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http://www.fiberline.com

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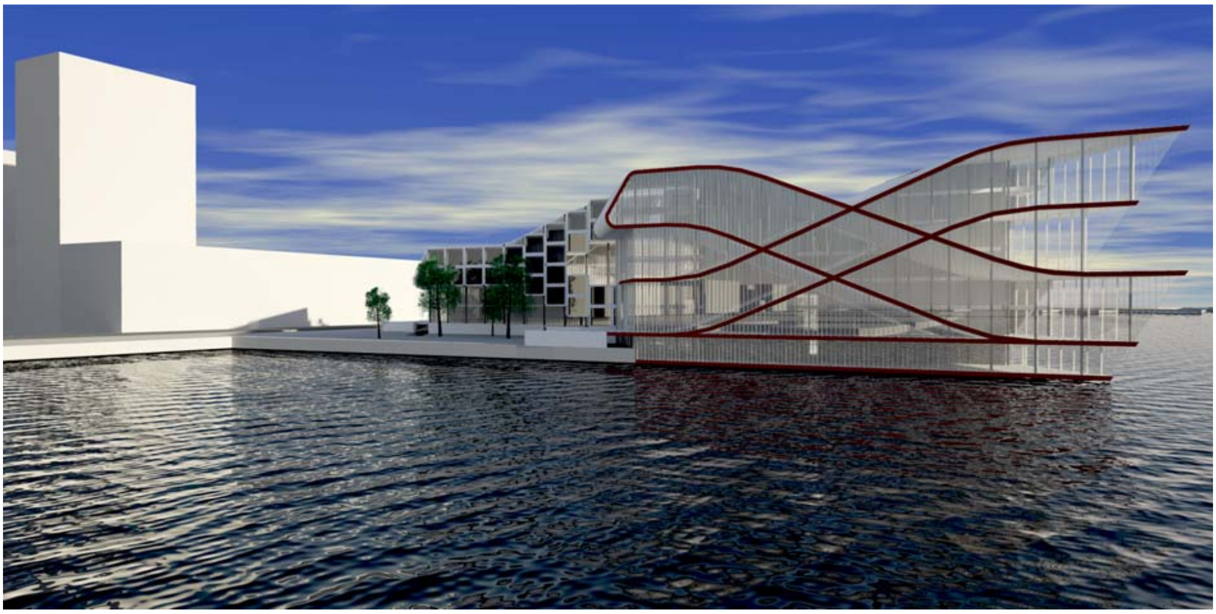
http://www.strongwell.com/pultrusion/

http://www.thifaso.com/unitized_structural.html

PART D

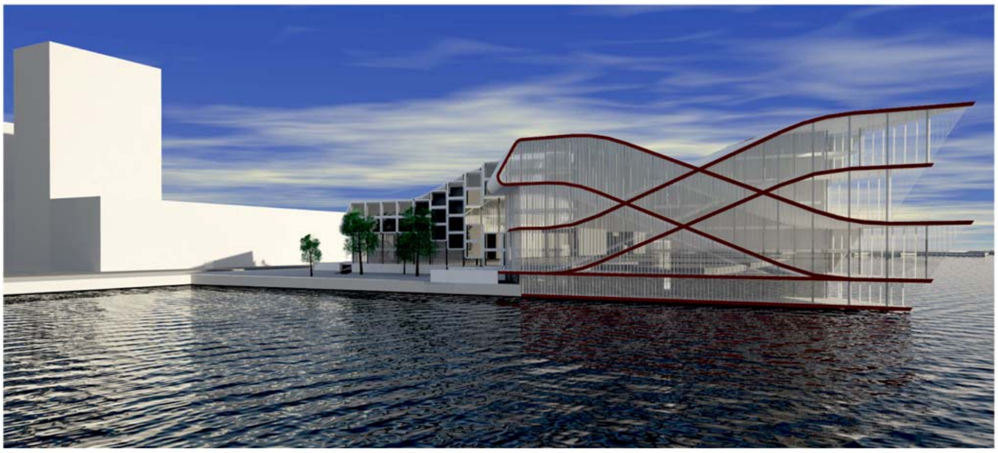
Presentation



Architectural Engineering
Building Technology

Dual Graduation Track

Composite - Hotel Design



P5-presentatie, Lex Oosterom

Dual Graduation

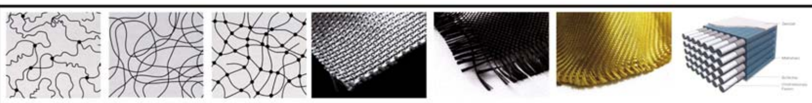
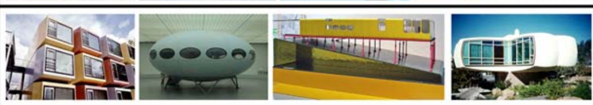
Architectural Engineering
Building Technology

vrijdag 9 november, 2012

A-docent: Jan Engels
E-docent: Tillmann Klein

Composite - Hotel Design

Composiet als Uitgangspunt

Material	
Semi Finnished product	
Sub-component	
Component	
Building Part	
Building	

Composite - Hotel Design

Part A: Uitgangspunt / Concept

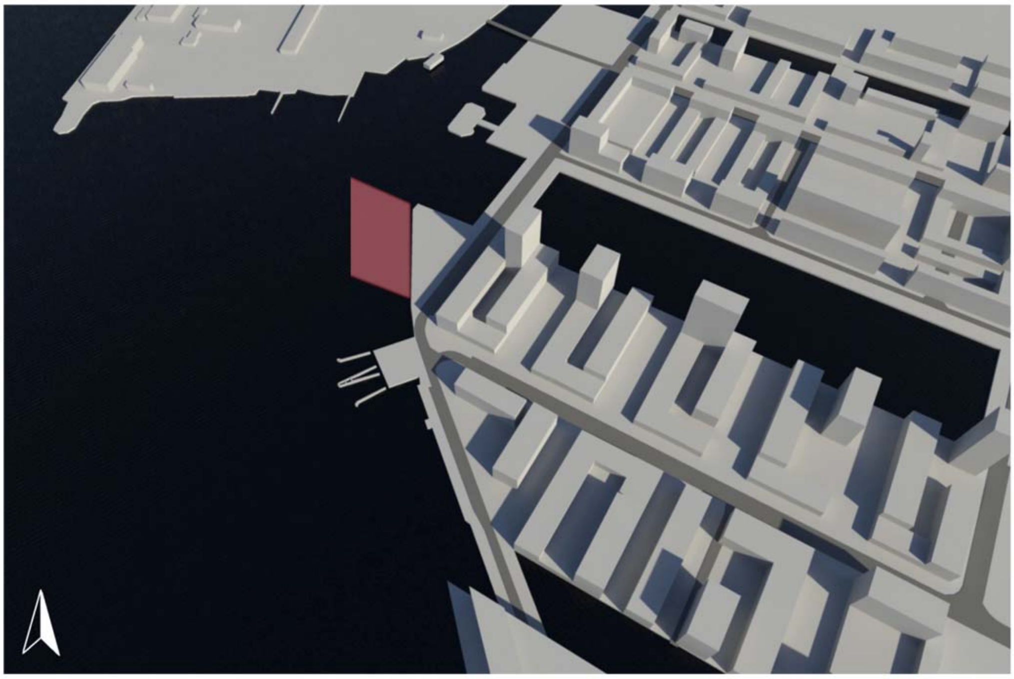
Part B: Ruimtelijke beleving hotel

Part C: Voorzieningen hotel / Kamers

Part D: Gevel

Amsterdam, Buiksloterham

Buiksloterham - Locatie Hotel

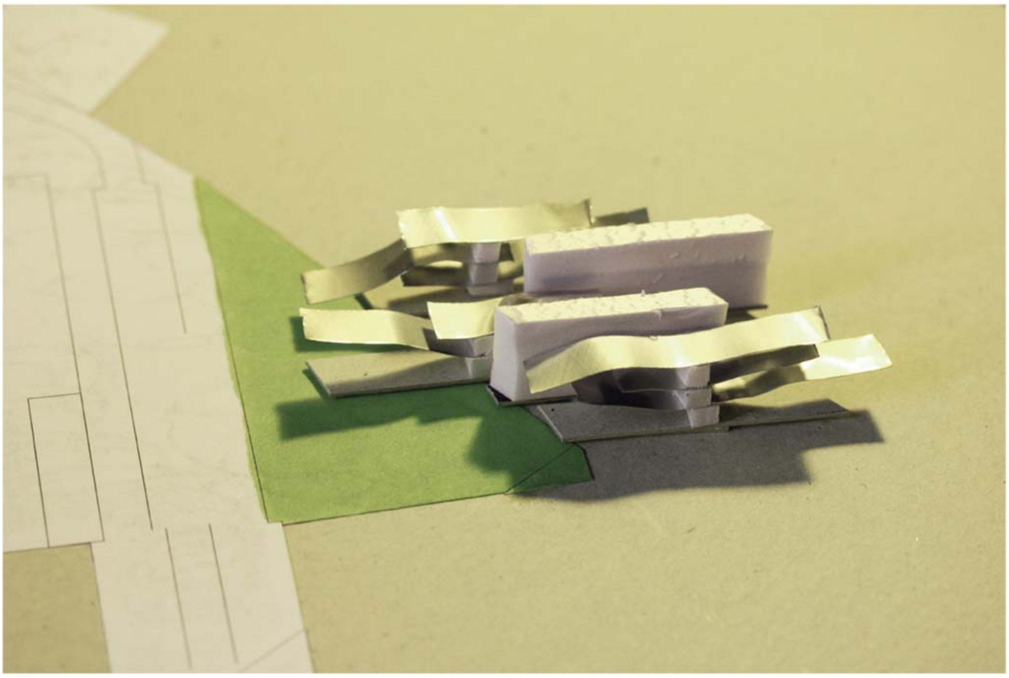


Uitgangspunt /Concept - Functies/Sandwich - Kamers/Modulair - Gevel/FRP

Impressie Locatie

Uitgangspunt /Concept - Functies/Sandwich - Kamers/Modulair - Gevel/FRP

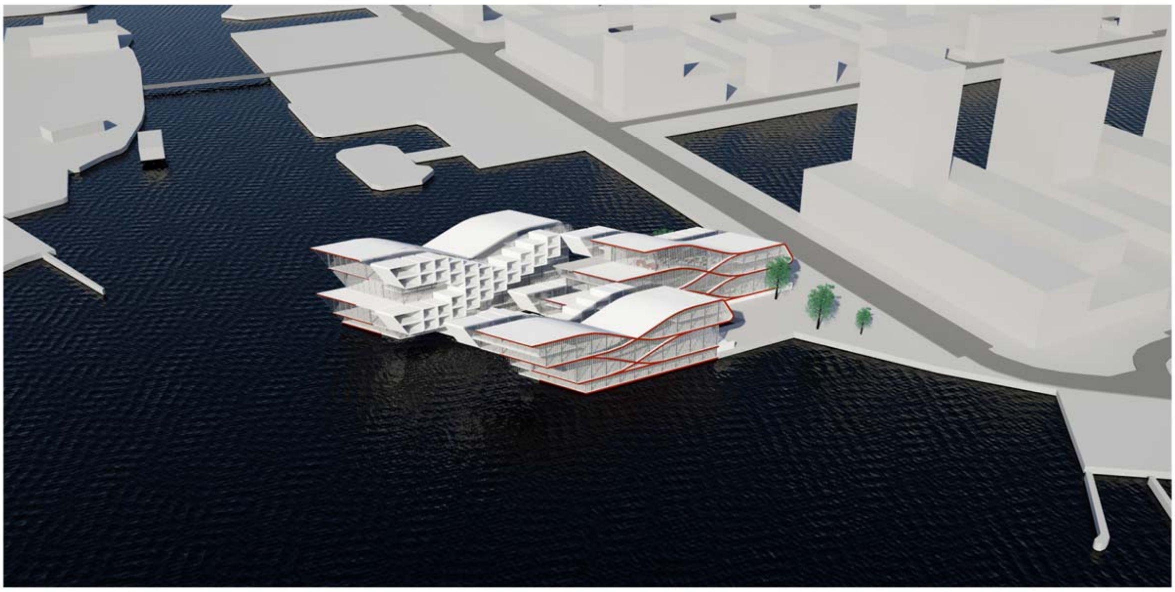
Concept



Composite - Hotel Design Part A 7

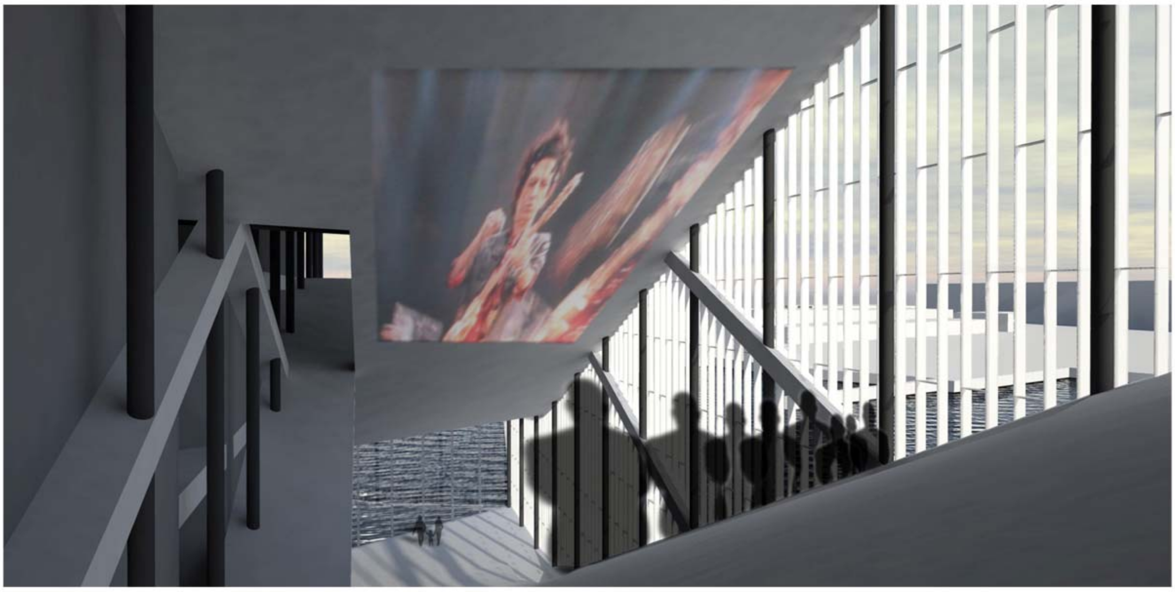
Uitgangspunt /Concept - Functies/Sandwich - Kamers/Modulair - Gevel/FRP

Ontwerp

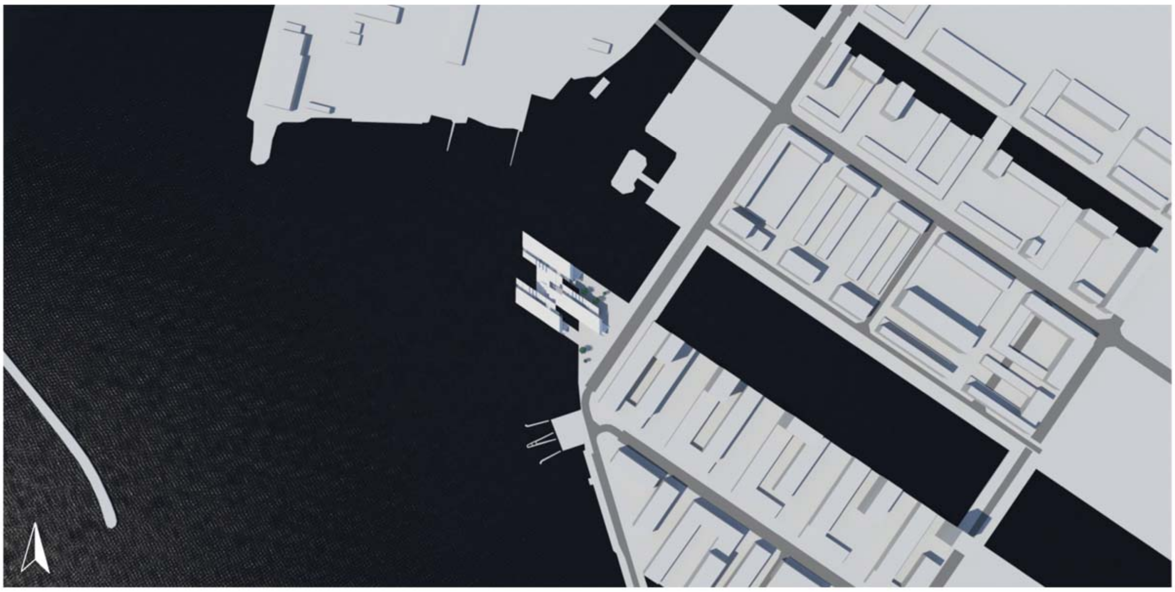


Composite - Hotel Design Part A 8

Ontwerp

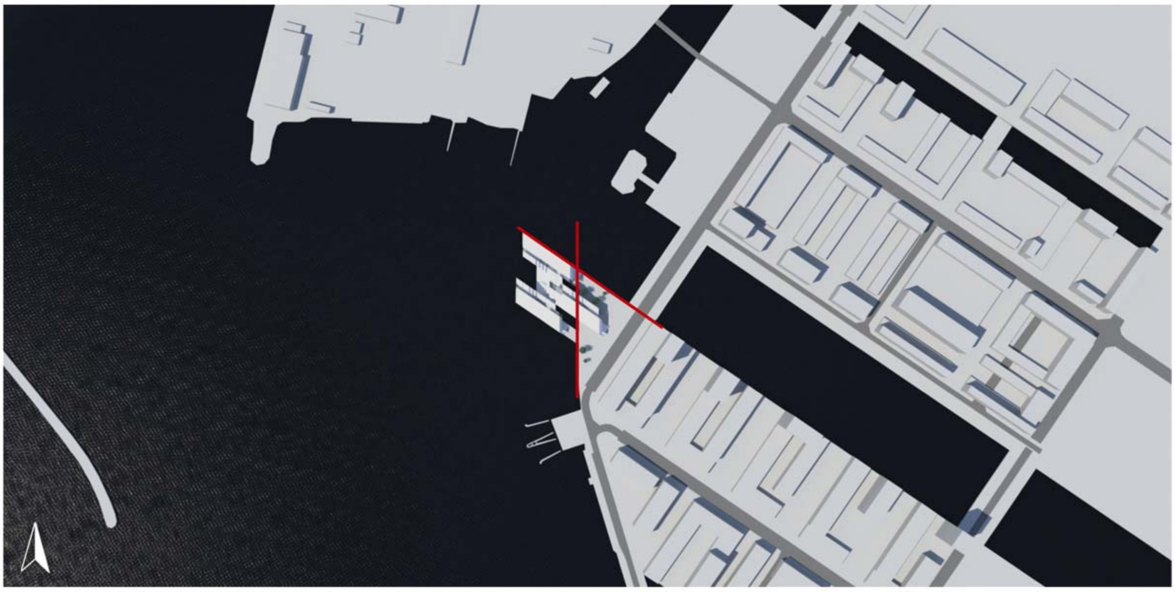


Compositie Hotel



Uitgangspunt /Concept - Functies/Sandwich - Kamers/Modulair - Gevel/FRP

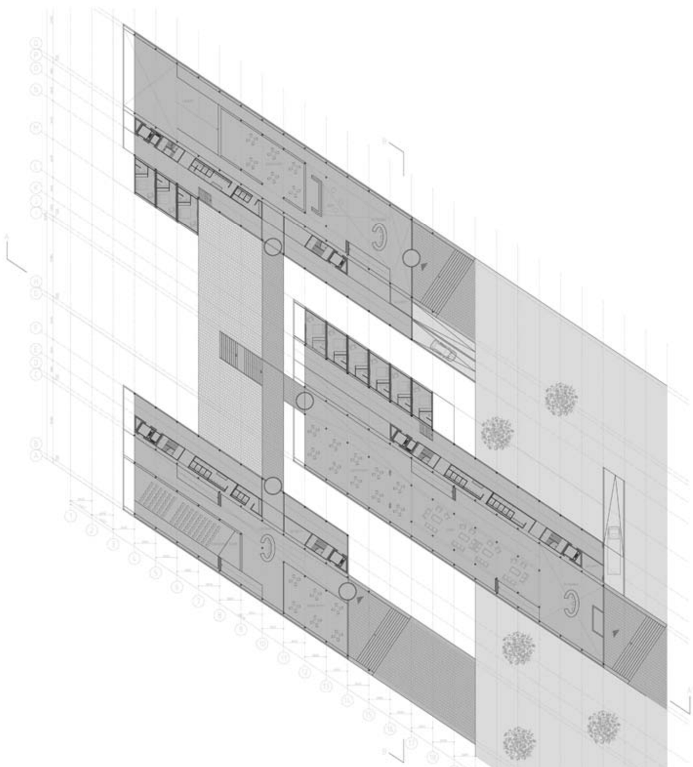
Compositie Hotel



Composite - Hotel Design Part A 11

Uitgangspunt /Concept - Functies/Sandwich - Kamers/Modulair - Gevel/FRP

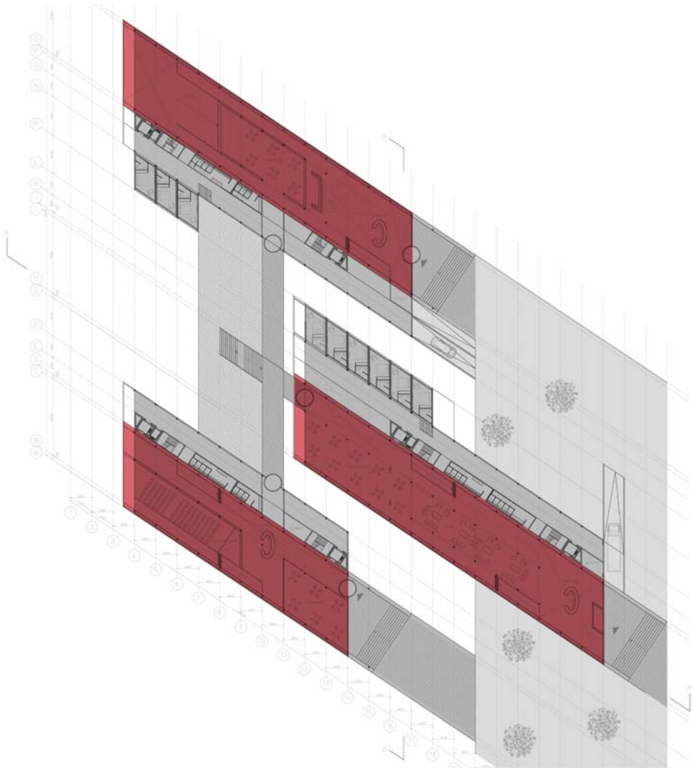
Compositie Hotel



Composite - Hotel Design Part B 12

Uitgangspunt /Concept - Functies/Sandwich - Kamers/Modulair - Gevel/FRP

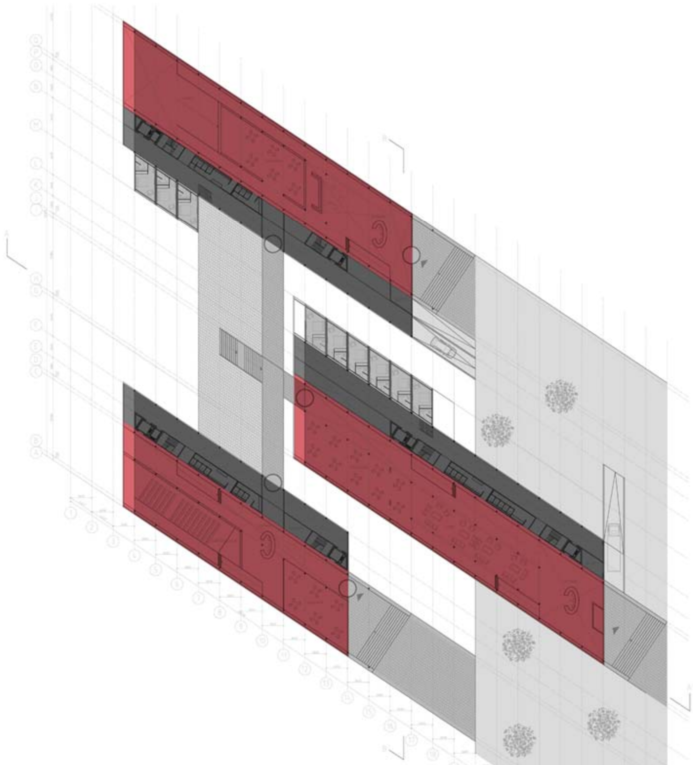
Compositie Hotel



Composite - Hotel Design Part B 13

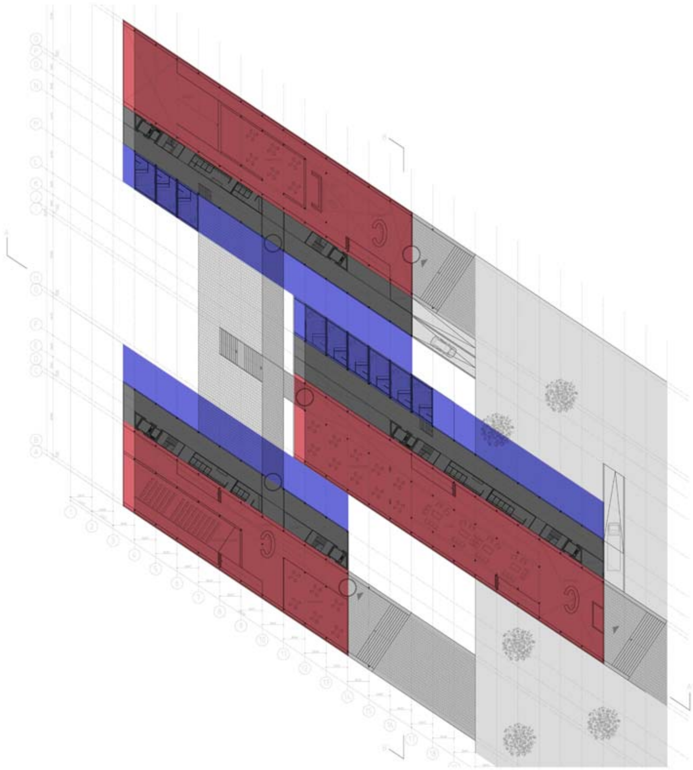
Uitgangspunt /Concept - Functies/Sandwich - Kamers/Modulair - Gevel/FRP

Compositie Hotel



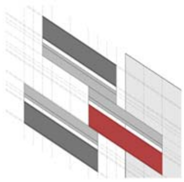
Composite - Hotel Design Part B 14

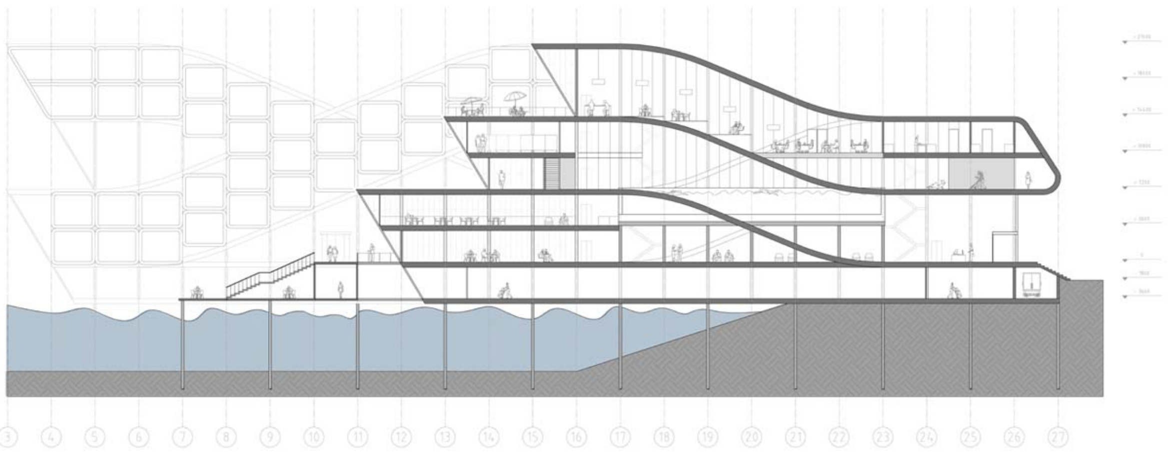
Compositie Hotel



Uitgangspunt /Concept - Functies/Sandwich - Kamers/Modulair - Gevel/FRP

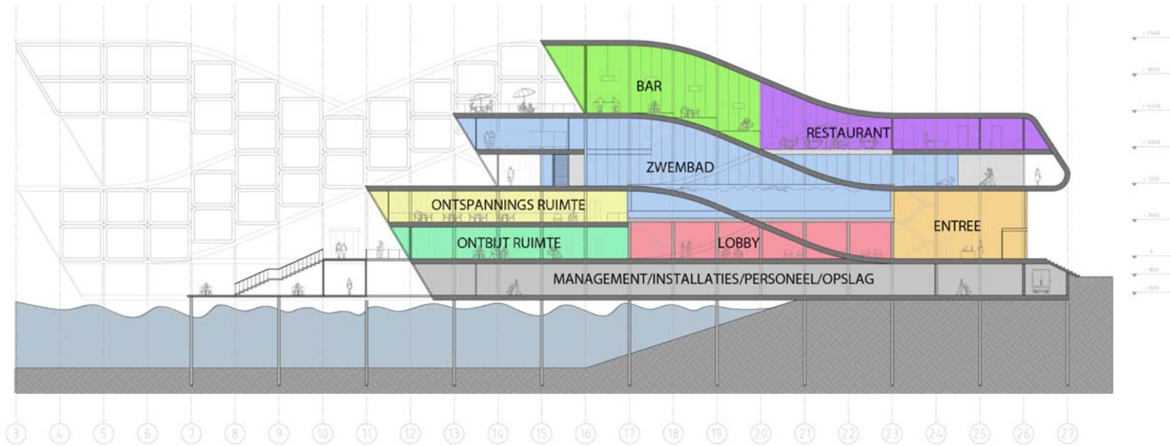
Functieverdeling





Uitgangspunt /Concept - Functies/Sandwich - Kamers/Modulair - Gevel/FRP

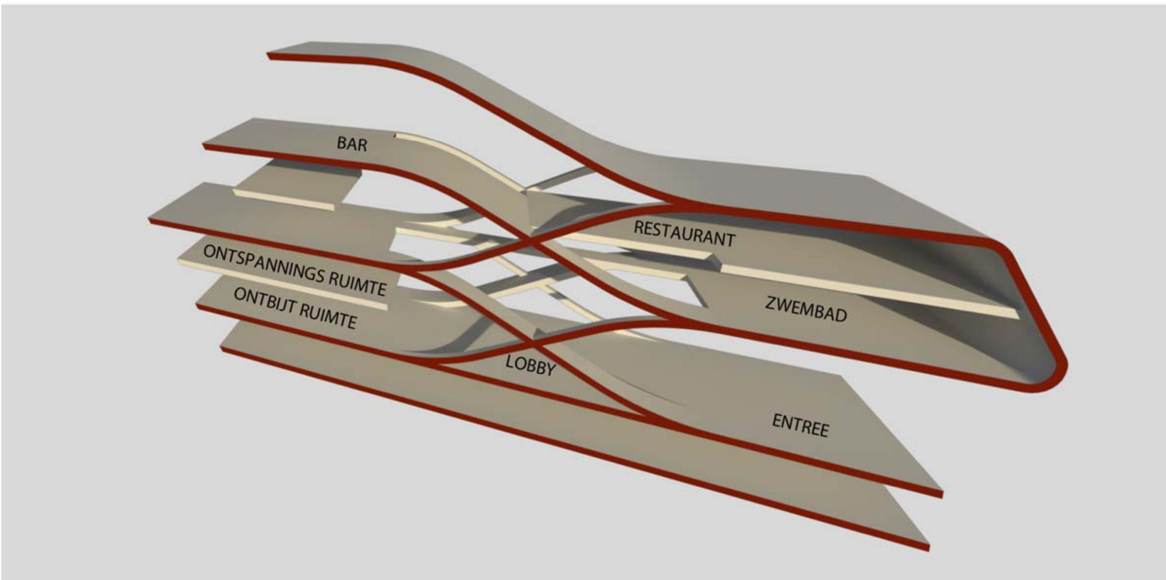
Functieverdeling



Composite - Hotel Design Part B 17

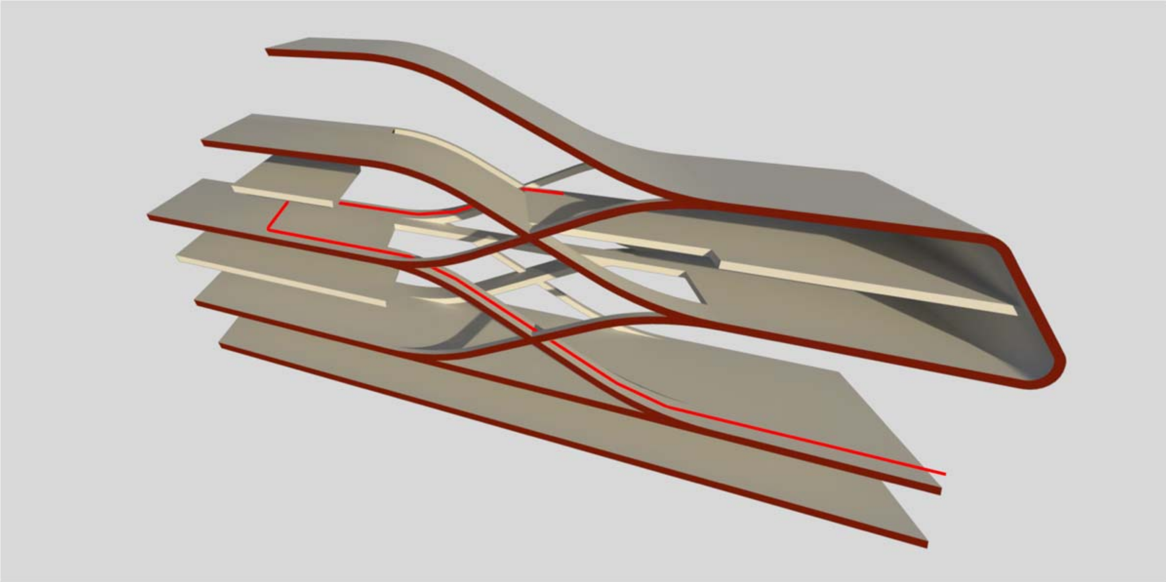
Uitgangspunt /Concept - Functies/Sandwich - Kamers/Modulair - Gevel/FRP

Functieverdeling



Composite - Hotel Design Part B 18

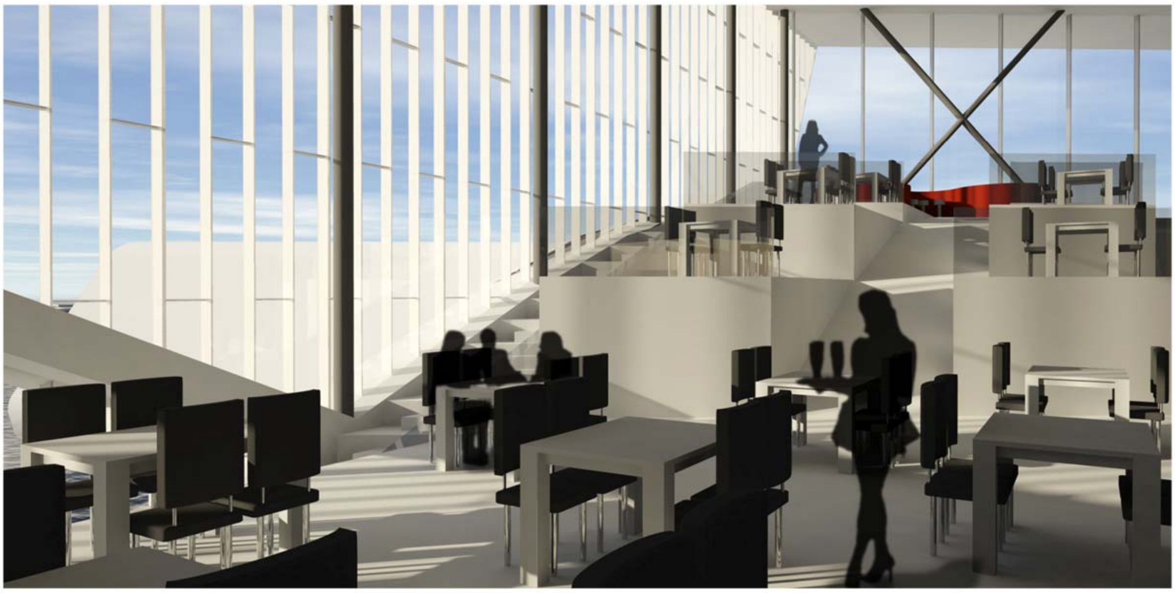
Route Bezoeker



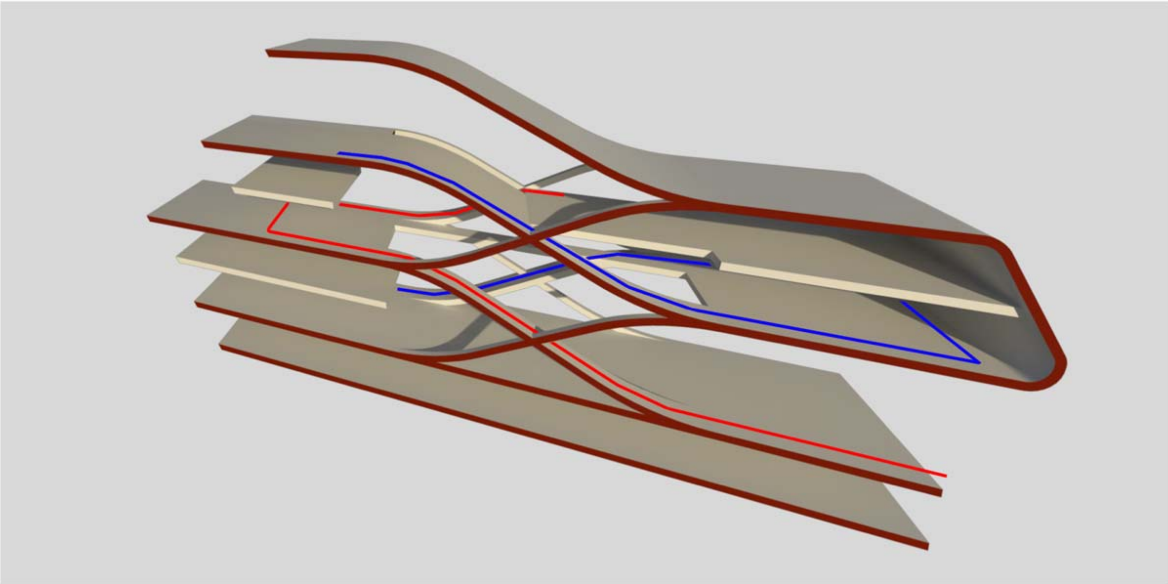
Hal

Zwembad

Restaurant

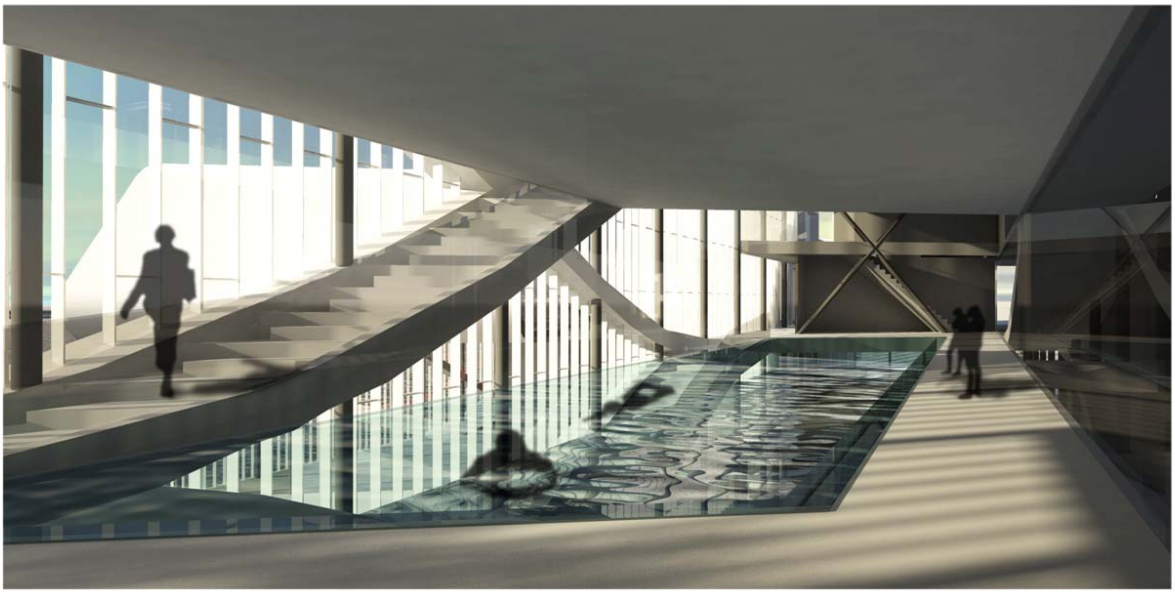


Route Gast



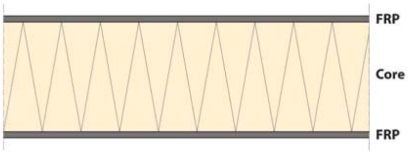
Ontbijtruimte

Zwembad



Bar

Onderzoek Sandwichconstructies



Verschillende combinaties FRP

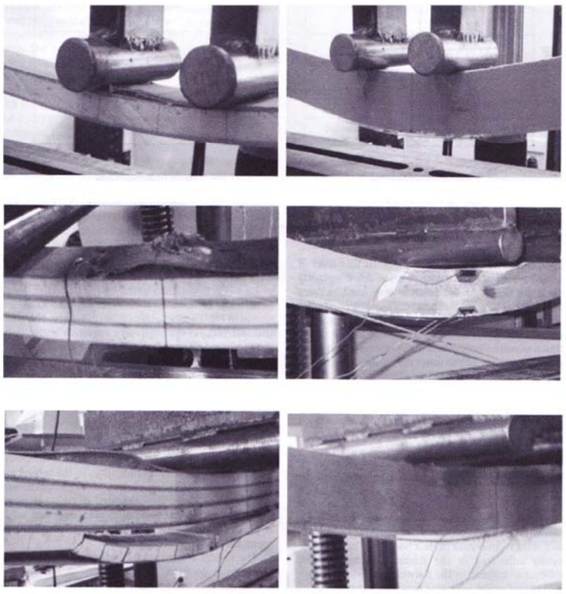
- Polyester - Glasvezel
- Epoxy - Koolstofvezel
- Epoxy - Aramidevezel

Verschillende Core Materials

- Foam
- Honeycomb
- Holle elementen

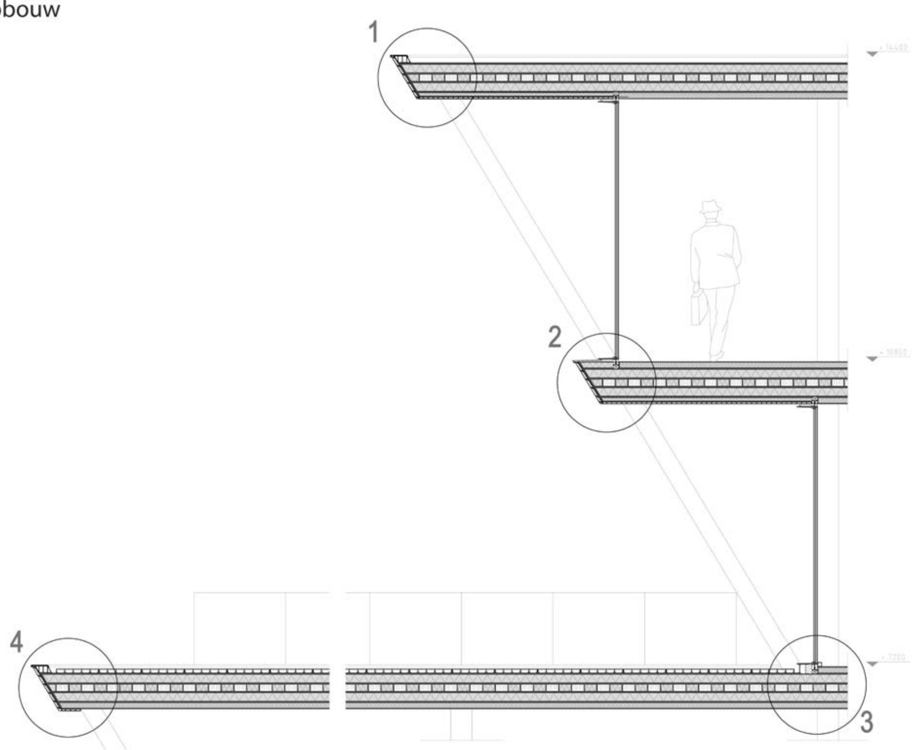
Uitgangspunt /Concept - Functies/Sandwich - Kamers/Modulair - Gevel/FRP

Onderzoek Sandwichconstructies

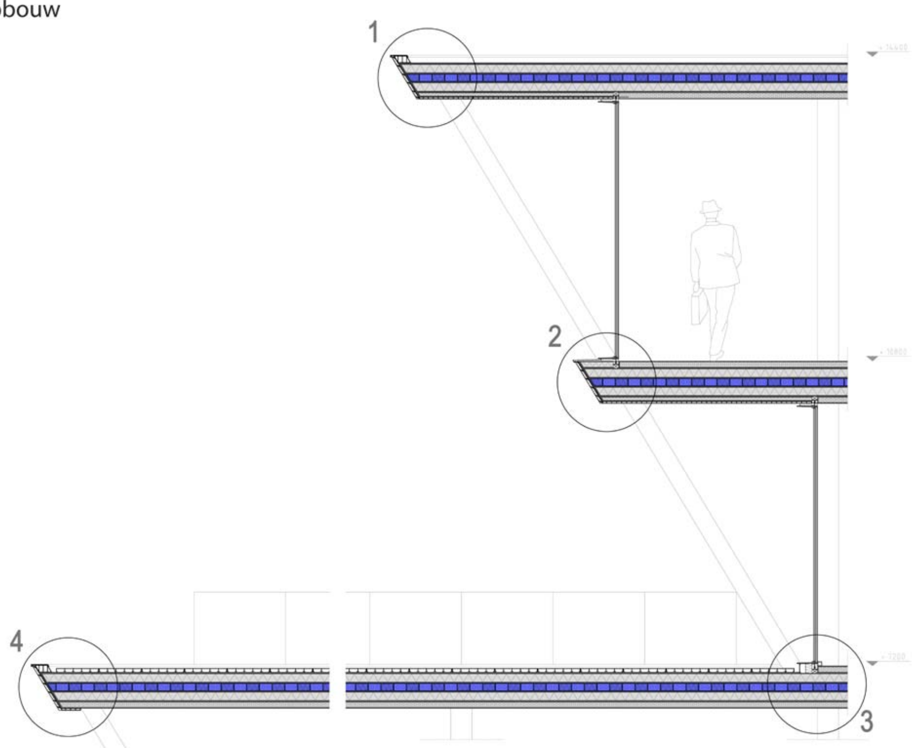


	Thickness, mm	Layer, mm	Composite, mm	Deflection, mm	Load, kN/m2	Weight, kg/m2
Epoxy Carbon 3	309	103	13	36,49	10,61	264,18
Epoxy Carbon 3	300	100	14	36,44	10,62	264,84
Epoxy Carbon 3	321	107	12	36,15	10,62	265,32
Epoxy Carbon 3	312	104	13	35,83	10,63	265,98
Epoxy Carbon 3	333	111	11	36,13	10,64	266,46
Epoxy Carbon 3	303	101	14	35,75	10,64	266,64
Epoxy Carbon 3	324	108	12	35,52	10,64	267,12
Epoxy Carbon 3	294	98	15	35,91	10,65	267,30
Epoxy Carbon 3	345	115	10	36,46	10,65	267,60
Epoxy Carbon 3	336	112	11	35,52	10,66	268,26
Epoxy Carbon 3	348	116	10	35,87	10,67	269,40
Epoxy Carbon 3	363	121	9	36,03	10,71	272,34
Epoxy Carbon 5	320	64	8	36,20	10,71	272,80
Epoxy Carbon 5	305	61	9	36,00	10,72	273,90
Epoxy Carbon 5	340	68	7	36,04	10,73	274,70
Epoxy Carbon 5	290	58	10	36,35	10,74	275,00
Epoxy Carbon 3	381	127	8	36,12	10,76	277,08
Epoxy Carbon 3	384	128	8	35,59	10,78	278,88
Epoxy Carbon 5	280	56	11	35,99	10,79	279,10
Epoxy Carbon 5	365	73	6	35,78	10,79	279,60
Epoxy Carbon 5	270	54	12	35,99	10,83	283,20
Epoxy Carbon 3	402	134	7	36,28	10,84	283,62
Epoxy Carbon 3	405	135	7	35,77	10,86	285,42
Epoxy Carbon 5	260	52	13	36,31	10,88	287,30
Epoxy Carbon 5	395	79	5	35,76	10,88	287,50
Epoxy Carbon 3	429	143	6	36,18	10,96	293,76
Epoxy Carbon 5	255	51	14	35,57	10,97	294,40
Epoxy Carbon 3	432	144	6	35,70	10,98	295,56
Epoxy Carbon 5	430	86	4	36,35	11,01	298,40
Epoxy Carbon 5	245	49	15	36,42	11,01	298,50
Epoxy Carbon 5	435	87	4	35,57	11,05	301,40
Epoxy Carbon 4	360	90	11	39,95	11,09	304,88
Epoxy Carbon 4	348	87	12	39,72	11,10	305,76
Epoxy Carbon 4	376	94	10	39,75	11,11	306,40
Epoxy Carbon 4	336	84	13	39,83	11,11	306,64
Epoxy Carbon 3	462	154	5	36,08	11,12	307,50
Epoxy Carbon 4	324	81	14	40,25	11,12	307,52
Epoxy Carbon 4	392	98	9	40,01	11,12	307,92
Epoxy Carbon 3	465	155	5	35,64	11,14	309,30
Epoxy Carbon 4	316	79	15	40,00	11,16	310,80
Epoxy Carbon 4	412	103	8	40,08	11,17	311,84
Epoxy Carbon 4	436	109	7	40,12	11,25	318,16
Epoxy Carbon 5	485	97	3	35,91	11,28	321,30
Epoxy Carbon 3	501	167	4	36,29	11,32	324,84

1/20 Vloeropbouw



1/20 Vloeropbouw



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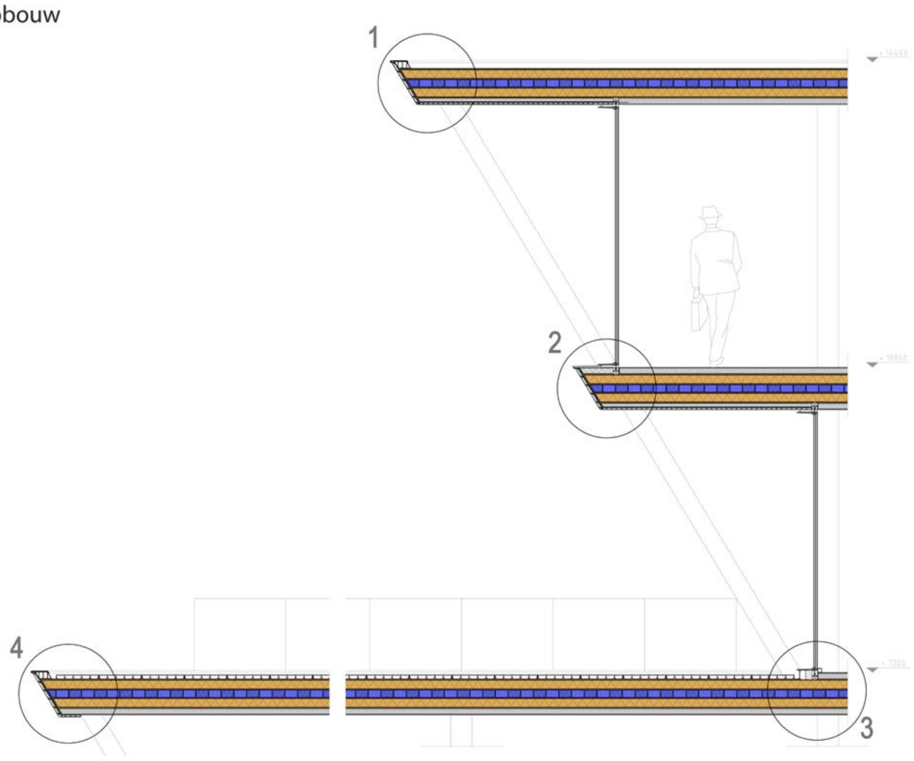
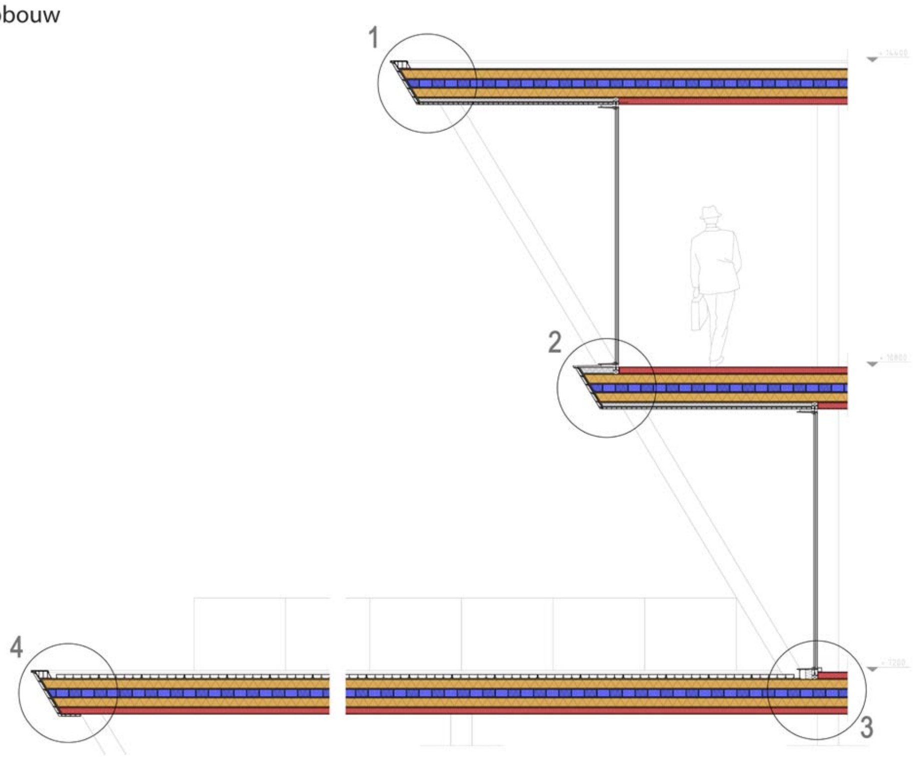
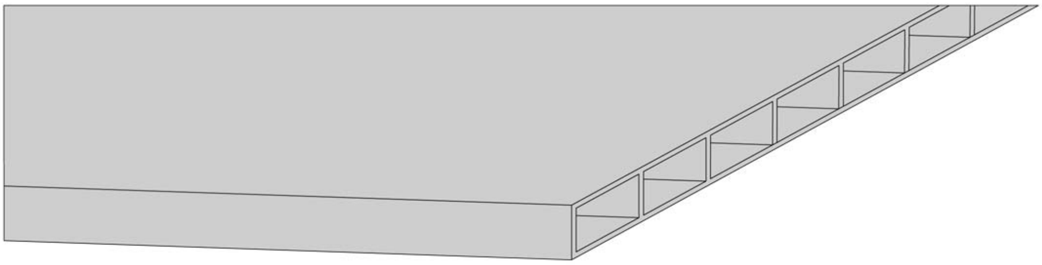


Uitgangspunt /Concept - Functies/Sandwich - Kamers/Modulair - Gevel/FRP

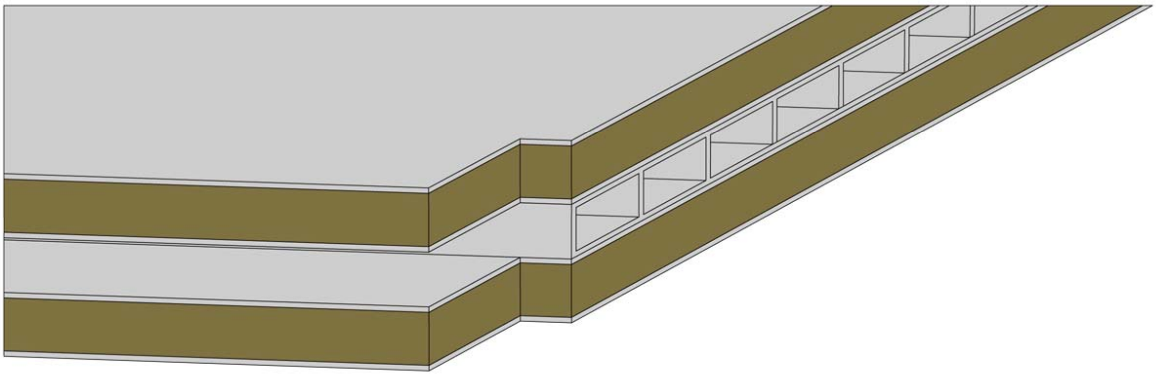
1/20 Vloeropbouw



Productie - Constructie opbouw



Productie - Constructie opbouw



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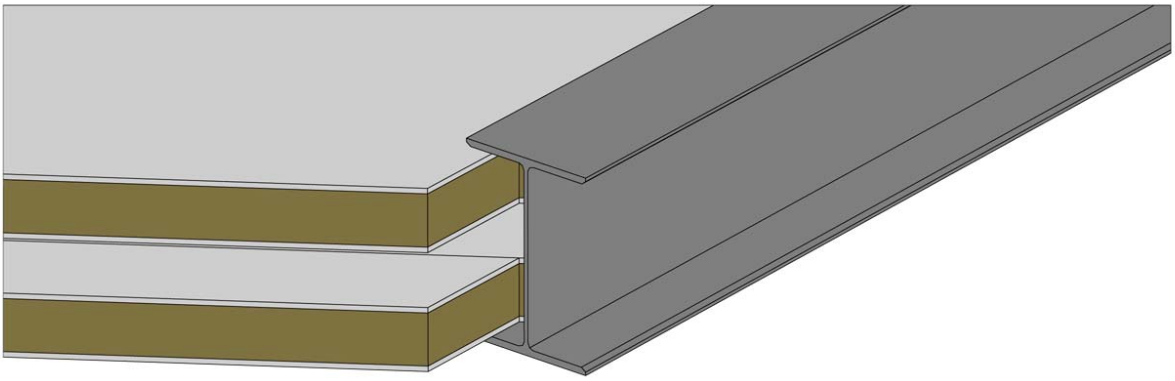

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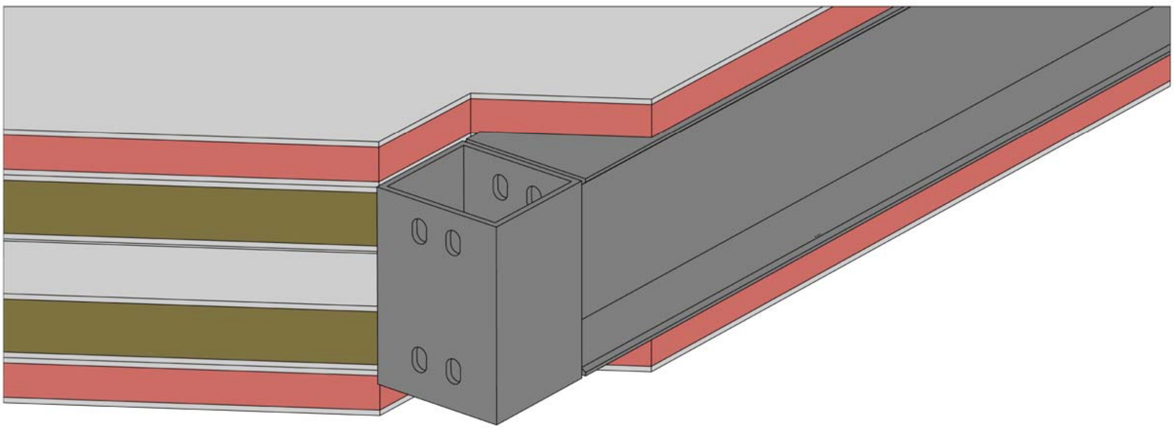

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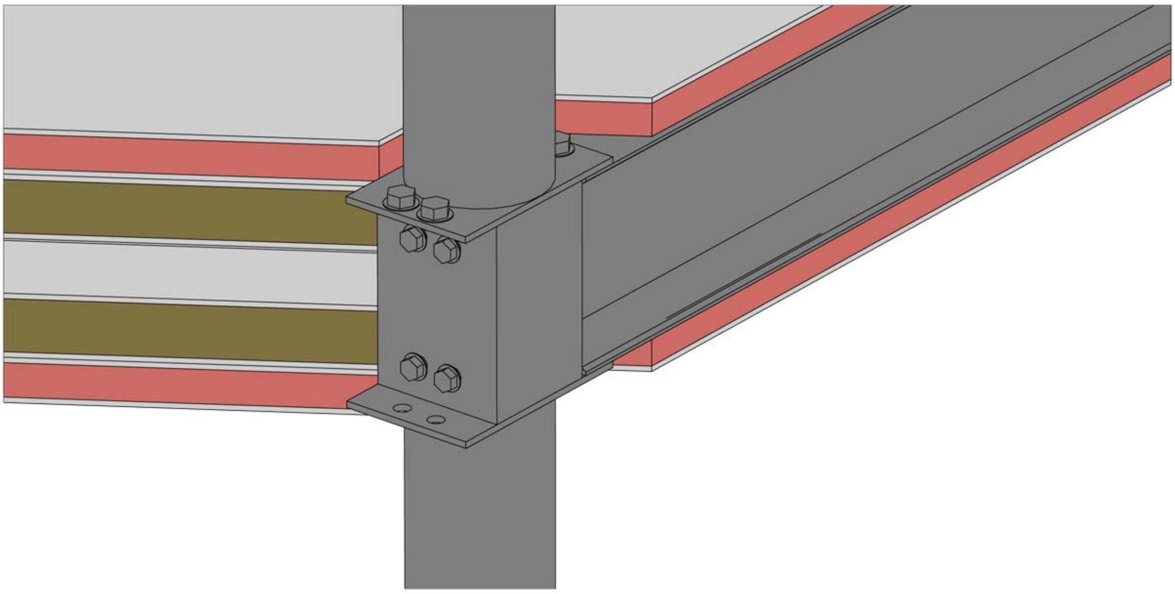
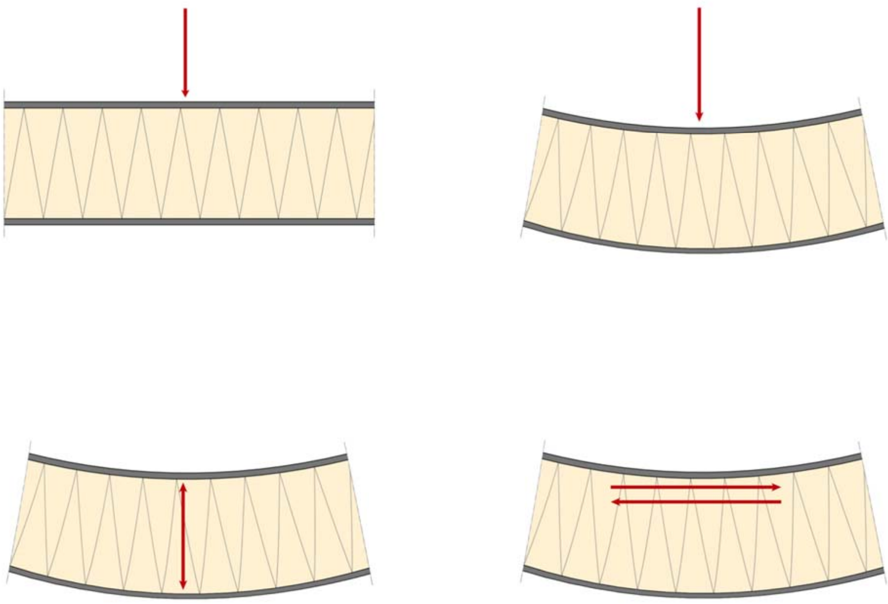
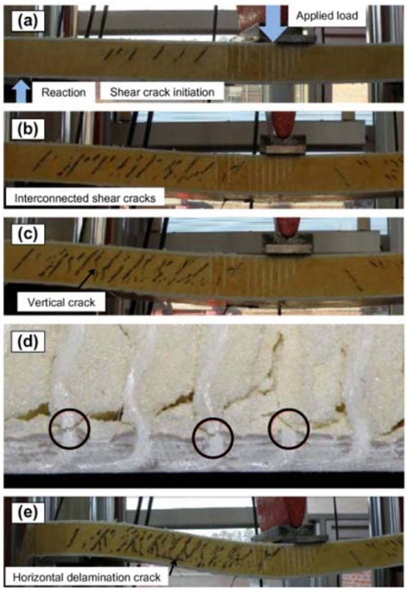


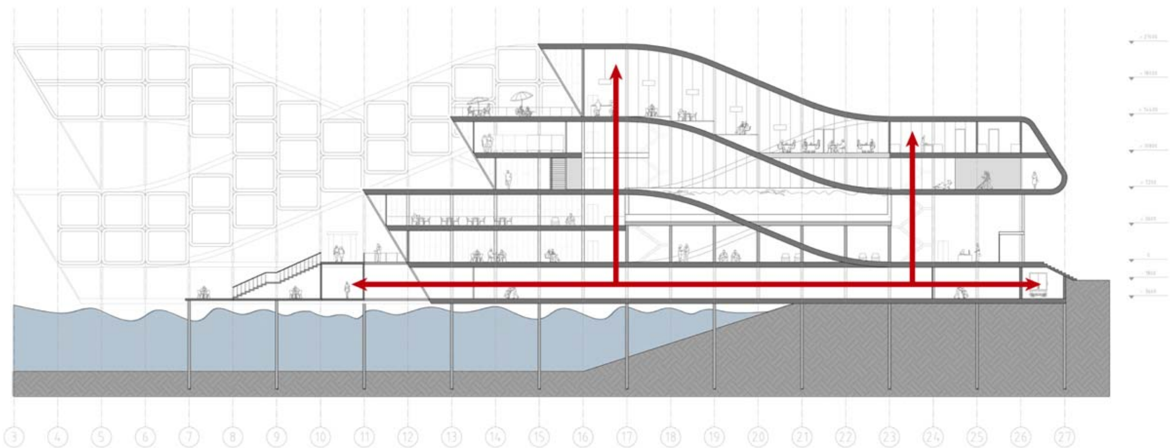
Werking Sandwichconstructie



Onderzoek Sandwichconstructies



Route Personeel



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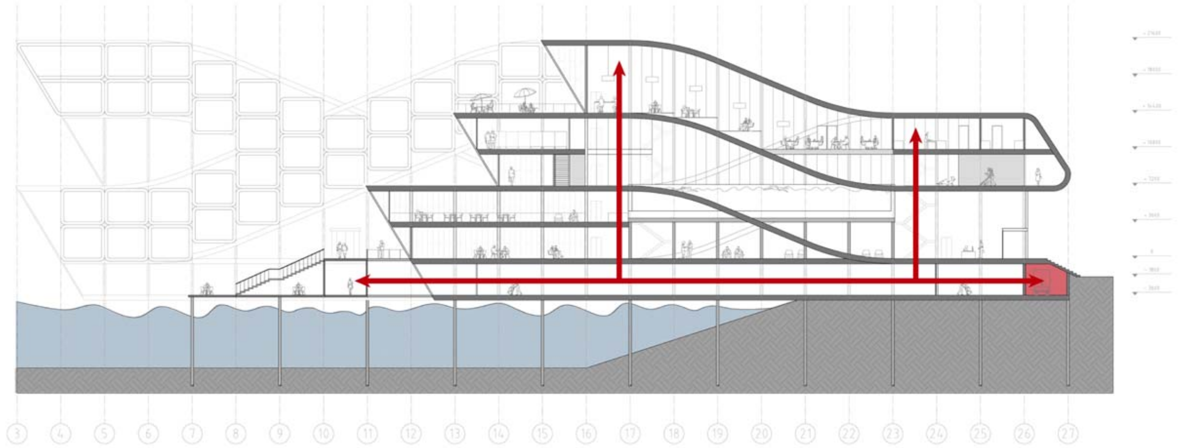

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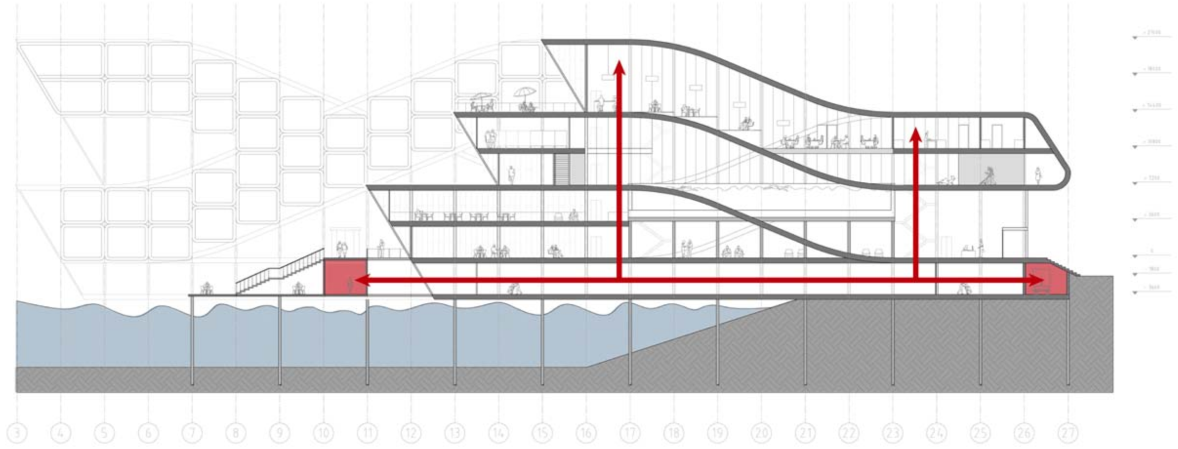


Deck

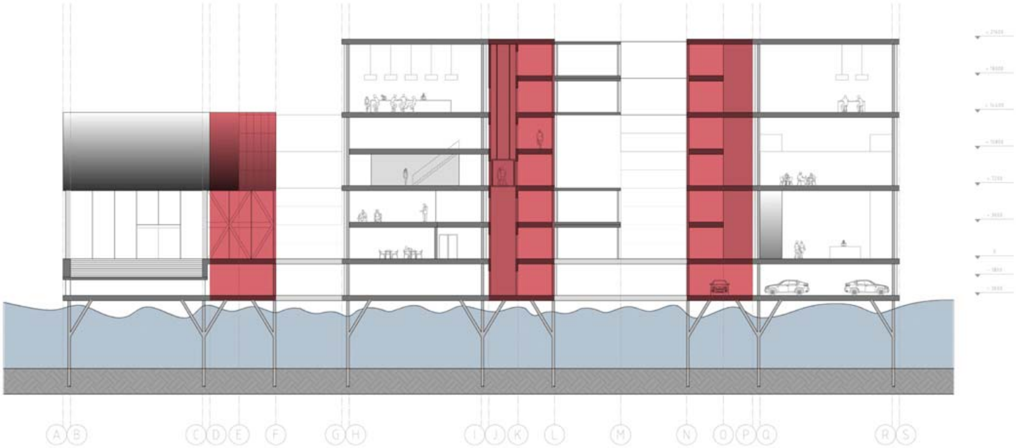
Route Personeel

Route Personeel

Uitgangspunt /Concept - Functies/Sandwich - Kamers/Modulair - Gevel/FRP

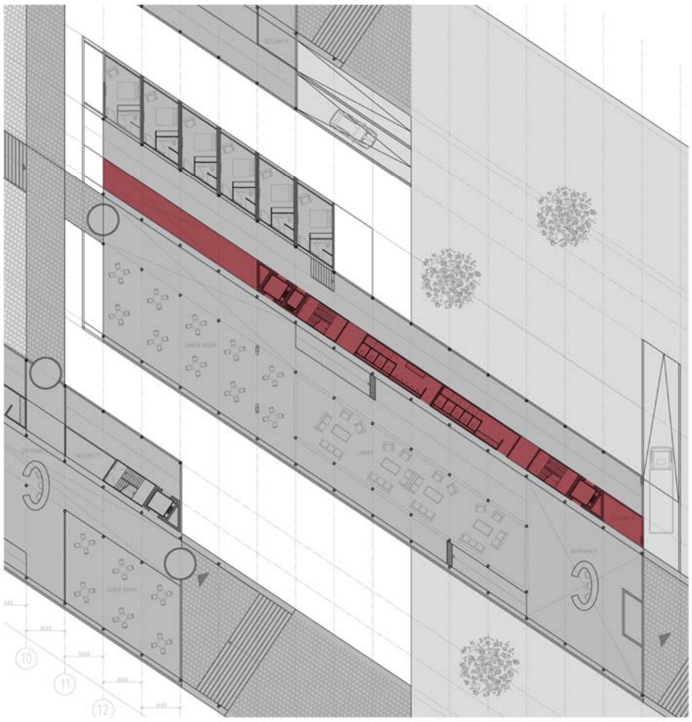
Route Personeel

Overgangszone



Uitgangspunt /Concept - Functies/Sandwich - Kamers/Modulair - Gevel/FRP

Overgangszone



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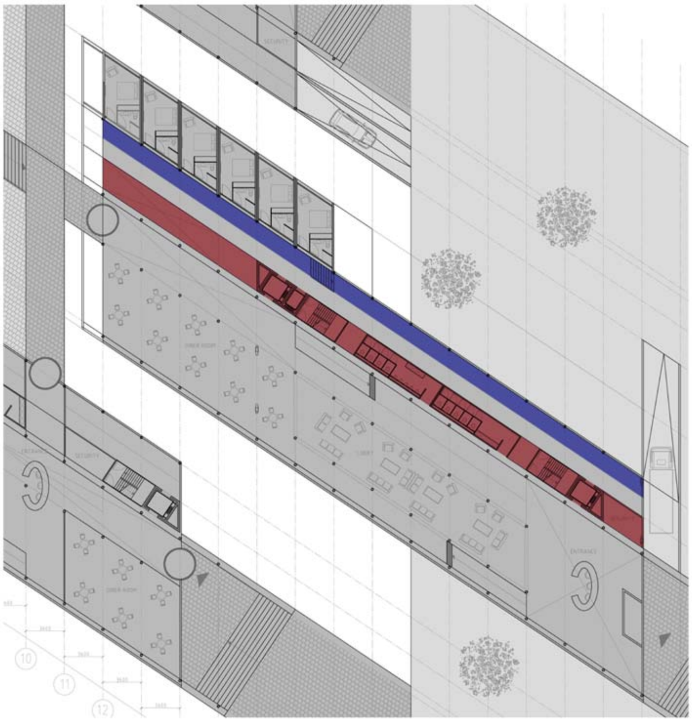

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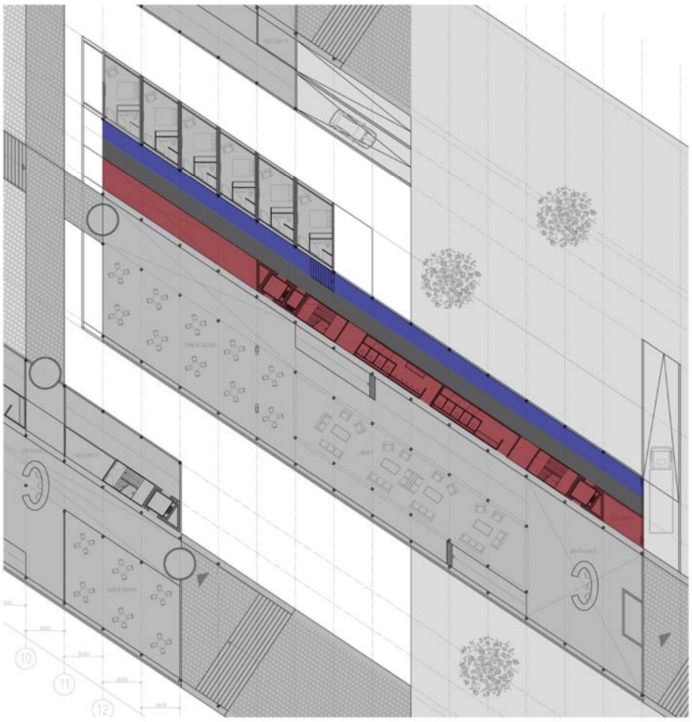

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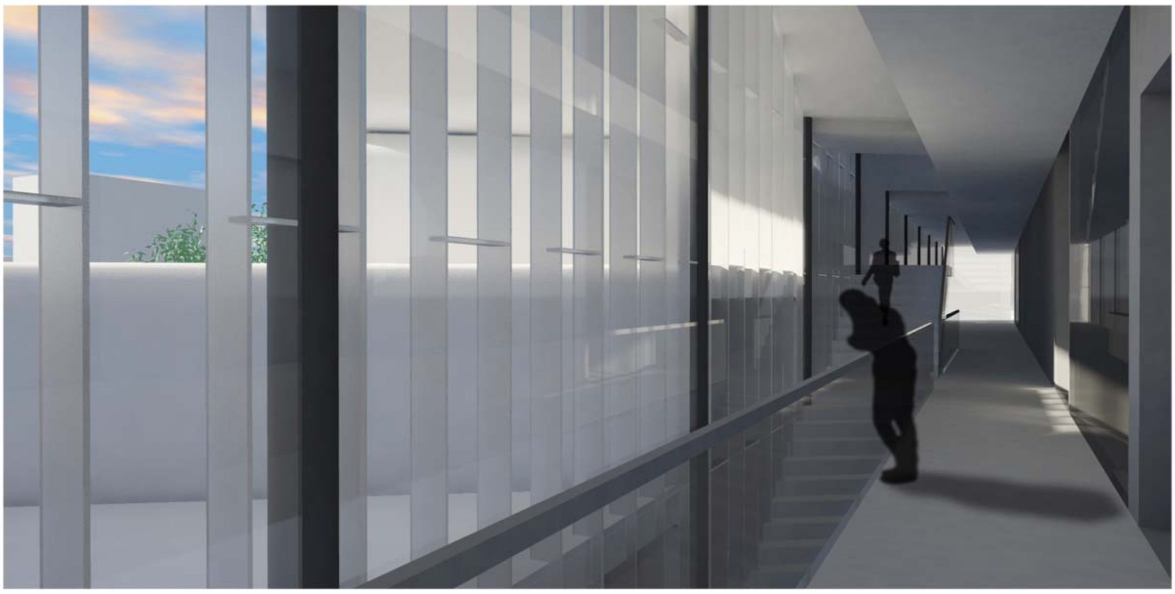


Kamers

Uitgangspunt /Concept - Functies/Sandwich - Kamers/Modulair - Gevel/FRP

Kamers

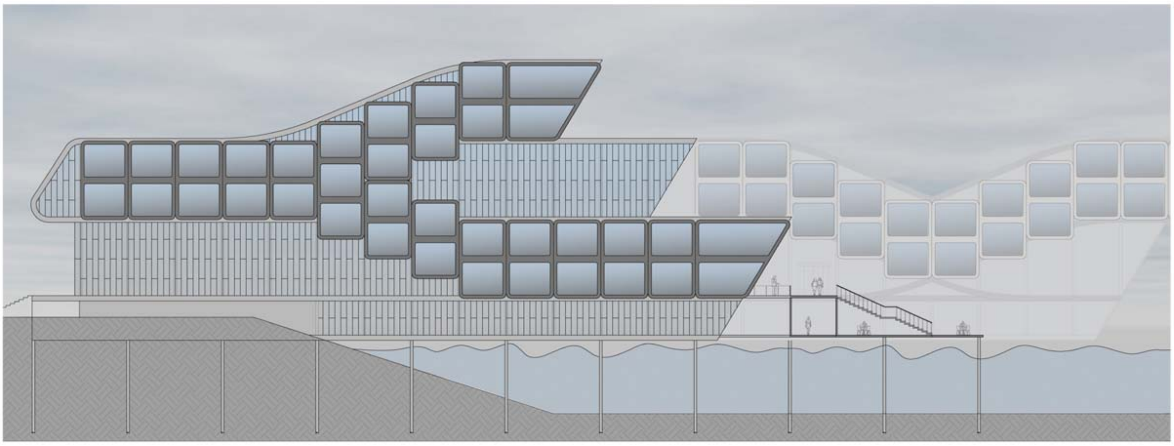
Composite - Hotel Design Part C 53

Uitgangspunt /Concept - Functies/Sandwich - Kamers/Modulair - Gevel/FRP

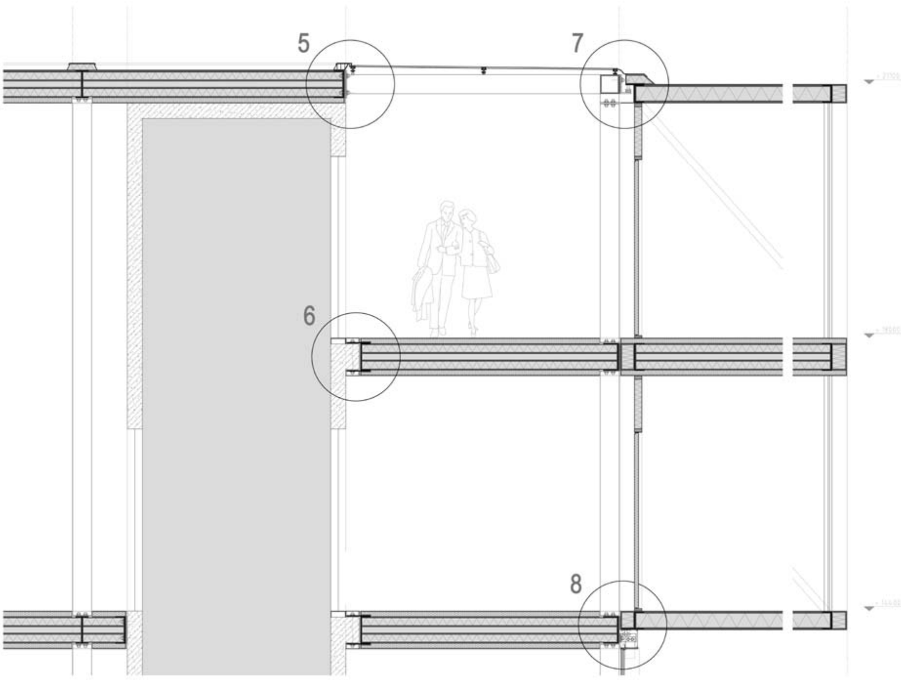
Kamers

Composite - Hotel Design Part C 54

Kamers



Constructie



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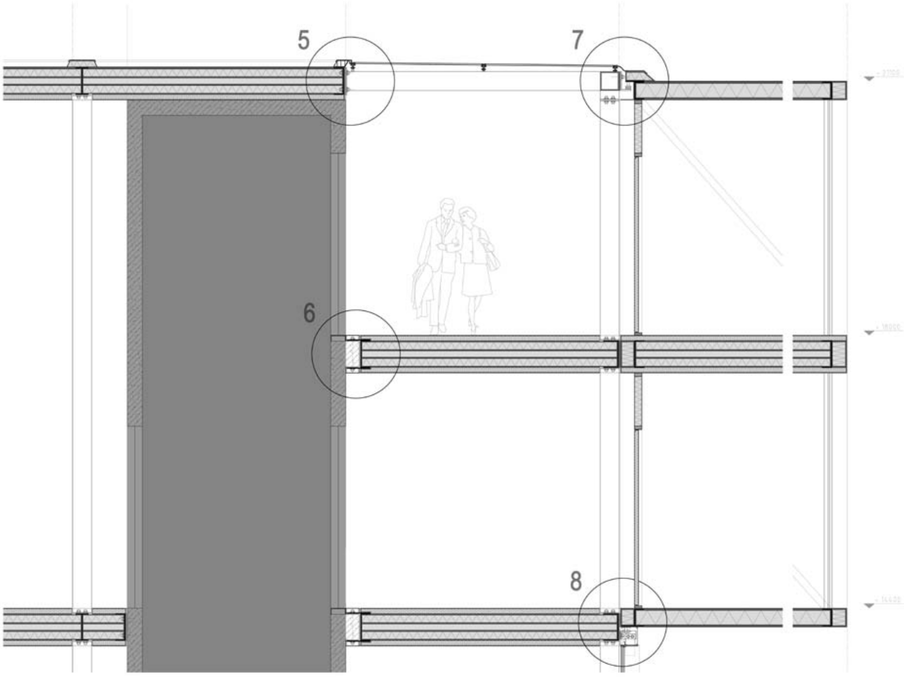

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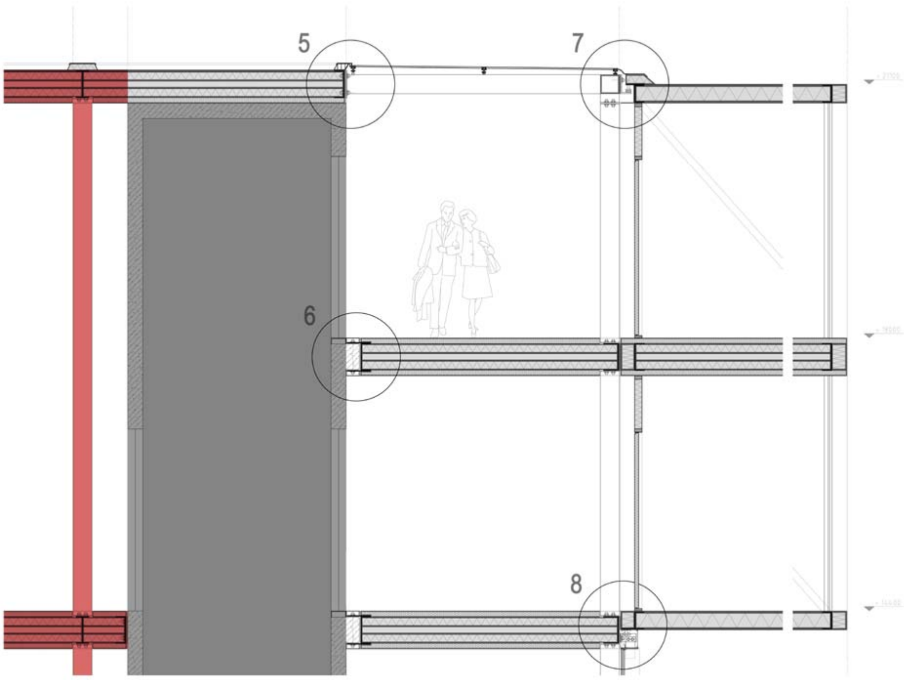
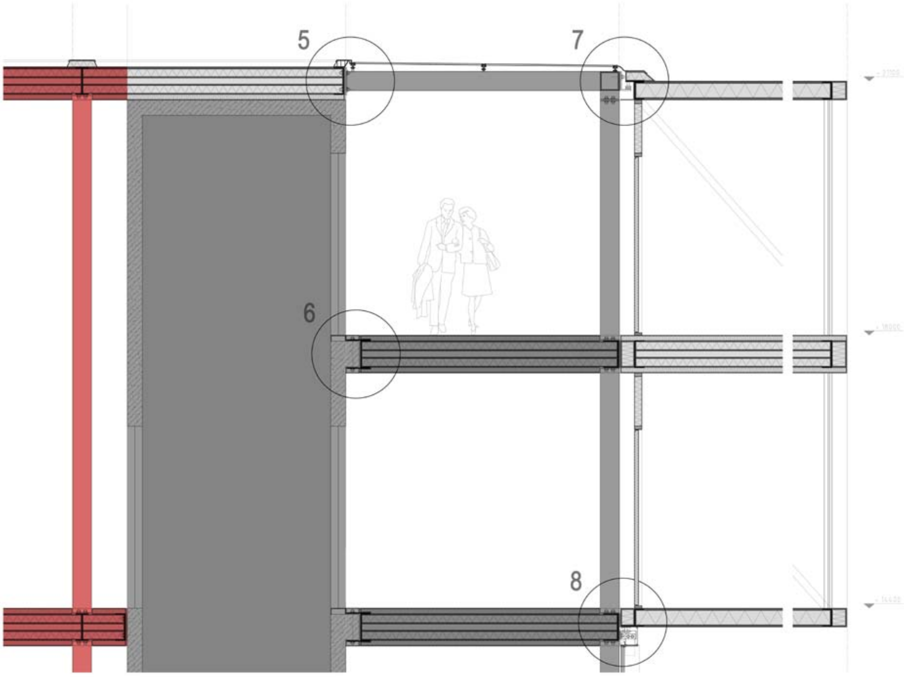


Uitgangspunt /Concept - Functies/Sandwich - Kamers/Modulair - Gevel/FRP

Constructie

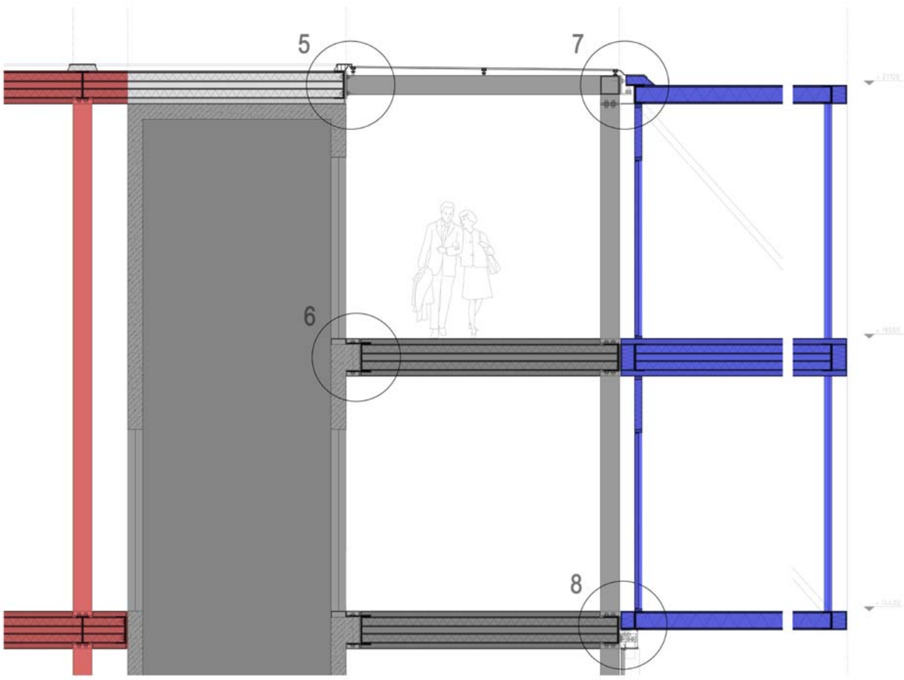


Composite - Hotel Design

Part C 59

Uitgangspunt /Concept - Functies/Sandwich - Kamers/Modulair - Gevel/FRP

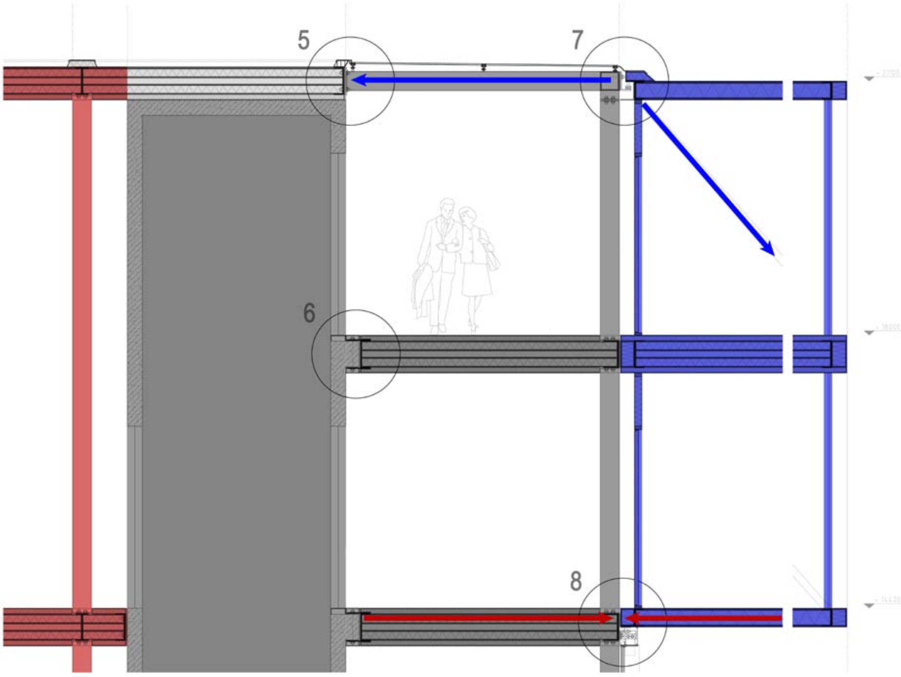
Constructie



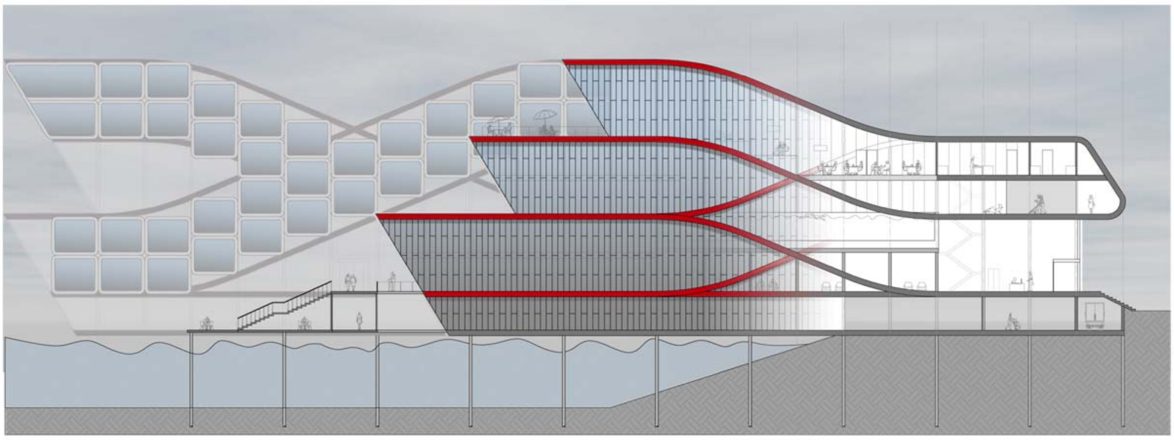
Composite - Hotel Design

Part C 60

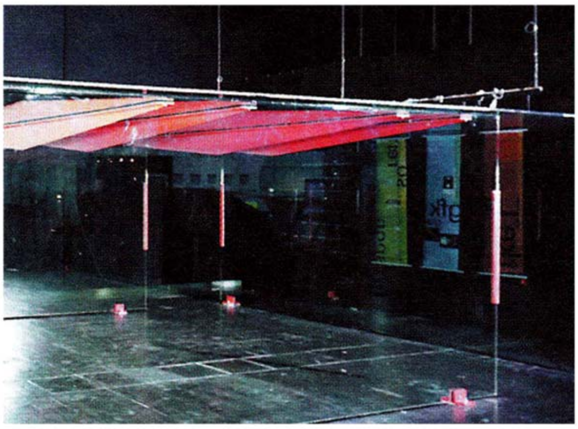
Constructie

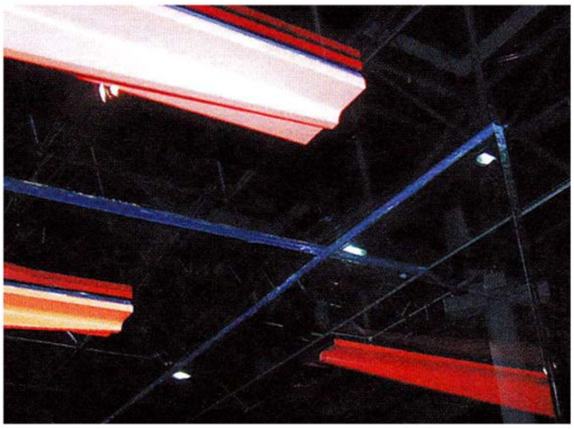


Concept Gevel

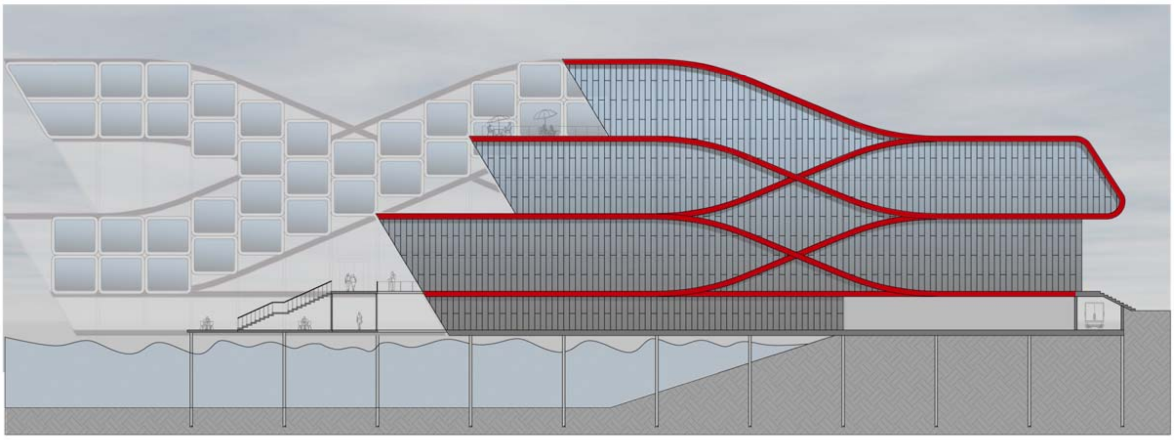


Uitgangspunt Constructie

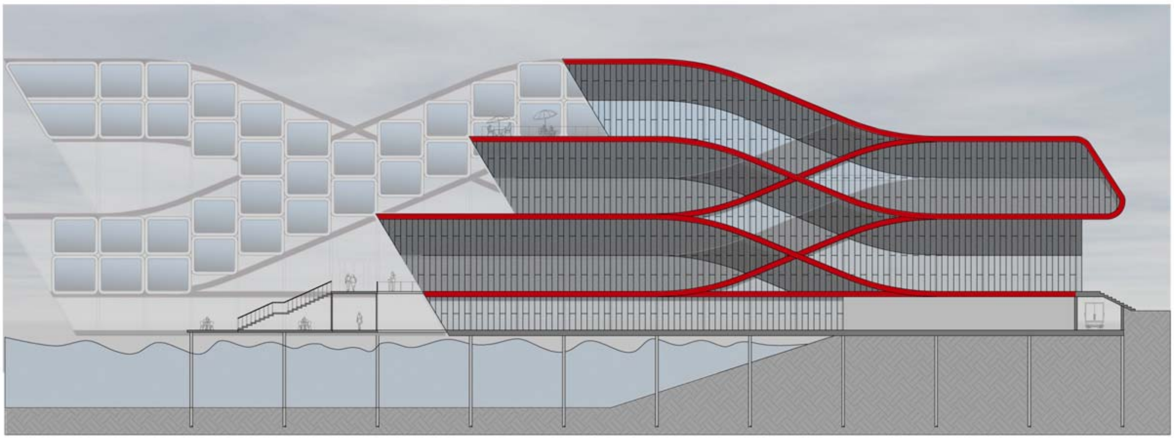




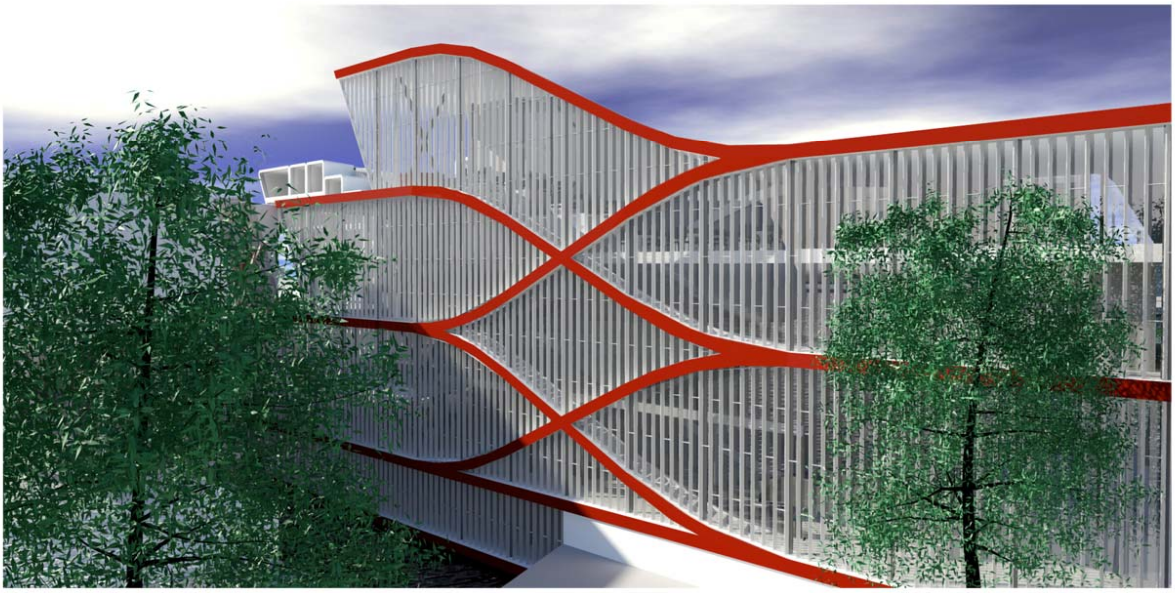
Gevel Ontwerp



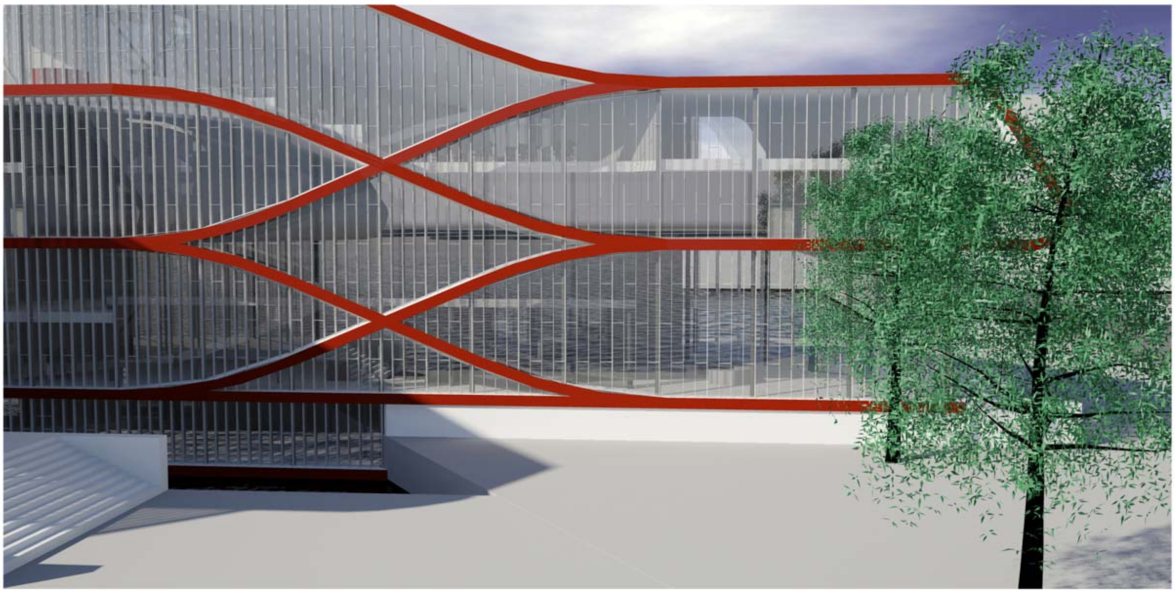
Zonwering



Gevel dicht

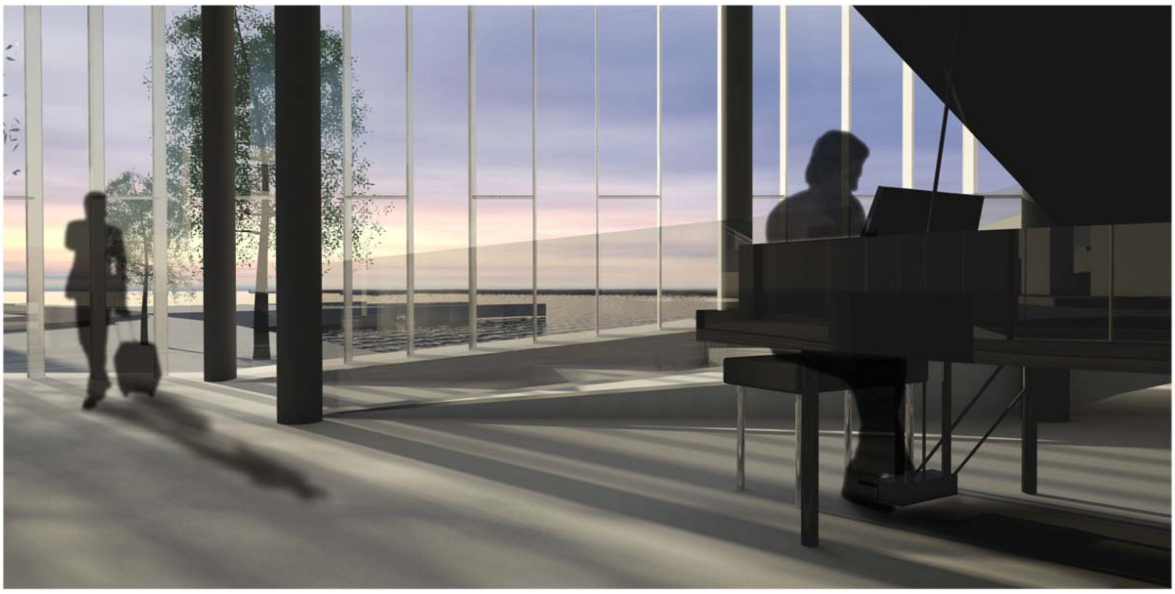


Gevel open

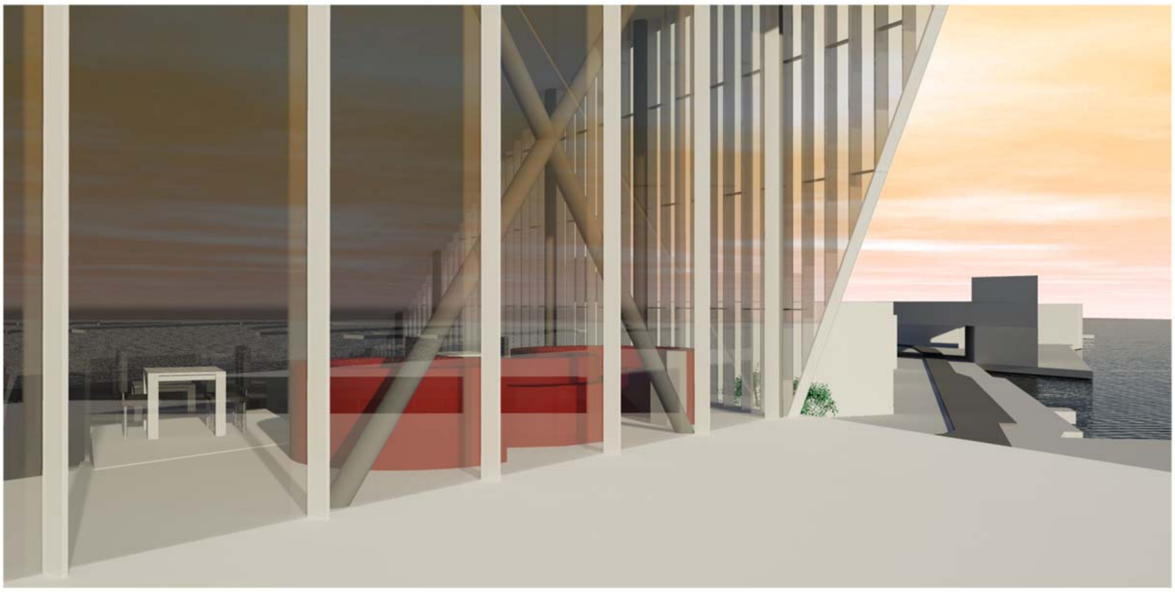


Gevel dicht

Gevel open

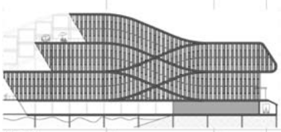


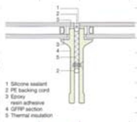
Kopgevel



Rekenmodel

FACADE BUILDING TECHNOLOGY DESIGN





Bending	w	=	36	200
Youngs Modulus	E_FRP pultruded	=	28000	N/mm2
	E_glass	=	68000	N/mm2
	n_composite	=	0,41	
Yield Strength	σ_GRP pultruded	=	193	N/mm2
	σ_glass	=	38	N/mm2
Width Element	b	=	2165	mm
Height Element	h	=	7200	mm
Thickness glass1	t_glass1	=	4	mm
Thickness glass2	t_glass2	=	4	mm
Thickness spacer	t_spacer	=	8	mm
Height FRP	h	=	250	mm
Thickness FRP	t_FRP	=	28	mm
Thickness FRP modi	t_FRP modified	=	11,53	mm
Area	A_glass1	=	8660	mm2
	A_glass2	=	8660	mm2
	A_FRP	=	7000	mm2
	A_FRP modified	=	2882,35	mm2

Centre	z_glass1	=	2	mm
	z_glass2	=	2	mm
	z_FRP	=	125	mm
	z_total	=	239,02	mm
	z_glass-stress	=	26,98	mm
	z_glass1 modified	=	12,98	mm
	z_glass2 modified	=	24,98	mm
	z_FRP	=	114,02	mm
Load Cases	q	=	4,13082	N/mm
Weight	FRP pultruded	=	2100	kg/m3
	Glass	=	2450	kg/m3

$$\sigma = \frac{M}{W} \qquad W = \frac{I}{Z} \qquad M = \frac{1}{8} \cdot q \cdot l^2$$

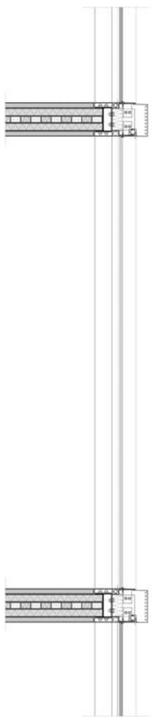
$$I = \frac{1}{12} \cdot b \cdot h^3 + A \cdot z^2 \qquad w = \frac{5}{384} \cdot \frac{q \cdot l^4}{EI}$$

Load		
Temporary load	0,56	kN/m2
Safety factor	1,5	
Permanent load	0,89	kN/m2
Safety factor	1,2	
Total load	1,908	kN/m2
	0,001908	N/mm2

Bending and Stresses

					FRP		Glass	
	I	w	kg/m	M	W	σ	W	σ
FRP pultruded + glass	5,94E+07	3,58E+01	57,13	2,68E+07	2,48E+05	107,77	2,20E+06	12,16
FRP pultruded	3,65E+07	1,42E+02	14,70	2,68E+07	2,92E+05	91,78		

Gevelopbouw 1/20



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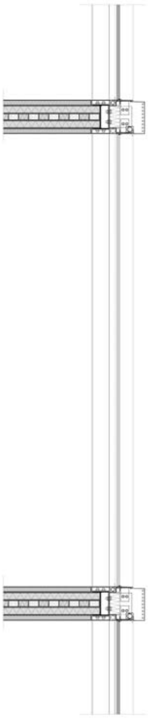
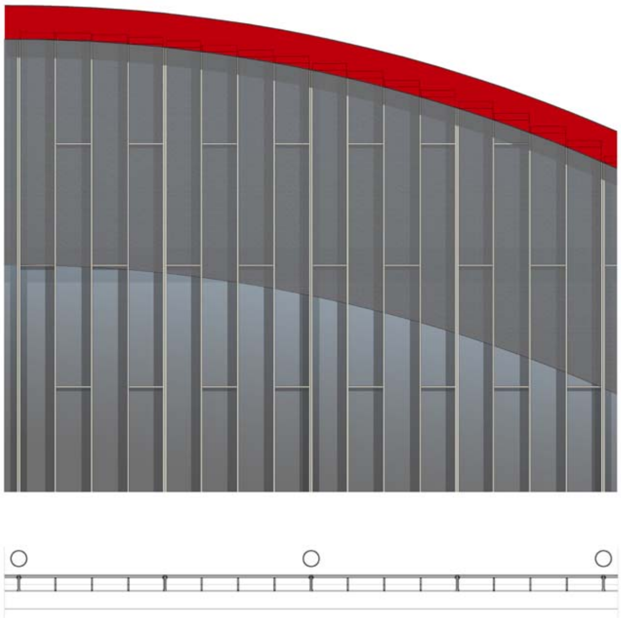
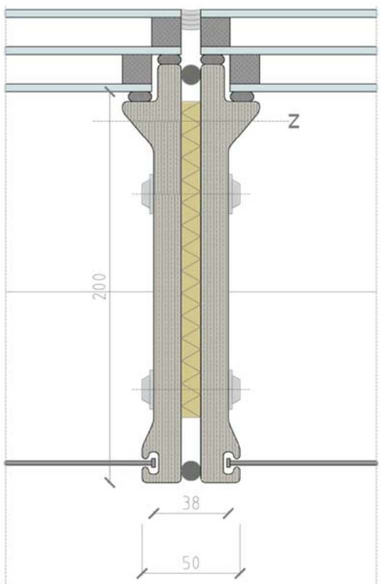
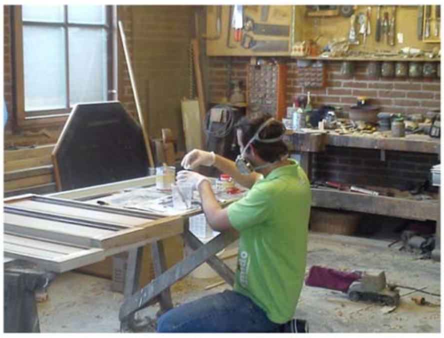




FRP-profiel

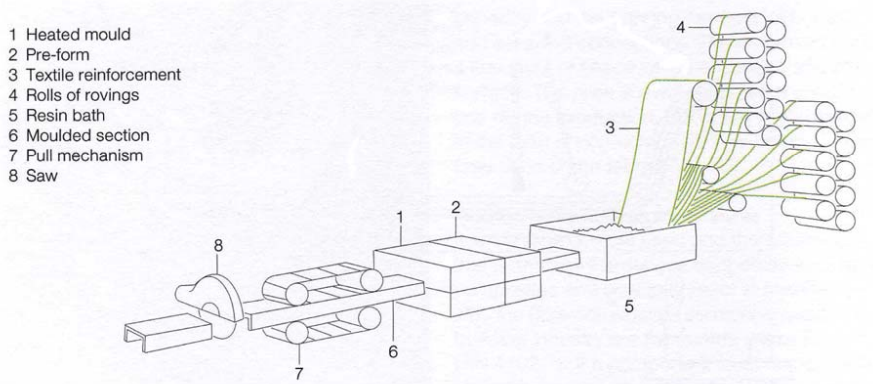


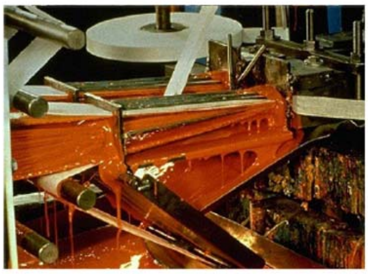
Productie



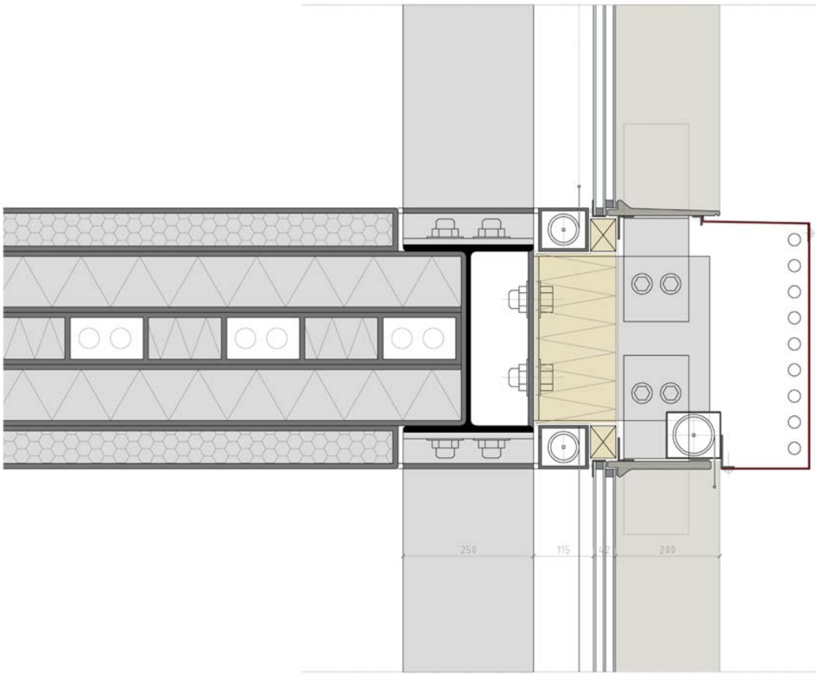
Uitgangspunt /Concept - Functies/Sandwich - Kamers/Modulair - Gevel/FRP

Productie - Pultrusie

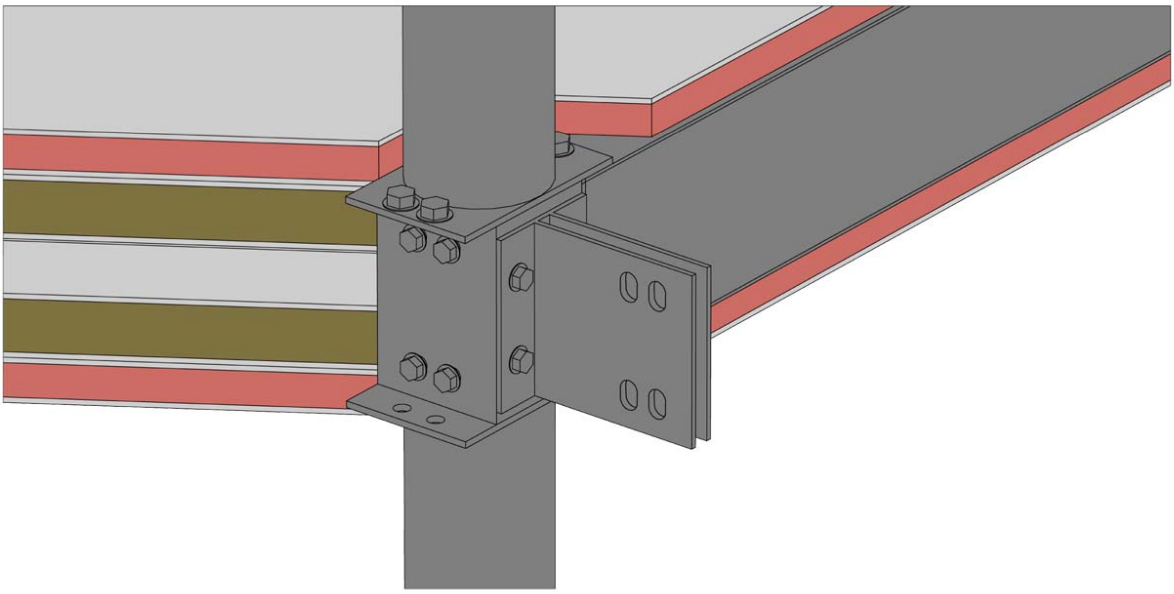




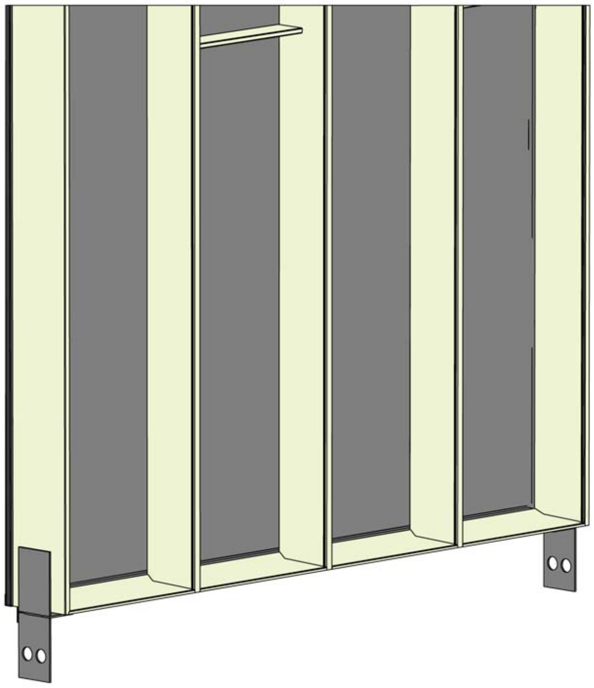
Aansluiting Gevel-Vloer



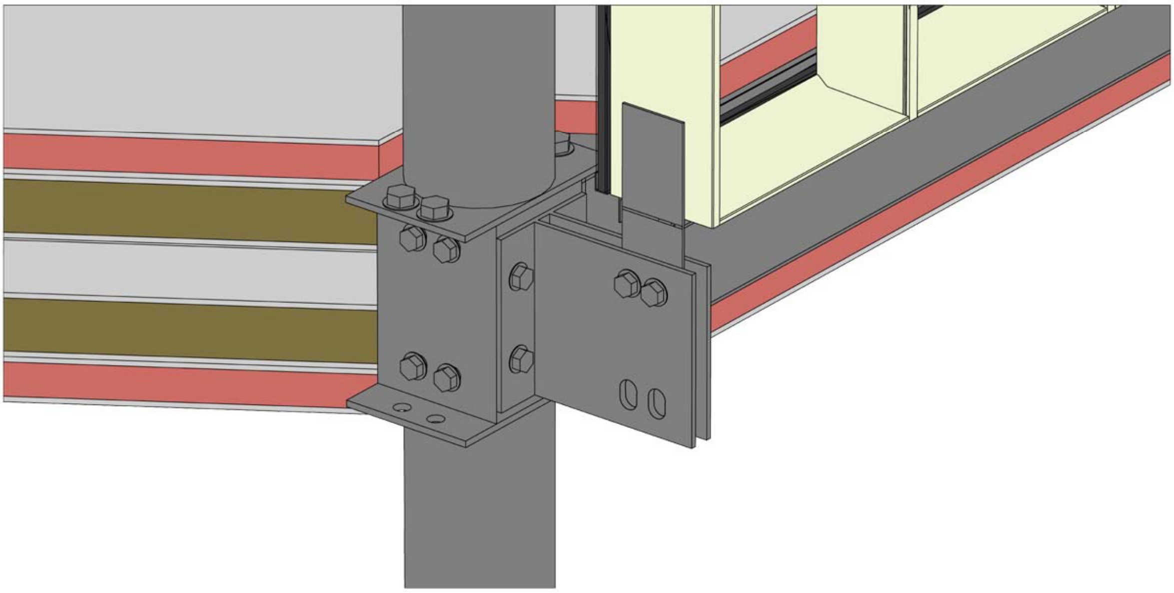
Productie - Constructie opbouw



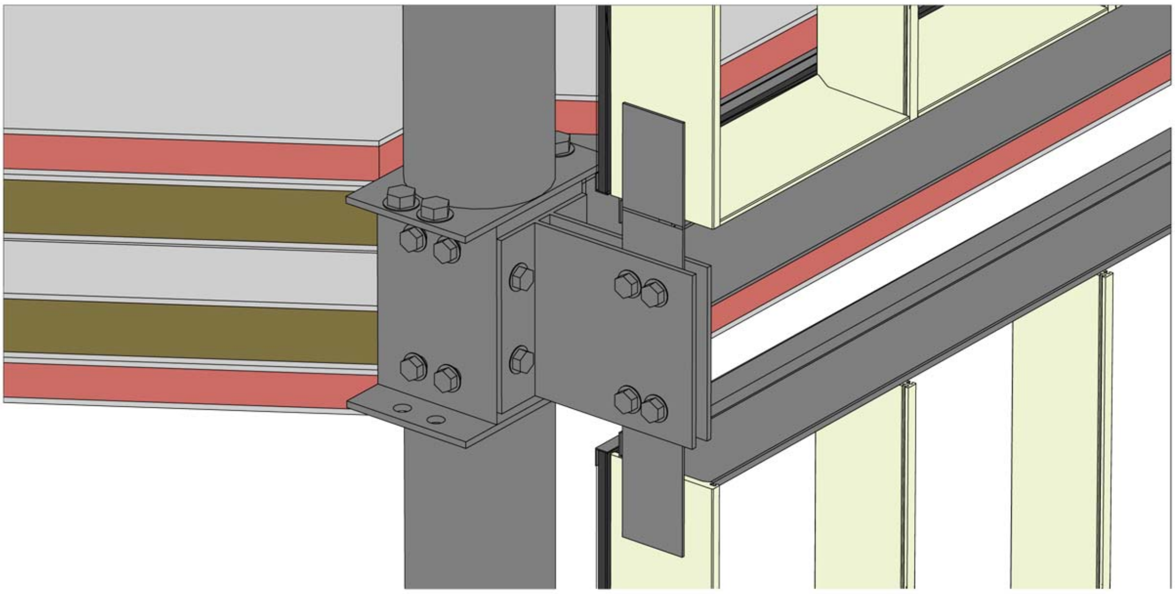
Productie - Constructie opbouw



Productie - Constructie opbouw

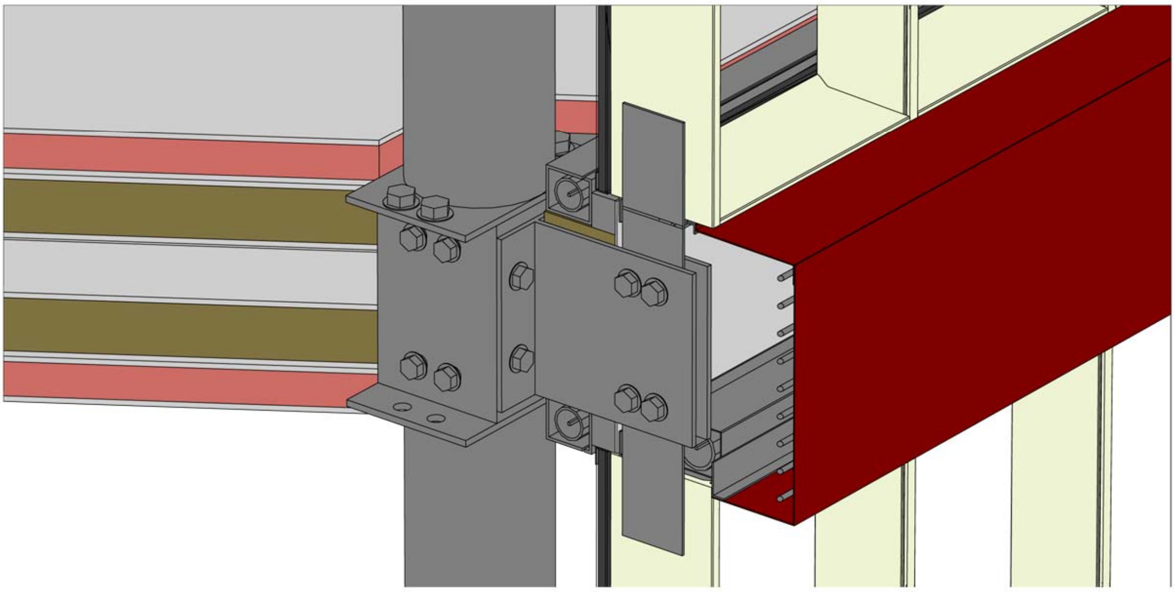


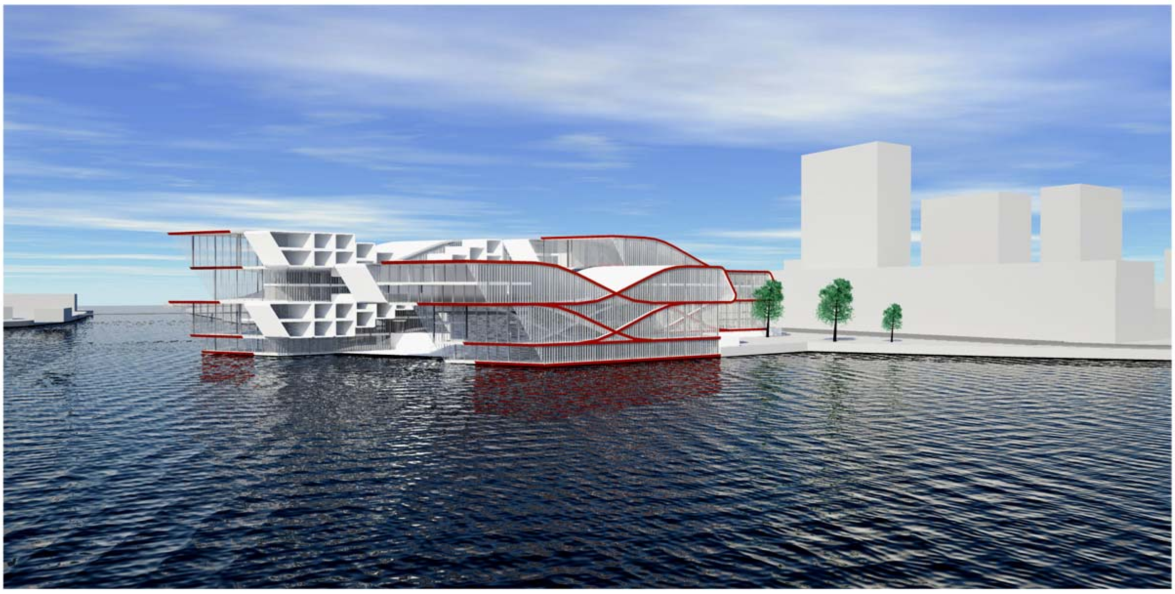
Productie - Constructie opbouw

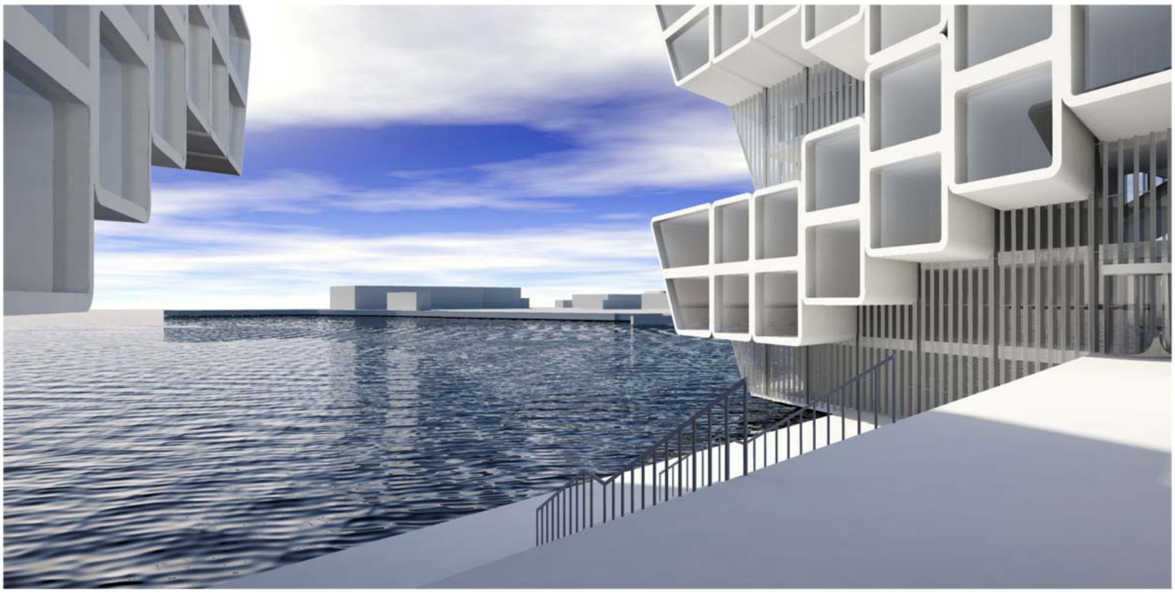


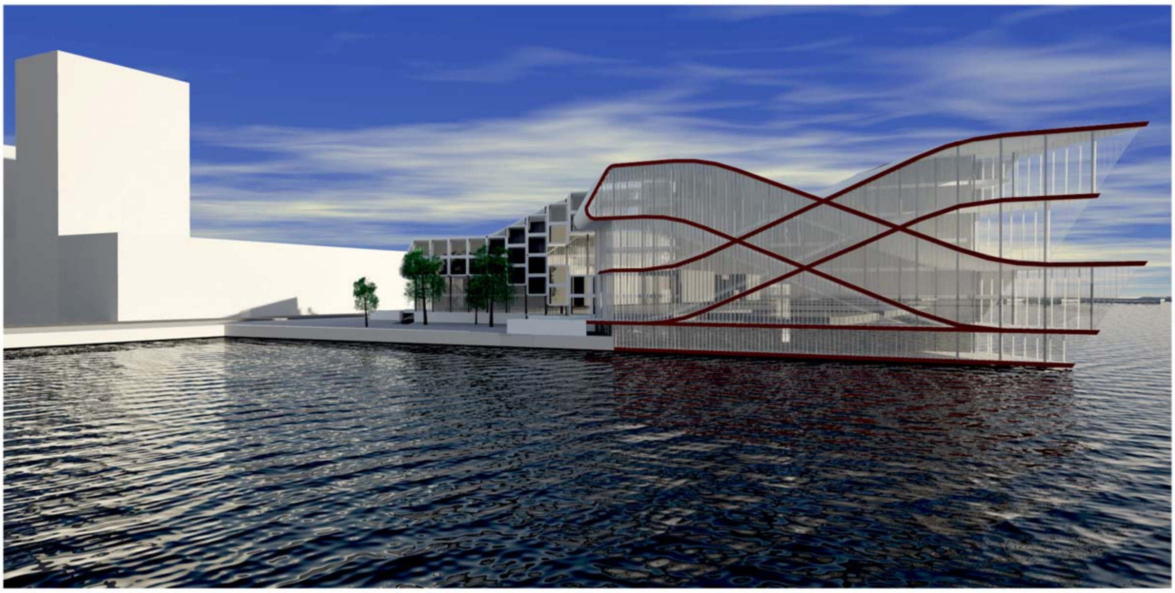
Uitgangspunt /Concept - Functies/Sandwich - Kamers/Modulair - Gevel/FRP

Productie - Constructie opbouw









Reflection

Research and Design

This report describes the building technology part of a dual graduation project. During both the architectural and the building technology part, the research topic has been plastics with a special interest for fiber reinforced plastics (FRP). Several aspects have been researched varying from the material itself to semi-finished products and complete facades made with this material. The knowledge gained has been used to determine starting points for the design which in case of the façade design of the building technology part was the application and design of an extreme slender FRP-glass based façade. During the process research has been done after this type of construction from which the results can be read in the first chapters of the report. During the architectural part of the project these starting points were determined based on prior knowledge. Simultaneously to the in depth research to the technical aspects of this construction type, a study has been done after the most suitable distribution of the façade elements within the architectural context. On a larger scale the research and the design were independent from each other during this part of the project. Note must be made that the prior knowledge gained about FRP-glass structures during the architectural part learned the basic principles according to a façade like this. Knowing which guidelines needed to be taken into account, the technical research and design could be made simultaneously. The true input from the research into the design can be found in the details. They show the slenderness of the construction, in the façade overview drawings this is no more than just a line. In general, decisions are based on the possibilities of FRP, production process and feasibility while respecting the architectural boundary conditions set in the first part of the project.

Starting this part of the project with an analysis of the development of FRP in facades during the last decades was a smart move in the process for determining the position of FRP and the functions it is used for. The knowledge gained during the architectural part has also been of great importance during this part of the project. Decisions became less complicated by this, something which was not always the case during the architectonical part of the project since a lot of knowledge had to be gained then. The presence of an architectural concept for the façade provided starting points on which the façade design could be based. During one particular stage of the process this concept was lost for a moment which resulted in a design which on a technical level could function well enough but on an architectonical level this certainly was not an improvement. When realizing this, things came back on track and the road to the final result went smoother than expected. At the end everything tends to fall into place.

If anything could be learned from this process it will be the fact that keeping in mind the main goal and boundary conditions is extremely important in order for the process to be efficient and productive. Keeping the bigger picture in mind during the different stages of the process and the decision making should improve the efficiency of the project and probably the design as well.

Project in the wider social context

FRP has been used in architecture since the late 1960’s, however major steps in developing the application field of this relatively new material have been taken during the last decade. Due to enhanced production processes different types of materials have become available with properties specially adjusted for specific projects. Due to this a unique and efficient designs can be made which stand example for the wide variety of options FRP’s have to offer. This project contributes to that specific area as well. The high level of experimental design and the use of material properties to shape the design results in a project which represents the possibilities of this specific material. Plastics are used in a wide variety of application fields, however they are certainly not always presented at their best. Clients and consumers are given the impression that a plastic product is a less product since in a lot of cases it is an imitation of an already existing product which used to be made with a different material. As a result of this the high-tech material properties and shaping options are forgotten which could be considered a waste. The use of plastics and in this case FRP’s in such a way that the design benefits from the material properties should be a starting point in the majority of projects based on this material.

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APPENDIX A

Composite Reference Projects

The Boeing 787 Dreamliner

Boeing has launched the 787 Dreamliner as a super-efficient airplane. In principle there are two models 787-8 and the slightly bigger 787-9. These airplanes are able to do big-jet ranges while being a mid-size airplane. This is the result of the light materials used in the airplane, which is why the Dreamliner uses 20 percent less fuel than today's similarly sized airplanes. 80 % of the materials used are carbon composites. They make up for 50 % of the total weight and primary structure. These materials are used in the wings and fuselage. Not only the flying range and fuel efficiencies have improved as a result of the composites but also the assembling of the airplane has become a lot more efficient. Building a one piece fuselage eliminates 1500 aluminum sheets and 50.000 fasteners.

The numbers:

Cross section	5,74 m
Wing span	60 m
Length	57 m (787-9 – 63 m)
Height	17 m

The superior strength of the composite fuselage, compared with one made of aluminum, will allow the passenger cabin to withstand higher pressurization, equal to the air pressure at an altitude of 6.000 feet instead of the usual 8.000 feet. This makes Boeing is able to control cabin temperature, humidity and ventilation in a far better way.

The production of the 787 had to be automated in order to be able to mass produce airplanes. Traditionally, making large composite structures has been a slow, manual process, and the quality of the finished parts depended on the craftsmanship of experienced workers. When this was about to be automated several concerns came to mind about how to maintain quality, meet weight targets and stay within original budges estimates.
As a result of the carbon reinforced plastics being more tougher than aluminum, fewer maintenance will have to be made. It also suffers less from corrosion which in general will make the airplane more efficient than any other plane in the world. According to Alan R. Mulally, Boeing's CEO, they always wanted to design in composites but only recently the material costs have become competitive with aluminum. However since CRP is a different material than aluminum, it has different specifications which all need to be taken into account. For example when an aluminum plane is hit hard by a service vehicle it normally only dents it while in case of CRP plane it will crack. This issue has been solved by using a special impregnation on the fibers. The epoxy that provides strength and hardness is surrounded by a polymer with a different density. This combination makes the surface less prone to impact damage, and if damage does occur it prevents cracks from spreading.

The advantages on the production side can be found in the fewer and simpler parts compared to aluminum. However the production of the parts especially the fuselage have become more complex. The sheer size of the 5.74 meter diameter fuselage sections requires multiple layers of carbon-fiber tape to assure structural integrity. Each added layer of tape increases the likelihood of variations or flaws. When the first barrel came out of the oven, there certainly were flaws, bubbles on the skin. This could the material weaker and eventually cause cracks by allowing water to seep under the surface, then freeze up and expand at high altitudes. When barrel 3 came out of the oven it had fewer defects. However after nine barrels there still were defects which had to be eliminated. The problem turned out to be in the mold. In the process carbon fiber material is laid down on the mold which than starts to rotate as the plastic carbon fiber tape is applied. The structure is then wrapped and placed in a huge oven for curing. While in the oven the barrel is under enormous pressure, which essentially squeezes the layers of composite material together. Every composite part that is cooked this way has a certain level of porosity which is normal but in case of the Dreamliner the amount of porosity increased in time. The problem as said is the mold which changes size as it is heated in the oven. This must be taken into account when the fuselage barrel is made. Some of the material had been machined off to get the mould back to the proper size, but as a result there were places that leaked. This caused the bubbles during curing. Also the connection between the wings and the fuselage turned out not to be sufficient. When the wings were flexed to their limed some of the composite material delaminated. Boeing had to redesign these areas and eventually ad some weight back to the frame. These problems clearly shows situations which eventually always will occur when using new techniques, materials or in this case working on a different level. This is not a traditional material of which we know every in and out but these are materials and techniques under construction.

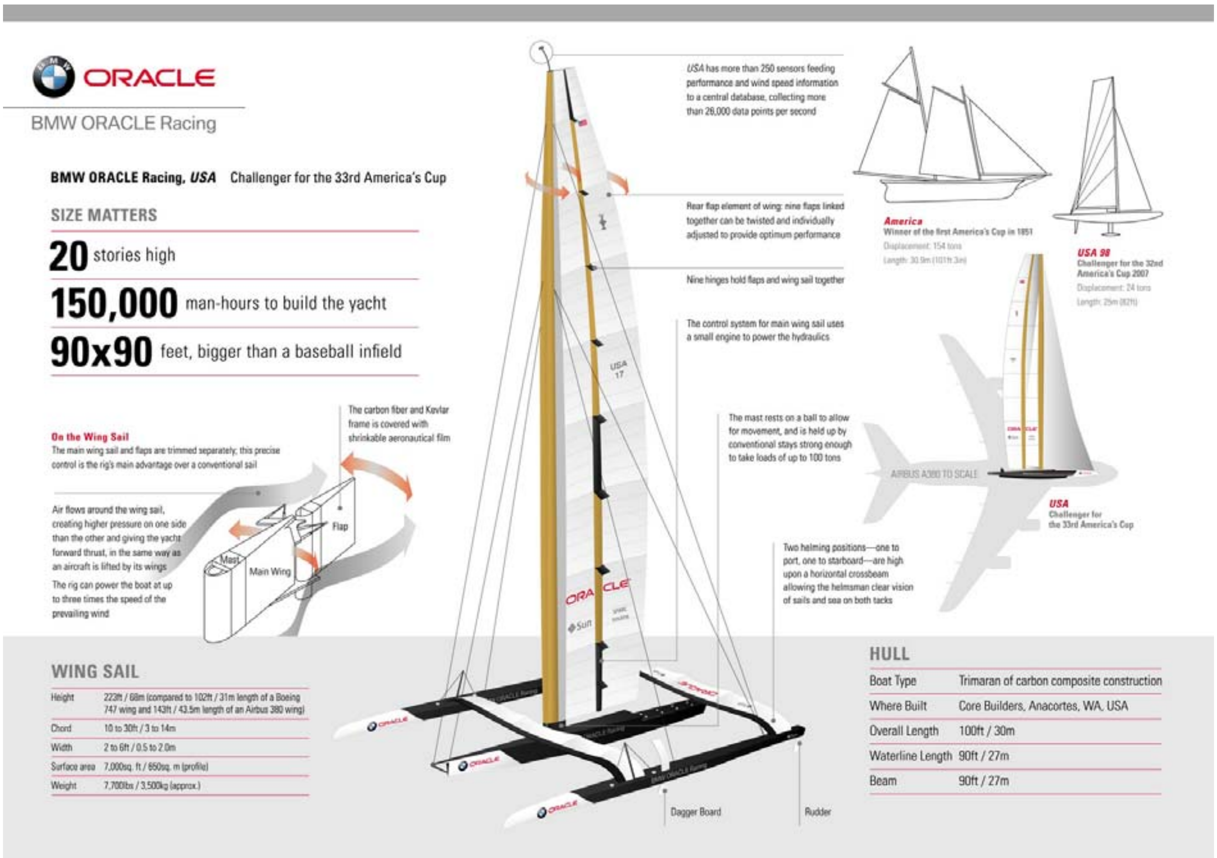
The failure modes of composite materials are less predictable than in aluminum. Crack growth in aluminum is relatively linear after initiation, and can be easily detected visually or with standard non-destructive techniques. However, carbon-fiber composites do not display the effects of fatigue and evidence of crack growth as readily as aluminum. In addition, carbon-fiber composites are prone to delamination if moisture or corrosive elements enter the composite matrix. To prevent major disasters as a result of these possible material failures, Boeing has introduced a specific maintenance program to regularly inspect and repair.

Project: USA 17, Trimaran of carbon composite construction
Designer: Van Peteghem and Lauriot Prévost (VPLP) and design team of Mike Drummond
Year: 2009
Location: Produced by Core Builders, Anacortes, WA, USA
Source: - www.americascup.com
- http://www.vsail.info/tag/bmw-oracle/page/3/

Points of interest:
The USA 17 is the larges trimaran in the world build for the Deed of Gift challenge for the 33rd Amerca's Cup. The yacht has an overall length of 34.5 meters and a height of over 60 meters. The yacht has the ability to sail up to 2.5 times the wind speed. Also due to it's speed it never sails upwind (the difference is only 5%). The weight of the yacht has a lot to do with all of this. The floating hulls are made out of carbon composite. This construction consists of a sandwich construction with two carbon skins less than 1mm thick laminated over an ultra-light honeycomb core. The hulls are built in two halves in female moulds. After being released from the moulds the internal bulkheads and structure are added before the two halves are bonded together to create a single hull. Due to the used materials the result is an extremely stiff and light structure. Besides the hulls and mast there is an other remarkable modification. In the traditional setting the yacht had two sails but in November 2009 the yacht had a rigid sail wing built. The performance results of this adjustment are impressive. The wing is made out of CRP



Conclusion:
The forces which will be applied to the construction as a result of the wind are very large. The used carbon construction has the ability to handle them well and at the same times reduces the weight of the yacht, resulting in less resistance. Even the rigid sail wing can be handled by the carbon construction. In this case it actually is all about lightness, this is what gives the yacht it's biggest performance enhancement. Besides that the stiffness of the construction contributes as well, the loads are transferred in a more efficient way. This is not always wanted since the internal forces will be larger, it depends on the situation.



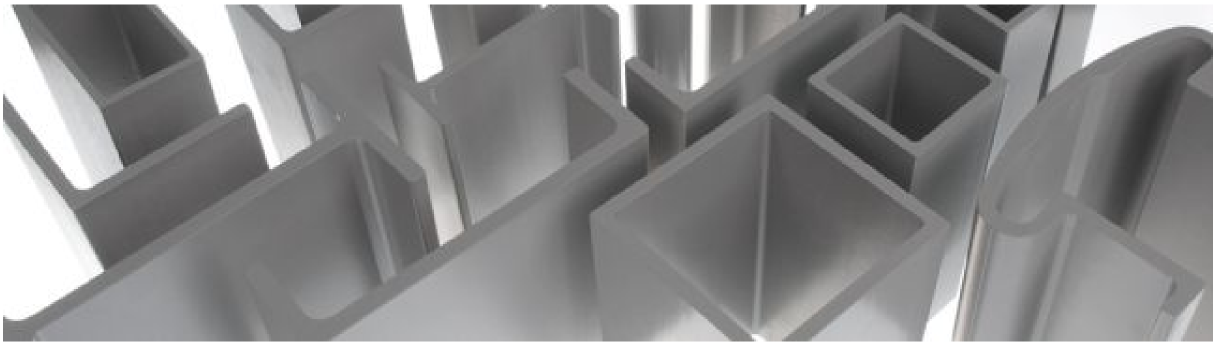
BMW ORACLE Racing
BMW ORACLE Racing, *USA* Challenger for the 33rd America's Cup
SIZE MATTERS
20 stories high
150,000 man-hours to build the yacht
90x90 feet, bigger than a baseball infield
On the Wing Sail
The main wing sail and flaps are trimmed separately; this precise control is the rig's main advantage over a conventional sail
The carbon fiber and Kevlar frame is covered with shrinkable aeronautical film
Air flows around the wing sail, creating higher pressure on one side than the other and giving the yacht forward thrust, in the same way as an aircraft is lifted by its wings
The rig can power the boat at up to three times the speed of the prevailing wind
Flap
Mast
Main Wing
USA has more than 250 sensors feeding performance and wind speed information to a central database, collecting more than 26,000 data points per second
Rear flap element of wing: nine flaps linked together can be twisted and individually adjusted to provide optimum performance
Nine hinges hold flaps and wing sail together
The control system for main wing sail uses a small engine to power the hydraulics
The mast rests on a ball to allow for movement, and is held up by conventional stays strong enough to take loads of up to 100 tons
Two helming positions—one to port, one to starboard—are high upon a horizontal crossbeam allowing the helmsman clear vision of sails and sea on both tacks
Dagger Board
Rudder
America
Winner of the first America's Cup in 1851
Displacement: 154 tons
Length: 30.9m (101ft 3in)
USA 98
Challenger for the 32nd America's Cup 2007
Displacement: 24 tons
Length: 25m (82ft)
AIRBUS A380 TO SCALE
USA
Challenger for the 33rd America's Cup
WING SAIL
Height 223ft / 68m (compared to 102ft / 31m length of a Boeing 747 wing and 143ft / 43.5m length of an Airbus 380 wing)
Chord 10 to 30ft / 3 to 14m
Width 2 to 6ft / 0.5 to 2.0m
Surface area 7,000sq. ft / 650sq. m (profile)
Weight 7,700lbs / 3,500kg (approx.)
HULL
Boat Type Trimaran of carbon composite construction
Where Built Core Builders, Anacortes, WA, USA
Overall Length 100ft / 30m
Waterline Length 90ft / 27m
Beam 90ft / 27m

Project: Fiberline FRP construction profiles
Designer: Fiberline
Year: 2003
Location: -
Source: Fiberline design Manual, www.fiberline.com

Points of interest:
Pultruded profiles with shapes like that of steel profile. The material used for these elements is Fiber Reinforced Plastic (FRP). This consist of a resin made out of epoxy, polyester or phenol, combined with glass fibers which can be woven in all kinds of patrons. The composite material which is created by this has an very favorable strength to weight ratio. However this material lacks of stiffness due to it's relatively low modulus of elasticity. This can result in large deformations which in most situations are unwanted. Fiberline makes in the very beginning of it's manual two recommendations about the use of the products: Point loading of profiles is not advisable since the glass fibers will be damaged by this. In cases of permanent load, Fiberline profiles should not be used to more than a maximum of 1/3 of the ultimate limit state load, to minimize the risk of stress corrosion.

At this moment there are no buildings constructed with Fiberline profiles. The product is mainly used for planks, railings and staircases. When a solution can be found for the fire endurance of the elements and they are dimensioned in such a way the deflection will be within the tolerated boundaries, it might be an option to use these elements as part of the primary load-bearing structure of a building. The production methods and speed will change because of this. The elements can be connected with bolts and nuts or in some cases with glue.

Besides structural profiles, the company also offers a range of façade solutions. The most important advantage in accordance with conventional building materials, is the thermal insulation values of the product. As a result of this, one element can be used on the outside as well as on the inside. This means smaller details because several functions can be combined into one element.



Conclusion:
With the use of these profiles, the weight of the construction or the façade can be reduced. Also the size of the façade elements can be smaller when compared with conventional building materials. But most importantly it doesn't matter if the profiles are on the outside or on the inside of the building due to their thermal insulating properties. This gives the designer the freedom to situate the elements at any location.

Project: Eyecatcher Building
Designer: Fiberline??
Year: 1998
Location: Basel, Switzerland
Source: - Plastics in Architecture and Construction
-http://cclab.epfl.ch/page-13730-en.html
-www.fiberline.com

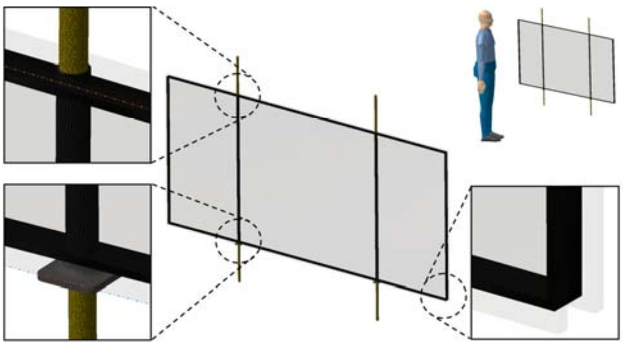
Points of interest:
Five storey building with a FRP load bearing structure. This is the tallest building in the world with a composite construction made out of FRP. Standardized profiles from Fiberline are used for this construction. Is has been build for an exposition where it was about to show the possibilities of FRP as a construction material. As a result of the thermal insulating properties of the material, the facade has been placed between the construction elements. This makes the total package thinner but it also shows the construction on both sides of the building. The building has a total height of 15 meters and has a floor space of 10 x 12 meter. The composite used consists of Polyester as the matrix and E-glass for the fibers. The profiles used are produced by pultrusion. The construction can be disassembled as a result of making all the connection with bolts. After the exposition the structure was taken apart and moved to its final location were it now serves as an office building.



Conclusion:
What about this building says, look I'm made from plastics? Even being this the first building ever made with a structure entirely build from FRP, nothing has been done with is. The façade seems to be placed between the elements which results in the construction being on the outside as well on the inside. Besides that nothing is different from a traditional type of building made from steel.

Project: Composite Façade InHolland
Designer: InHolland Compositelabaratory, TNO, TU-Delft, Syntens, Octatube (building – Rietveld Architects)
Year: 2007-2009
Location: Delft
Source: - www.grootcomposiet.nl/downloads/publicaties
- http://www.inholland.nl/NR/rdonlyres/8589260B-7E26-42F0-9D29-1C04A9D622CA/0/Factsheetcomposietgevel.pdf
- http://www.inholland.nl/Composietenlab/Content/Nieuws/Japans+bezoek+voor+composietgevel.htm?SourceGuid=
- http://architectuur.nl/project/hogeschool-inholland-delft/

Points of interest:
The atrium of the Hogeschool InHolland Delft, has an innovative composite façade made out of glass and Kevlar. The façade has a height of 13 meters, which spans over four floors and has a thickness of 45mm. This is the highest and thinnest glass façade in the world. The innovative technology behind the designs lays in the use of cables made out of carbon and aramide(Kevlar) fibers. The cables are developed by Prince Fibre Tech and are based on the Japanese 'pitch-based' fiber. The cables have a stiffness 70% higher than steel. This itself is an innovation which generates a lot of possibilities. The stiffness is needed to prevent the façade from buckling as a result of its own weight. This is the first time fibers like these are used in architecture. On this moment the Japanese company Sumitomo works on a fiber five times as stiff as steel.
During wind loads of 12 bft, the façade can have a deflection of 300mm. This would cause problems when using 90 degree corners since the glass plates in that point have nowhere to go. This has been solved by giving the plates at the corners a lens shape and by placing a composite element at the corner. In first design plans, the cables were located in the cavity between the glass plates. The glass plates would have tubes integrated through which the cables could go. In reality the cables are not placed inside the glass on two of the three facades, but behind the glass. The thickness of the glass hasn't changed but the appearance has. At first the façade would be flat on both sides but as a result of replacing the cables the façade is no longer flat on the inside. This has been done out of safety precautions. The spacers of the glass are also made out of composite.





Conclusion:
The use of composites in a way like this creates the opportunity of designing extreme slender constructions. The fibers being stiffer than steel but still being a lot lighter is the factor which makes this possible. This project shows that it is not only composite designs which can be innovative but that also the reinterpreting the conventional ways of designing with regular building materials can develop itself. However the moment in this construction is something which won't be tolerated in most designs but since this is the first of its kind it is likely these problems can be solved in the future for example with the product Sumitomom intends to develop. Nevertheless a product which has a higher stiffness as steel can be of great importance in a variety of applications.

Project: Futuro
Designer: Matti Suuronen
Year: 1968
Location: muliple
Source: - www.bertings.nl
- Booimans van Beuningen museum, Rotterdam

Points of interest:
Mobile home designed in the sixties which shows the house of the future. The design obviously based on a spaceship is made entirely out of FRP. The demand on this house back in the day was very enormous, some even thought it might have solved the housing problems around the world. During the oil crisis of 1973 the production of this plastic home became unprofitable. Everything you need to live has been integrated in the design. Some of the specifications are:

- polyester exterior
- available in multiple colors
- height of 4 meters
- diameter of 8 meters
- weight 4000 kg
- floor space 25 m^2
- moveable by helicopter

One of the ideas behind this home was the ability to place it at places which normally were unsuitable for building because of the rough surface. This design can be transported through air which means it can be placed almost everywhere. The interior is integrated in the design. As the name does expect, the interior has a lot of futuristic elements. This means a lot of curved shapes are used, something unique for the time being. The design consists of 16 elements which are bolted together, there are two different shapes. The elements are light enough to be assembled without cranes.




Conclusion:
Innovative modular design with FRP in which all functions haven integrated. However according to the architect the modules can be stacked but from that point of view they certainly do not have the right shape. When this is about to be done, the metal frame should be placed on top of another module. This would probably result in failure of the whole since these are point loads, something FRP cannot handle very well. For the time being this design has a lot of smart solutions, like the connection details.

Project: Façade, Stedelijk Museum
Designer: Benthem Crouwel Architects, Holland Composites Industrials (HCI)
Year: 2011
Location: Amsterdam
Source:
- http://www.architectenweb.nl/aweb/archipedia/archipedia.asp?ID=6816
- http://bouwwereld.nl/project/naadloze-luifel-voor-stedelijk-museum/
- http://www.bouwmagazines.be/Magazines_Facade/LaatsteUitgave/Facade.pdf
- http://www.prodim.eu/webpage/2/71/Job%20case%20HCI%20-%20gevelbekleding
- http://www.dexigner.com/news/23488#ixzz1eQcmJQfJ
-http://www.teijinaramid.com/2011/07/first-panels-in-place-on-the-new-facade-of-the-stedelijk-museum-in-amsterdam/
- http://www.dexigner.com/news/23488
- http://www.hollandcomposites.nl/referenties/53/Nieuw-Stedelijk-Museum-Amsterdam/

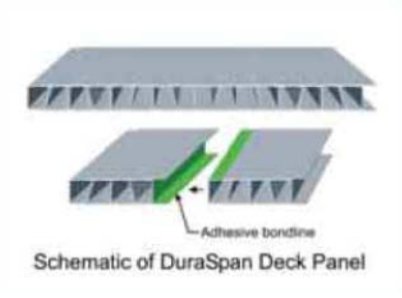
Points of interest:
Benthem Crouwel Architects designed the new façade for the 'Stedelijk Museum' in Amsterdam. The design consists of a seamless composite surface which already is called the 'Bathtub'. It has a total area of 3000m^2 with only three dilatation seams. The production of this façade has been done by the company Holland Composites Industrials. They surveyed all components and produces them. The structure is made of 271 sandwich elements which are build of special materials. Since the façade needed to be smooth with as little as possible seams, a combination of aramid (Twaron) and carbon (Tenax) fibers has been used. Vinylester resin has been used as matrix and the core consists of PIR foam blocks. The facing plies on the in- and outside consist to two layers of Twaron fabric with a layer of Tenax fabric in between. The fibers are oriented perpendicular towards each other. In total 4850 kg of Twaron and 4050 kg of Tenax has been used. This fiber combination has a negative thermal expansion coefficient while the foam core has about the same thermal expansion coefficient but this is positive. The result of this is an element with little to no deformations when talking about thermal expansion. With its length of 100m it only expands 1mm per degree Celsius in temperature difference. Normal glass fiber reinforced panels would expand over two and a half times as much. The panels have a width of 3 meters and a length up to 15 meters. The panels are mounted on site with a special glue which is injected trough small holes in the surface. After that the seams are filled with composite material and grinded till they are completely smooth. All other seams are filled and grinded as well in order to apply the final layer. The final layer consists of a special polycyloxaan paint which has a glossiness degree of 70%. This facade when finished will be the largest composite facade in the world.

Conclusion:
As a result of an innovative use of material properties an extremely long facade can be produced almost out of one piece. A combination of different materials has resulted in sandwich panels with almost no thermal expansion which allowed the designers to create a facade with a surface of about 3000m^2 with only three seams. The fibers used in this product are extremely expensive and therefore cannot be used in every project. In this case they are partly sponsored and their also is a large amount of money available to realize this project.

Project: bridge deck elements
Designer: Duraspan (bridge deck elements)
Year: 2000
Location: -
Source: www.martinmariettacomposites.com

Points of interest:
What are the advantages of DuraSpan bridge decks:

- Lower weight: one-fifth the weight of a comparable concrete deck.
- Resistant to corrosion and freeze/thaw cycles, resulting in longer life expectancy and lower maintenance costs.
- Rapidly installed using light equipment, which substantially reduces construction time and labor costs.
- Solid Surface: capable of being topped with skid-resistant overlays.
- Capable of achieving composite action: Bridge designers often utilize DuraSpan to achieve composite bending action with the bridge's beams, thereby increasing the beams ability to resist bending and deflection.
-



DuraSpan bridge decks are made of FRP's and currently available in two configurations.

	Depth	Weight	Allowable Beam Spacing
DuraSpan 500	5.00" (127 mm)	0.62 kN/m2 (62 kg/m2)	1.52 m
DuraSpan 766	7.66" (195 mm)	0.91 kN/m2 (91 kg/m2)	3.05 m

The panel length equals the bridge deck width or staging width. DuraSpan limits the design strains to 20% of the ultimate capacity, this is a rule of thumb borrowed from the aerospace industry. Conservative deflection criteria often drive the design strains even lower than this 20% criteria. As a result the product has an extremely high safety factor for strength and sees negligible effects from fatigue and creep. The design of FRP structures is typically driven by their deflection requirements. Use of innovative geometry and optimal fiber orientations can enhance the stiffness of the product. Martin Marietta Composites utilizes its patented deck tube design and fiber lay-ups to achieve optimal stiffness and cost effectiveness.
The bridge deck elements are produces by Creative Pultrusions, Inc., a world leader in composites. Individual pultruded tubes are sent to a fabrication facility, where they are assembled into panels using adhesive.

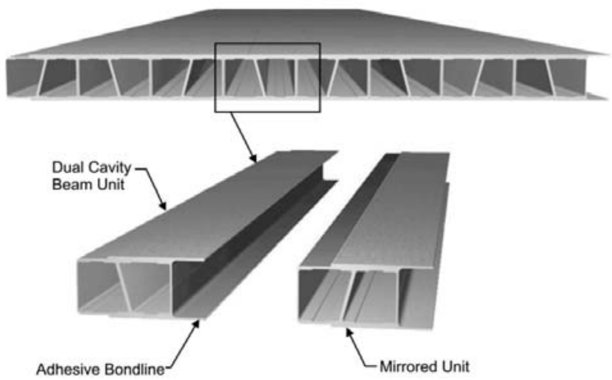


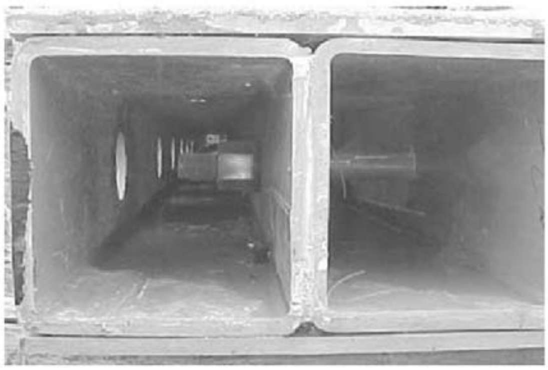
Conclusion:
The load on a bridge deck is far higher than that of a building floor. This in combination with the safety factor of 20% of the ultimate capacity makes that these elements are capable of spanning larger gaps in building design then the ones used in bridge design. Also the composite action might be a powerful tool since several elements can be combined which makes they all can be more slim. However connecting the elements on the head and tail might be difficult since they are designed to be connected on the sides.

Project: Fire performance water cooled of bridge deck elements
Designer: Durospan (bridge deck elements)
Year: 2005
Location: Composite Construction Laboratory
Source: Keller T. et. al., *Fire endurance of loaded and liquid-cooled GFRP slabs for construction*, Composites part A 37 (2006) 1055-1067
Keller T. et.al., *Structural response of liquid-cooled GFRP slabs subjected to fire – Part 1: Material and post-fire modeling*, Composites part A 37 (2006) 1286-1295

Points of interest:
The fire endurance of fiber reinforce polymer materials is the most critical barrier to the potential widespread as a Construction material of primary load-carrying components in buildings. Fire regulations require a 90-minute fire endurance for residential buildings with more than three floors. Compared to concrete, the mechanical properties of polymer composites degrade at far lower temperatures. Experiments have been done in which water cooling was applied to bridge deck elements from the company Durospan. This concept has developed further and involves the integration of the following functions into multifunctional GFRP building components: structural load-carrying, structural fire resistance and interior climate control. Additional functions that can be integrated are the thermal insulation and architectural aspects such as the introduction of natural light through transparency or translucency when using glass fibers.
Circulating water in the cellular panel structure ensures the fire safety. Under normal circumstances, the temperature fo the circulating water can be regulated which then regulates the air temperature in the rooms. The large area of the emitting surfaces allows heating in the winter and cooling in the summer with only slight variations in the water temperature. The low thermal conductivity of GFRP allows the merging of the load-carrying structure and the thermally insulating façade into a single-layer load-bearing building envelope.

The safety by liquid cooling using water is provided by three different mechanisms:
At first the use of water greatly increases the thermal mass of the components, this can absorb heat. If this mechanism is not sufficiently effective, the temperature of the components raises to a level that causes boiling in the water. Large amounts of energy will then be used to change the state of the water from liquid to gas. This isothermal phase change absorbs more than five times the amount of energy required to change the temperature of the same quantity of liquid water by 100 degrees Celsius. The energy stored in the water vapor will be carried away from the heated areas by its natural buoyancy and by the flowing water. The final mechanism is not a true defense but may provide some added safety in real-world conditions. Should there be a location where the FRP components has eventually burned through, there is a great reservoir of water that will discharge from that location. The results of the experiments show that liquid cooling could significantly increase the fire performance and resistance of the cellular GFRP slabs. The liquid-cooled specimens could resist up to 120 min with approximately half of their original laminate thickness remaining. The experiment also showed that the critical failure mode of non-liquid cooled cellular GFRP slabs exposed to fire is not a tensile failure in the damaged hot face, but an instability-induced failure on the relatively cold compression side due to the loss of lateral support of the fibers through the softening of the resin. Delaminated tensile-stressed fiber layers can still remain load carrying if anchored in support regions not exposed to fire





Conclusion:
Using this technique means constructing a watertight system in which a constant flow of water can be ensured. These FRP floor elements are extremely light in comparison with floors made out of concrete. This can be an advantage while constructing the building or in situations where no heavy construction is allowed. However when filled with water, these elements will gain a lot of weight. This is something to keep in mind while considering the use of liquid cooled elements.

Project: Shipping Container
Designer: -
Year: -
Location: -
Source: - http://www.ect.nl/aboutect/EducationalInformation/DeContainer/Pages/default.aspx

Points of interest:
The shipping container is a great example of how a modular system influences several working fields. In 1966 landed Sea-Lands container ship for the first time in the harbor of Rotterdam. It carried a little over 200 35-feet containers. Sea-Land is not the inventor of the container but it was the first who introduced ships which only carried containers, the use of modular elements. The used containers are available in several dimensions. One of the interesting points about the shipping container is the possibility to connect them to each other or to the truck or ship they are transported by, with so called stackers. Each corner of the container has a couple of openings in which a stacker can be placed. In principle this allows an infinite connection between containers. This invention has led to several impressive ships which nowadays are able to carry over 10000 40-feet containers. On this moment it is no longer the size of the ships which limits the amount of containers to be transported but it's the route which holds back the expansion. The width and depth of several channels does not allow ships this large to pass. All containers have a registration code which tells who's the owner, size, type and serial number. As a result of this they can be tracked down since the original products which now are inside can not be seen from the outside. In principle a container is never opened during its travel. Customs checks are done in the harbor and not at the border which usually is the case. This increases the speed of transporting the containers. Besides that the containers are tax free as a result of the standardization.

In order to stack the containers properly the size is very important since the connections are located on the corners. In order to control this, appointments about size and tolerances are made. Manufacturers of products and packaging industries use the dimension of the container to scale their products in such a way a container can be stuffed as efficient as possible.

Conclusion:
The shipping container is probably one of the most expanded modular systems in the world when talking about components. As a result of this, transporting costs can be much lower and there is a significant decrease of traveling time.

Project:	Space Box
Designer:	Holland Composites, Mart de Jong
Year:	2003
Location:	-
Source:	www.hollandcomposites.nl
	web.tue.nl/cursor/bastiaan/jaargang49/cursor29/achtergrond/special.html

Points of interest:
The space box is a small house completely made out of fiber reinforced plastic. With a floor area of 18 m^2 and an empty weight of 2500 kg, this is housing module which can easily connected with others but also one which can be moved easily. In most situations a foundation is not needed because of the low weight. The modules are delivered in a finished state and they only need to be placed on site. Connections for electricity, water and sewage are provided.
An interesting part of these modules is their way of fabrication. Each module consists of five FRP sandwich elements which are glued together. For every element a mold is needed. All layers are placed in this: fibre sheets, foam blocks and again fiber sheets. The whole package is now placed in a vacuum bag which pushes the layers into the shape of the mold.

In practice it turns out that the thermal and acoustical isolation doesn't work properly. This might be the result of the lack of mass or a construction which is to thin. On this moment these modules are only used as a temporary housing solution for students. If this concept is to be explored further, these insulation problems must be solved. The inside finishing of the walls consists of plasterwork. The used FRP modules are very strong but not that stiff which means there might be cracks in the plasterwork. Also the points at which the modules are connected turn out to be very vulnerable, there are several cases in which these points were about to leak. This however is not so much a failure of the design but more a misstep while connecting the modules.



Conclusion:
The idea and the materials used for the construction of the modules is innovative. However the material used has specific properties which might have exploited even more. The use of plaster on the inside wall was not the result of practical considerations but this was done in order to give the user the idea of being in a regular home. This might be conceived as a design failure. When using materials in an innovative way, why shouldn't the user profit?

Project: Modular building systems
Designer: De Meeuw
Year: -
Location: -
Source: www.demeeuw.com, product information brochures

Points of interest:
De meeuw produces modular building systems to sectors in which the option of rapid building is a big advantage. It focuses primarily on hospitals, educational buildings and temporarily structures. The company offers different types of building systems and almost all of them offer several components. The modular elements which can be delivered differ from finished buildings to modules which can be stacked and connected to each other. The latter one offers several cladding possibilities which means the view of the building can be determined by the owner while the construction and part of the interior are standardized modules. This results in a flexible system which is able to adapt itself to the whishes of the users in a certain way. It's not only the fast building process which makes this type of construction interesting, its also the ability to make changes and additions to a building without bringing it down first. Materials used in these modules are: steel in the construction, concrete on the floors and several different materials are used for the finishing and cladding of the components.

There are also disadvantages to the use of these systems. All the modules are self supporting which means that if they are connected there are two columns standing side by side. In some cases the modules are visible. This shouldn't have to be a disadvantage but it is something to keep in mind. This has consequences for the building and the design. These systems have a limited building height. Three, max four storey's can be achieved. This is the result of a standardized construction which can't handle more forces. Additional support is needed when a higher building is wanted. Also the fire performance as a limiting factor in building multiple storey buildings.

Conclusion:
As a result of the relatively heavy construction it is not possible to construct multiple storey buildings which can be supported by a standardized construction. When a lighter construction will be used with the same strength it might be possible to construct buildings with more than four storey's. However the limited fire performance then becomes a topic of interest.