CHALMERS
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Design of an FRP Eco-bridge

A Feasibility Study from Structural Design and Life Cycle Cost Analysis Perspective

Master's thesis in Structural Engineering and Building Technology

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Department of Architecture and Civil Engineering
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Cover:
Sandsjöbacka Eco-bridge.

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ABSTRACT

The Swedish Transport Administration hopes to in the future construct eco-bridges over larger roads and railroads to prevent fragmentation of Swedish natural areas and to reduce road accidents involving wild animals. Such projects affect the mobility in the vicinity during construction and it is of interest to shorten the time taken until completion. Fibre Reinforced Polymers (FRP) are strong, yet lightweight materials that enable prefabrication of structures. FRP bridges can be quickly assembled on site using light cranes and could thus reduce the construction time in eco-bridge projects.

The aim of this study was to investigate the feasibility of FRPs as building material for construction of eco-bridges. A literature study was performed to gain knowledge of FRP as a building material. To investigate the structural feasibility, the Sandsjöbacka Eco-bridge over E6 south of Gothenburg made in reinforced concrete was redesigned using FRP. Two superstructures were designed, one with glass fibre-polyester and one with carbon fibre-epoxy. The designs were made using hand calculations based on *Prostpect for New Guidance in the Design of FRP*. A FEM model was developed for verification and buckling analysis. Furthermore, a life cycle cost analysis was performed to compare the FRP eco-bridges and the concrete eco-bridge to investigate the economical viability of such a project.

The study showed that the most important aspects to design against are creep deflections and buckling of the webs. It was also shown that GFRP can be less expensive than reinforced concrete by up to 42% and that CFRP can be less expensive than reinforced concrete if the whole life cycle is considered and social costs are included. It was concluded that to take full advantage of the economical possibilities of FRP, the potential manufacturers should be involved early in the project to help lowering the construction cost of FRP.

Keywords: FRP composites, GFRP, CFRP, eco-bridge, LCC analysis

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PREFACE

This thesis was carried out at the Department of Architecture and Civil Engineering, division of Structural Engineering at Chalmers University of Technology during the spring of 2018. We would like to thank our supervisor and examiner Reza Haghani and our supervisor from WSP Mohsen Heshmati, whom without this thesis would never have seen the light of day.

As this is our last work performed at the university we would also like to thank friends and family for their continuous support during our academic years.

Göteborg June 2018
Emelie Hällerstål
Victor Sandahl

Nomenclature

Greek letters

δ	Fibre mass proportion (-)
η_{cf}	Conversion factor due to fatigue (-)
η_{cm}	Conversion factor due to humidity and moisture (-)
η_{ct}	Conversion factor due to high temperatures (-)
$\eta_{cv,20}$	Reference value of reduction for 20 years creep (-)
η_{cv}	Conversion factor due to creep (-)
η_c	Total conversion factor (-)
γ_g	Partial safety factor permanent load (-)
γ_M	Partial factor (-)
γ_q	Partial safety factor variable load (-)
γ_{M1}	Partial factor (-)
γ_{M2}	Partial factor (-)
λ	Buckling value (-)
ν_r	Poisson ratio for resin (-)
ν_{12}	Poisson ratio for FRP (-)
ν_{f1}	Poisson ratio for fibre in direction 1 (-)
ϕ_{UD}	Empirical reduction factor (-)
ψ_0	Reduction factor for periodic loads (-)
ψ_2	Reduction factor for periodic loads (-)
$\sigma_{c,max}$	Max compressive stress ULS (MPa)
$\sigma_{t,max}$	Max tensile stress ULS (MPa)
$\sigma_{t,quasi}$	Max tensile stress under quasi-permanent load (MPa)
τ_{max}	Maximum shear stress for ULS load (MPa)
ε_{f1a}	Fibre direction strain limit (-)

Roman lower case letters

d	Discount rate (%)
f_s	Design shear strength (MPa)
f_{1c}	Design compressive strength in direction 1 (MPa)
f_{1t}	Design tensile strength in direction 1 (MPa)
f_{2c}	Design compressive strength in direction 2 (MPa)
f_{2t}	Design tensile strength in direction 2 (MPa)
f_{ka}	Failure stress in direction of fibre for one ply, compression of tension (MPa)
$f_{Rk,cr}$	Characteristic value of the creep rupture limit stress (MPa)
n	Year (-)
t_v	Accumulated load duration (h)
w_c	Hourly time value of car drivers (SEK/h)
w_t	Hourly time value of truck drivers (SEK/h)

Roman capital letters

C_n	Cash flow for year (SEK)
E_1	Young's modulus in direction 1 (GPa)
E_2	Young's modulus in direction 2 (GPa)
E_r	Young's modulus of resin (GPa)
E_{1a}	Young's modulus in direction 1 for compression or tension (GPa)
E_{f1}	Young's modulus of fibre in direction 1 (GPa)
E_{f2}	Young's modulus of fibre in direction 2 (GPa)
$E_{x,ply}$	Young's modulus for one ply, x the fibre direction (GPa)
G_f	Shear modulus for resin (GPa)
G_k	Self-weight (kN/m^2)
G_R	Shear modulus for resin (GPa)
G_{12}	Shear modulus (GPa)
L	Length of span (m)
L_r	Length of affected road (km)
L_s	Service life (years)
N	Time with reduced speed (days)

$Q_{applied}$	Applied load (kN)
Q_{crit}	Critical buckling load (kN)
Q_{snow}	Snow load (kN/m^2)
Q_{soil}	Soil load (kN/m^2)
Q_{ULS}	ULS load (kN/m^2)
S_a	Normal speed on road (km/h)
S_a	Reduced speed on road (km/h)
T	Time
V_f	Fibre volume fraction (GPa)
V_x	Variation coefficient (-)
X_d	Arbitrary design property
X_k	Arbitrary characteristic property

1 Introduction

1.1 Background

Most animals have a need for movement. Some move frequently within their territories while other make long journeys between summer and winter. Roads and rail roads prevent animals from crossing over by discouraging them and sometimes even by killing them in accidents (Swedish transport administration, 2012). These roads create barriers in a previously continuous landscape and divides nature into smaller areas. This effect is called fragmentation and can severely reduce the gene pool of animal populations in the area and create problems with inbreeding. To combat this effect different methods can be applied. One such method is to build bridges over roads, so called wildlife bridges or eco-bridges.

Fibre Reinforced Polymers (FRP) is a composite material where high strength fibres are mixed with a durable polymer matrix to create a strong and light material (Zoghi, 2014). FRP was for a long time mainly a material used in aerospace engineering, marine construction and similar areas which demands high strength to weight ratio or in applications where extreme chemical resistance is needed. In civil engineering the cost of a project is often the deciding factor and thus traditional materials such as concrete, steel and timber have seen more usage. In Europe today, FRPs are no longer viewed as novel materials and are regularly used in bridge projects where the high strength to weight ratio is particularly important (Ascione et al, 2016). An FRP bridge is prefabricated in a factory and due to its low weight, it can be transported easily to the construction site and be assembled in a very short time. For example the *Kolding bridge* in Denmark was assembled on site over a railway in only 18 hours.

Most of the wildlife bridges built in Sweden today are built almost exclusively out of concrete. This is possibly due to a long standing tradition of concrete road bridges and consequently a lot of experience in this field. However, in the future new wildlife bridges will have to be built over already existing roads and there is a request to keep the roads in operation during construction. This means that a great amount of effort needs to be placed on the logistics and planning of the project to not interfere with road operations and extra care must be taken to ensure the safety of motorists. With FRP materials the construction time on-site can be kept to a minimum which reduces the time in which the traffic on the road is disrupted. Furthermore FRP materials superior degradation resistance could make them more economically viable in projects such as viaducts or wild life crossings where the life of the bridge often is expected to have a very long service life. The Swedish Transport Administration will in the future make significant investments in shaping the infrastructure into the landscape and prevent fragmentation of nature. FRP which makes use of off-site manufacturing and on-site assembly can thus simplify and make substantial savings to projects.

1.2 Aims and Objectives

The aim of this study was to investigate the feasibility of using FRP as a material for eco-bridges. To achieve this the following two objectives were determined:

- Redesign the Sandsjöbacka eco-bridge in FRP using *Prospect for New Guidance in the Design of FRP*.
- Compare the new design with Sandsjöbacka eco-bridge by the means of an LCC analysis.

1.3 Method

Firstly a literature study was performed. This study focused on collecting information about eco-bridges in general and the Sandsjöbacka eco-bridge in particular. Another reason was to gather knowledge about how FRP behaves and how it is typically produced and used in structural engineering.

Two different FRP alternatives were designed. Namely GFRP and CFRP. This was done by first conceiving an initial design where different structural systems where considered. Then a detailed design was carried out using hand calculations and following the design code *Prospect for New Guidance in the Design of FRP* and FEM analysis using the FE-program Abaqus.

Finally a life cycle cost analysis was performed on the Sandsjöbacka eco-bridge and the two FRP alternatives and a comparison between the alternatives was done to investigate the economic viability of the FRP eco-bridge options.

1.4 Limitations

There are several types of wild life crossings but this study will only focus on eco-bridges. The study will focus on the structural part of the design. No design of the flora on top of the eco-bridge has been done and aesthetic concerns have been disregarded. No detailed design has been made on the supports for the eco-bridges. The design code used is limited to *Prospect for New Guidance in the Design of FRP*. Furthermore, in the life cycle cost analysis, environmental and ethical issues will not be included.

2 Literature Study

2.1 Eco-bridges

The Swedish Transport Administration differentiates between an eco-bridge and the more general term fauna bridge. A fauna bridge can be any bridge with the intention of letting wildlife pass over larger roads. They are often combined with smaller roads intended for lighter traffic or walking trails for humans that sojourn in nature. However, the efficiency of fauna bridges is directly related to the amount of adaptation towards animals. All human activity discourage animals from using the bridge and therefore reduces the efficiency while planting bushes and grass increases the efficiency. There are examples of fauna bridges that range from being 'fauna adapted' by placing gravel next to a road, to bridges with just a small service road and heavy vegetation. All with different degrees of efficiency.

A more strict way of creating a fauna bridge is to build an eco-bridge, which seeks to mimic the surrounding nature as good as possible. To accomplish this the bridge must not seem foreign and all vegetation used to dress it up should come from the local flora. It must be isolated from the road it crosses meaning that an eco-bridge should have a robust barrier that protects animals from sound and light that is present on the road. In the document *Vägar och gators utformning* the Swedish transport administration recommends a minimum width of the crossing of 30 m to not discourage shyer animals from using the bridge.

In Sweden there are today only a few eco-bridges (Trafikverket, 2017). However, the first eco-bridge was built in France already in 1950 and a lot more has been built since. Examples of other countries that have a lot of eco-bridges are Norway, Germany and the Netherlands.

2.1.1 Eco-bridge E6 at Sandsjöbacka

Just south of Gothenburg is Sandsjöbacka nature preservation area. The international road E6 cuts through this area creating a significant barrier effect and divides the preserve into two parts. On this background the Swedish Transport Administration decided to build several wildlife crossings to reduce the fragmentation. The total cost for the eco-bridge at Sandsjöbacka was 80 million SEK in which the Swedish Transport Administration has payed PEAB 57.4 million SEK to construct the eco-bridge. This eco-bridge is the first of its kind in Sweden as it is intended for the full fauna. In figure 2.1 the eco-bridge can be seen.

img/sandsjobacka_eco-bridge.jpg

Figure 2.1: Sandsjöbacka eco-bridge.

The eco-bridge is a prestressed cast in situ concrete structure and was designed for a service life of 120 years. It is built in two spans of 27 meters each to make room for a possible expansion of the road from four lanes into six lanes. The total length of the eco-bridge is 64 meters and the width is 32 meters. On the site of the east support for the bridge there is a layer of clay of 11-13 meters and on the site for the middle support there is a layer of 5-7 meters of clay. At both these sites the bridge rests on piles. At the site for the west support, the layer of clay is only 1-1.5 meters and the support thus rests on the ground without the need for piling. The bridge deck is built as four T-sections that are supported by four columns at the middle support. The construction of the bridge has taken place while the road has been in operation and great care have been taken to ensure the safety of workers and motorist and that it should not interfere with societal functions that are dependent on the road such as emergency responses from police or ambulance. As a result, 600 m of E6 has had its speed reduced from 100 km/h to 70 km/h for the greater part of the construction phase.

A concept with a bridge having three spans where considered but discarded due to demanding big side structures that might prevent a future expansion of the road into three lanes. A number of different designs where also considered such as steel and timber bridges. These were discarded due to not living up to the demand of having a technical life of 120 years. Furthermore was the solution to build a prefabricated concrete bridge discarded as that demanded too much space for cranes and equipment which would make too big of an intrusion into the natural preserve during construction.

On the 26th of January 2017 during work with casting of the concrete, cracking sounds were heard and it was observed that unintended deformations on the supporting structure for the casting frame had occurred (Swedish transport administration, 2017). The work was immediately stopped and the decision was made to close E6 in case of a collapse of the structure to prevent accidents and injuries. The road was closed for approximately 27 hours during which the traffic had to be rerouted. In the official report *Översiktlig analys av formställningsdeformation 2017-01-27* it is concluded that the horizontal loads coming from the fresh concrete during casting had been underestimated. This led to the unacceptable deformations of the support structure and the appearance of a crack propagating from a roadside support. The consequences of this accident was that parts of the bridge had to be demolished and rebuilt. This increased the overall cost of the project and took additional time. The incident is also viewed negatively in the eyes of the public which can result in a lowered trust of the participants of the project.

2.2 Fibre Reinforced Polymers (FRP)

A composite material is often defined as a combination of two or more different materials that each retains its original form and properties and together forms a new material with better properties (Zoghi, 2014). FRP is a composition of a high strength material such as glass fibre or carbon fibre that is bound together by a polymer matrix material such as a thermoplastic or a thermoset. The fibres carry the load and the matrix provides dimensional stability. For this to work it is important that the ultimate strain of the fibres is much lower than that of the matrix while the stiffness of the fibres is higher than the matrix. Furthermore, it may contain fillers to make the composite less expensive and additives to increase certain properties such as thermal and electrical conductance or to fire proof the material.

2.2.1 Reinforcement

The reinforcement stands for 30-70 % of the volume of the FRP and the choice of reinforcement has therefore a large impact of the properties of the final product (Zoghi, 2014). The percentage of fibres in the composite is called *the fiber volume fraction* and it it the single most important factor that affects the properties of the final composite. The fibres function are to give FRP a high tensile strength and stiffness.

According to *Prospects for new guidance in the design of FRP* (PGD), the different fibres that are used today in civil engineering application are mainly glass fibres and carbon fibres even though there are several other, less used fibres in the market for example aramid fibres. Depending on which fibre is chosen and in which directions they are laid, it is possible to achieve different properties to best fit the purpose (Zoghi, 2014). Fibres can be placed in unidirectional, bidirectional or multidirectional orientation. An illustration of this can be seen in figure 2.2 Continuous fibres are usually arranged in a unidirectional orientation which gives the product a higher overall fibre direction strength but at the cost of a lowered strength in other directions (Mallick, 2007). Woven fabrics have a bidirectional orientation while braided fabrics a multidirectional orientation. With multidirectional fibre placement it is possible to achieve an isotropic composite material.

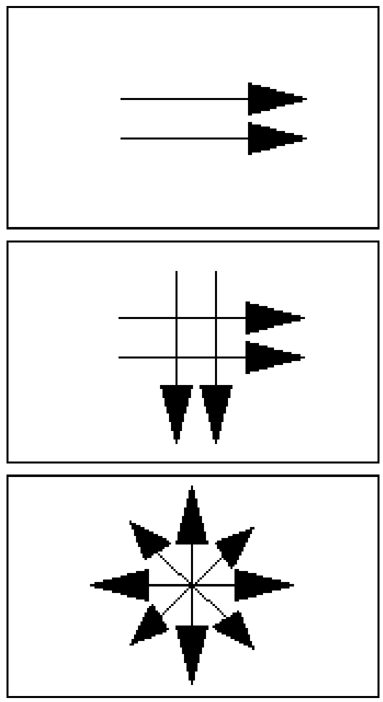


Figure 2.2: Schematic drawing of fibre layouts. Unidirectional first, bidirectional second and multidirectional last.

2.2.1.1 Glass fibres

Glass fibre is the most common of the reinforcements (Zoghi, 2014). The main advantage of glass fibre is that it is cheaper than other alternatives while the disadvantages are that it has lower strength and stiffness, a higher density and a lower fatigue strength and resistance to abrasion which means that it needs protective coating. The most common glass fiber is E-glass due to its low cost, but there are several different types of glass fibres with other enhanced properties (Mallick, 2007). Some examples are C-glass, which has better corrosion resistance or S-glass and R-glass, which have better strength and stiffness. In table 2.1, some selected material properties for E-glass and R-glass are presented.

Table 2.1: Properties of glass fibres (Ascione, L. et al, 2016, s.146).

Properties	E-Glass	R-glass
Density [kg/m^3]	2570	2520
Young's modulus [GPa]	73.1	86.0
Tensile strength [MPa]	2750	3450
Tensile Strain limit [%]	3.8	4.0
Compressive strength [MPa]	1750	2000
Compressive Strain limit [%]	2.4	2.4
Thermal expansion [10^{-6}/°C]	5.0	3.0

2.2.1.2 Carbon fibres

Carbon fibre is a high-performance fibre with high strength and stiffness in regard to its weight (Mallick, 2007). The use of carbon fibre is widespread in the production of sports equipment and leisure boats but during the last decades carbon fibres has become more common in civil engineering (Zoghi, 2014). The major disadvantage of carbon fibre is the expense and the energy consumption during production. It also has a low strain limit and lower impact resistance (Mallick, 2007). The different types of carbon fibre used are high strength fibre, intermediate modulus fibre and high modulus fibre. In table 2.2, the material properties for the three different types of carbon fibres are presented.

Table 2.2: Properties of carbon fibres. HS-high strength, IM-intermediate modulus, HM-high modulus (Ascione, L. et al, 2016, s.146).

Properties	HS Carbon	IM Carbon	HM Carbon
Density [kg/m^3]	1790	1750	1880
Young's modulus [GPa]	238	350	410
Tensile strength [MPa]	3600	4500	4700
Tensile Strain Limit [%]	1.5	1.3	0.6
Compressive strength [MPa]	2140	2100	1850
Compressive strain limit [%]	0.9	0.6	0.45
Thermal expansion [10^{-6}/°C]	-0.4	-0.6	-0.5

2.2.2 Matrix

Matrix materials for FRP can be divided into two categories. Thermoplastics and thermosets. The matrix component's main purpose is to provide the FRP with compressive and shear strength (Zoghi, 2014). It should also give the material dimensional stability, protect the fibres from the surrounding environment and redistribute load to these.

2.2.2.1 Thermosets

The most used type of matrix polymer for FRP materials in civil engineering applications are thermoset polymers (Zoghi, 2014). During production, a resin is mixed with a catalyst causing an exothermic process. As the material sets polymer chains are formed with strong bonds in between them, so called cross linking. A schematic drawing of how this cross-linking looks can be seen in figure 2.3. This cross linking gives the thermosets strong material properties and a resistance to chemical degradation. The manufacturing process is irreversible and once a chain is formed it cannot be remoulded giving a thermoset limited recyclability.

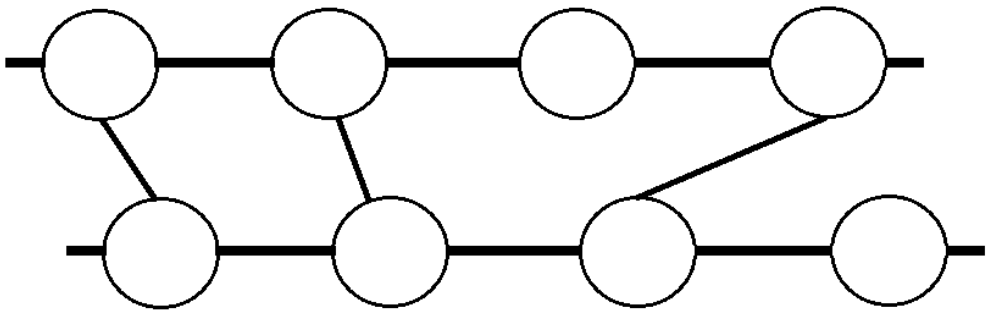


Figure 2.3: Schematic drawing of two polymer chains with strong cross-linked bonds that form a thermoset.

The properties of thermoset polymers are dependent on the service temperature and time (Zoghi, 2014). Thermosets have a viscoelastic behaviour when exposed to stress and the result of this is significant creep. These effects are increased with temperature. When temperatures are increased further and approach the glass transition temperature, a thermoset rapidly losses stiffness and strength as it transitions from a stiff dimensionally stable phase into a soft elastic phase. Most thermosets have a glass transition temperature between 65°C and 150°C. However, the service temperature of a structural element in civil engineering seldom fall outside the temperature range of -40°C to 40°C and thus this is often not a problem (Ascione et al, 2016). Despite this, adequate care must be taken if the service temperature regularly exceeds this range and measures must be taken to prevent strength loss in case of a fire.

Some common thermosets used in structural engineering are polyester, vinylester and epoxy (Ascione et al, 2016). The material properties of all polymers are highly dependent on the manufacturing process but generally epoxy is the stronger of the three. However, epoxy is also susceptible to UV-light and it must be protected from direct sun exposure (Chlosta, 2012).

In table 2.3 some material properties for three types of thermoset matrix materials in PGD are shown. The values are only indicative as the actual values of thermosets are heavily dependent on the manufacturing process.

Table 2.3: Thermoset material properties (Ascione et al, 2016).

Properties	Polyester	Vinylester	Epoxy
Density [kg/m^3]	1200	1100	1250
Young's modulus [GPa]	3.55	3.35	3.10
Tensile & compressive strength [Mpa]	55	75	75
Tensile & compressive strain limit [%]	1.8	2.2	2.5
In-plane shear modulus [MPa]	1350	1400	1500
Shear strength [Mpa]	50	65	80
Shear strain limit [%]	3.8	3.7	5
Thermal expansion [10^{-6}/°C]	50-120	50-75	45-65
Poisson's ratio [-]	0.38	0.26	0.39

2.2.2.2 Thermoplastics

The polymer chains of thermoplastic materials are formed by letting a resin cool in a mould of desired shape (Zoghi, 2014). When reheated the polymers loose its solid form and reenters a state of fluidity without destroying the chains. In figure 2.4 a schematic drawing of thermoplastic polymer chains can be seen. This gives thermoplastics an ability to be recycled that thermosets lack. Thermoplastic materials generally have a lower mechanical strength than thermosets and the use is thus less widespread. However, the service temperature of thermoplastic polymers can be as high as 130°C (Uddin, 2013). Thermoplastic materials also have a much higher ability for deformation resulting in a better impact response and fatigue strength. Furthermore it shows the same viscoelastic tendencies as thermosets but experiences lower creep. Common thermoplastic matrix materials are polypropylene, nylon or polyamide.

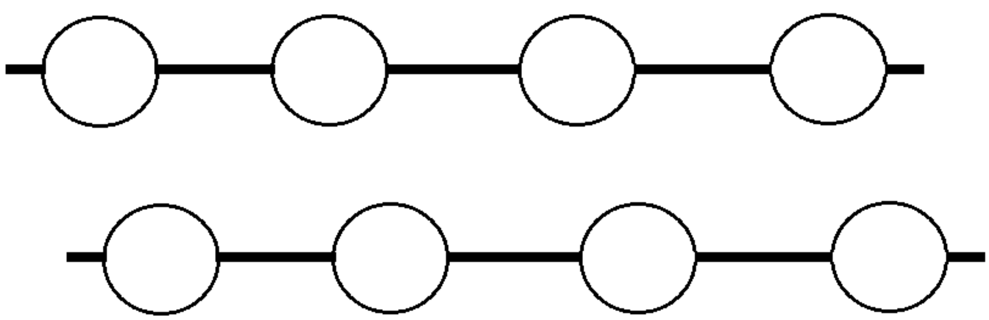


Figure 2.4: Schematic drawing of two polymer chains without cross linked bonds that form a thermoplastic.

2.2.3 Production of FRP elements

The production method of an FRP element has a big impact on the resulting quality and performance. It is therefore important that the manufacturing of FRP elements is both reliable and cost efficient (Mallick, 2007). There are many different manufacturing processes and in this section some of the most commonly used are presented.

2.2.3.1 Hand lay-up

A simple method is the hand lay-up method. First a mould is built which is shaped after the final element (Zoghi, 2014). This mould can be made out of a variety of materials. This is then treated with a release agent to make sure that the element come off without adhering to the mould. After these preparations are done the work on the element can start. Reinforcement fibres are impregnated with resin and placed layer by layer in the mould until the element have reached the desired dimensions. The element is then left to cure.

This method is done by hand and is straight forward and simple. The investment cost is also very low. However, the process takes time and requires manual labour throughout the entire production, which can be expensive, it is therefore not suitable for mass production.

2.2.3.2 Pultrusion

The pultrusion method is a fully automated process for creating long FRP elements such as rods or beams (Mallick, 2007). It begins with fibres being pulled off reels through a bath of resin where they are impregnated. Afterwards they are pulled into a die where the element is shaped and cured. When the element is fully solid it is cut off by a saw.

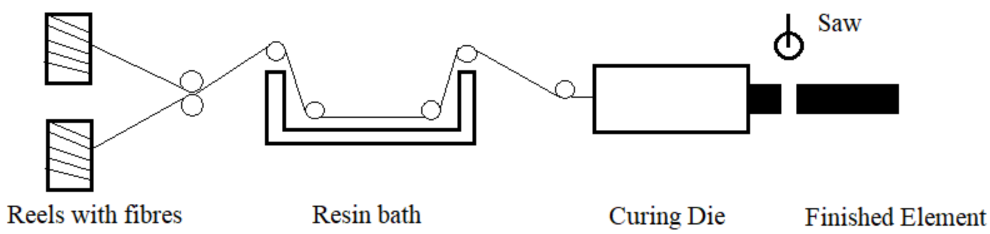


Figure 2.5: Schematic drawing of a simple pultrusion manufacturing process.

This method is suitable for mass production as it reliably produces elements of same properties in large quantities with minimal material waste (Zoghi, 2014). Different variations of this method exists, for example the curing of the element can be done both outside or inside a die. If done outside it relies on the room temperature to cure or if done inside a die, different cooling or heating equipment can be used to further detail where and when curing should occur. Another variation could be that some processes apply a surface layer around the element to give it a smooth finish. The shaping and curing can also be done in separate chambers. Elements made by this process can have any type of fibre and thermosetting matrix material. However, the resin used should have low viscosity and cure fast and it is therefore most suitable for polyester and vinylester. Epoxy is also used but has a tendency to stick to the die making extraction more difficult and cures slower resulting in a lower manufacturing rate.

2.2.3.3 Resin Transfer Moulding (RTM)

The RTM method allows for production of more complex elements than the pultrusion method. Two forms are built, one male and one female, to the shape of the final element. In between the two moulds dry reinforcement is placed and the mould is closed. The resin is then pumped into the mould and the element is left to cure.

There is a great degree of freedom of what type of element shape can be produced. However, the mould must be designed in a way that allows the resin to completely and evenly fill all empty spaces while simultaneously completely impregnate the fibres without disturbing their layout. Entrapped air must also have a way to exit the mould and space should be made for vents in the top of the mould. As this is a fully enclosed process the air quality for workers are much better than for processes with an open mould. The resulting finish of the element is also good and even, but the strength of the element is somewhat lower than can be achieved with the pultrusion method.

2.2.3.4 Vacuum Infusion Process (VIP)

The vacuum infusion process, VIP, is another closed mould process (Zoghi, 2014). It works similar to the RTM except the resin enters the preform with help of the atmospheric pressure. Dry material is placed on the mould and a thin plastic sheet is placed upon the material and sealed around the edges. The air is drawn out of the form, creating a vacuum, which makes the resin enter the mould. A schematic figure of the production method can be seen in figure 2.6. This results in minimal use of resin were high fibre contents can be achieved. This process is cleaner and has a quick start-up time compared to other mould processes. A disadvantage is that it is more complicated to set up than many other processes, with tubes both for vacuum and resin that should be correctly inserted. It is also a risk of getting small air leakages where air can get into the closed form and ruin the process.

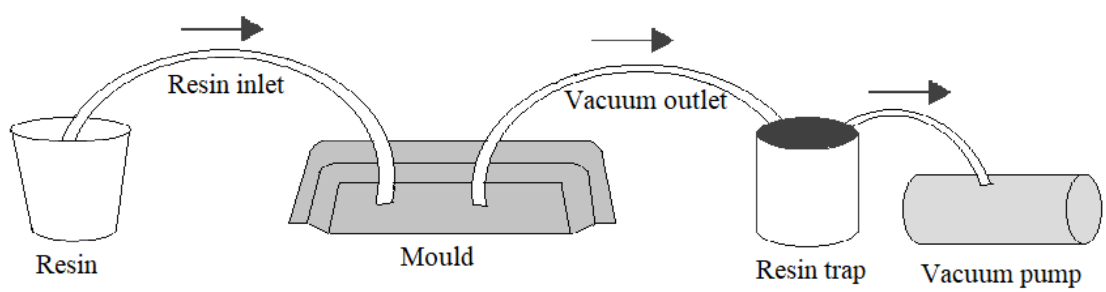


Figure 2.6: Schematic drawing of a vacuum infusion process.

2.2.4 Assembly

One of the reasons FRP is chosen as material for a new structure is the rapid assembly on site (Zoghi, 2014). The structural elements are prefabricated and can then, because of its light weight, be lifted with a smaller crane or with a helicopter. The different parts are then coupled with adhesion or bolts. These solutions are therefore good to use in bridges over highways and railways where it is difficult to close the road or railway below when erecting the bridge. There are several examples of bridges that has been assembled in only a few hours. For example, the Kolding bridge in Denmark was assembled in 18 hours (Fiberline). Further information about this bridge can be found in section 2.11. Another example is the footbridge Lleida bridge in Spain, which was lifted into place over a railway with a crane in only 3 hours (Zoghi, 2014). Because of its light weight and the easiness of lifting it in place it is possible to remove the bridge when needed after construction. One example of this is the Pontresina Bridge in Switzerland, which is lifted out each spring when the floodwater appears to protect the bridge from being damaged by the water.

2.2.5 Durability

One of the advantages with FRP is its durability (Zoghi, 2014). It has a much lower corrosion rate than for example steel and the general deterioration rate is usually very low. It also has a strong chemical resistance and has been used extensively as a material for tanks and pipes in direct contact with concentrated chemicals (Samuelsson, 2015). However, there is not an infinite durability and it is important to know what affects FRP and how it impacts the mechanical response of the structure.

2.2.5.1 Effects of temperature

An important parameter for temperature dependant effects in polymer materials is the glass transition temperature T_g of the matrix material as talked about in 2.2.2 (Zoghi, 2014). At this temperature, that can be as low as 60°C, the polymer loses its stiffness and turns into a rubber like material. The two phases are not discrete meaning a gradual transition occurs and mechanical properties can thus start to deteriorate below this point as the temperature approaches it. In more elevated temperatures during long time, there can be chemical changes in the FRP which affects the structural properties (Zaman et al, 2013). If the FRP is exposed to moderate temperatures, it suffers from higher risk of moisture problems because the diffusion in the material increases. In case of very high temperatures, for example fire, there is risk of collapse. Another problem could be with cyclic temperatures, when the temperatures goes from warm to cold in a short time. This could lead to residual stresses and create small cracks which the moisture could go into. There are numerous experiments done on the durability of FRP and many point to the fact that degradation over time becomes bigger with an increase in temperature (Heshmati, Haghani, Al-Emrani, 2017; Kumar Makineni, Sharma, Chandra Ray, 2007; Chen, Davalos, Ray, Kim, 2005). However, most civil engineering applications fall within the range of -40°C and 40°C and in this interval linear elastic material responses can be assumed (Ascione et al, 2016).

2.2.5.2 Moisture resistance

Polymer materials are permeable and allows for diffusion of liquids and gases. In a an experiment performed on FRP to steel adhesive joints at Chalmers University of Technology (Heshmati, Haghani, Al-Emrani, 2017), severe reduction in strength of FRPs can bee seen when exposed to moisture. It was shown that carbon fibre reinforced epoxy can lose up to 60% of its strength in prolonged exposure to salt water at a temperature of 45°C and 25% in prolonged exposure to salt water at 20°C. The corresponding loses of strength for distilled water where 50% at 45°C and 15% at 20°C. For a glass fibre reinforced polymer a strength loss of 50% where observed at 45°C and 20-30% at 20°C. It is concluded in the report that the drastic loss of strength in CFRP is due to degradation of the matrix resin moving the failure mode from fibre failure to resin failure. Glass fibres where shown to degrade along with the resin.

In a report from 2015, Energiforsk AB presents moisture damages done on GFRP tanks and pipes. This report gives examples of blistering on the surface of GFRPs caused by penetration of moisture. This poses no risk for tanks so long as a protective outer coating of resin is used to prevent the moisture from degrading the resin and glass fibres deeper down in the material. Such blistering is expected to occur at places where regular temperature changes are present.

2.2.5.3 Chemical resistance

Most resins and fibres used in civil engineering have a relatively good chemical resistance (Bengtsson, Magnusson, 2016). However, they are still susceptible and concentrated chemicals can cause damage. In combination with moisture absorption, acids can penetrate the material and start a deterioration process. This makes acid degradation a problem in marine environments and constructions that are in direct contact with soil. Acids that penetrate the material can cause debonding which eliminate the composite action between fibres and matrix. This is a severe problem as it nullifies the purpose of the material. In an experiment performed at the National Institute of Technology in India on Acidic degradation of FRP composites, it was found that the inter laminar shear strength (ILSS) of a glass fibre epoxy composite was reduced by 29-30% when exposed to a 40% HCL solution for 7 days. When exposed to 5% HCL solution for 7 days the loss of ILSS was 16-18%.

FRP composites are also vulnerable to alkali environments (Zoghi, 2014). One very common alkaline environment found in civil engineering is concrete and FRP structures can be affected even if they are in different parts of the construction through the movement of concrete contaminated water. Glass fibres are especially susceptible to alkali attacks and similar degradation on the resin can be seen as from acid attacks. In an experiment performed by West Virginia University and Korea Institute of Construction Technology (Chen, Davalos, Ray, Kim, 2005), GFRP and CFRP composites where exposed to different alkaline environments designed to mimic longtime exposure of field conditions for reinforcement bars in concrete. In tensile tests, the GFRP composites experienced a reduction of up to 50% while the CFRP composite had a loss of only 4%. Tests to determine the ILSS was also conducted and it was found that GFRP composites could lose of up to 12% of the strength when exposed to alkaline environment.

2.2.5.4 UV sensitivity

FRP exposed to UV-radiation may lead to degradation of the product, but only in the top surface of the material (Chlosta, 2012). Therefore, it is mainly an aesthetic problem, with discolouring of the material but it can lead to stress concentrations at the affected areas. It may also, in combination with other degradation processes create more severe problems. According to Chlosta, one degrading effect that can cause problem is when moisture affect an area which earlier has been exposed and degraded by UV-light. There are several ways to make the material more resistant to UV-radiation (Industrial Fiberglass Specialties, Inc., 2008). The most important design choice in this matter is which type of resin is used in the FRP. For example, there are polyesters which have the advantage over other types of resins that it has a resistance to UV-radiation far better than the alternatives. A few other hybrids has as well shown improved UV-resistance. There are also additives that can be mixed in with the matrix that improve the UV-resistance. Another solution is to cover the surface, either with a synthetic veil or with a coating. The solution using coating is the easiest, but also the most expensive.

2.2.5.5 Creep

While most fibre reinforcements are resistant to creep, the matrix resins are not (Clarke, 1996). Due to the viscoelastic mechanical behaviour of thermosettings, significant creep deformations can occur in pure thermosetting materials. The best creep resistance is gained by having a high amount of continuous unidirectional fibres in the composite. Bidirectional fibre placement have a lower creep resistance due to having a lower proportion of fibres in the main load direction. The worst creep resistance is offered by short noncontinuous multidirectional fibre placement. This is also showed in an experiment on the creep behaviour on GFRP elements performed at the University of Salerno (Ascione, Paolo Berardi, D'Aponte, 2016). Unidirectional pultruded GFRP elements where loaded over a period of 40 days and showed an increase of deformation due to creep of less than 2%. Simultaneously, pure resin elements showed an increase in deformation over time of up to 271%.

2.2.5.6 Fire

Most of the resins used in FRP composites are flammable (Chlosta, 2012). Already at $100°C$, creep and deformation of the material starts which can lead to buckling or even failure of the structure. When the temperature reaches $300°C$ the material emits smoke, toxic particles and soot into the air which makes it a health hazardous environment for the firefighters and other persons in the vicinity. Actions therefore need to be taken to guarantee the safety in case of fire.

The fibres are less flammable than the resins (Chlosta, 2012). Glass fibres are practically unaffected by fire and performs the best of the common fibres in fire and has a melting point at $1070°C$. Before that temperature is reached some softening of the fibres has occurred and the mechanical properties has been affected. Carbon fibres oxidate at a temperature of $350°C$ to $450°C$, which entails health hazard.

To protect the material against fire there are some different approaches (Chlosta, 2012). One very common way is to add flame retardant to the resin. These can be divided into two groups, those who operate in the condensed phase and those that operate in the gas phase. Flame retardant that operates in the condensed phase disrupts the decomposition of the material while the flame retardant for the gas phase disrupts the combustion in the flame. The optimal is flame retardant which operates in both phases. According to Zoghi (2014), the flame retardant additives could change the physical and mechanical properties of the material and should therefore be used with caution. Another common way to protect the structure without risking changing the properties is protective surface coatings. These coatings could be polymer coatings that work as a flame retardant, intumescent coatings which swells when it is exposed to fire or a thermal barrier (Chlosta, 2012). Important properties of the coatings are that it should be non-flammable and have the same thermal expansion as the material it is adhered to. It should also be thin, light-weight and preferably cheap. There is also according to Fiberline a resin called phenol which by itself has superior flame retardant and fire resistant properties compared to the other resin types (Fiberline, 2002).

2.2.6 Environmental impact

The environmental impact of FRP bridges can be lower than a bridge made out of traditional materials. In a paper published by the Ministry of Transport in the Netherlands written by Ryszard Daniel, an analysis is made on the environmental impact of a bridge regarding the choice of material. The conclusion of the paper is that building an FRP bridge proves advantageous from an environmental aspect if the entire service life is regarded and not just the production of the bridge.

2.2.6.1 Carbon emissions

An easy way to measure the environmental impact of a structure is to look at the carbon dioxide equivalent emissions. In the paper *Bridge Decks of Fibre Reinforced Polymer (FRP): A sustainable solution* the authors Mara, Haghani and Harryson analyses the task of changing a used up bridge deck on an existing bridge with either a new concrete deck or a new FRP deck. The conclusion is that a deck replacement with an FRP solution produces 20% less carbon emissions than a prefabricated concrete deck. It is further concluded that the difference in produced carbon emissions increases as the average daily traffic on the road increases. This is due to the short construction time of an FRP deck which leads to a shorter time in which the traffic must be rerouted.

2.2.6.2 Waste management and recycling

One important aspect when investigating the environmental impact is the waste management (Halliwell, 2006). Almost all disposal of FRP was earlier as landfill or incineration, but because of regulations from European Commission implemented in 2004 limiting landfill and incineration, other ways of disposal has been more and more used but landfill and incineration are still the most common ways of disposal today.

The absolute best way from an environmental view is to re-use the product, but this may not be an option because of other aspects, such as practicality (Halliwell, 2006). It could be difficult to disassemble the structure to re-use parts, it is often more expensive to get a certificate for the part that will be re-used than producing a new one and the parts could also be degraded and thus not have as good properties as it has had before. Therefore, usually the best way to handle the expired product is to recycle it. The European Plastics Converter (EuPC), the European Composites Industry Association (EuCIA) and the European Composite Recycling Service Company (ECRC) has investigated the waste management of FRP which resulted in three technologies of waste management (EuPC, EuCIA, ECRC, 2011). These are material recycling, chemical recycling and co-processing.

Material recycling is when the material is turned into new material that in the best of cases has the same properties or, more common, to get a new material with slightly worse properties as the original (Halliwell, 2006). Glass and steel are examples of materials that has, in theory, endless recycle circuits. This is not really the case with FRP, but there are solutions that could be included in this category. Thermoplastic could be melted and cooled endless times, but has shown some degradation in this process. Thermoplastic composites could also be ground and used in the resin as a type of reinforcement to improve the properties. This solution is not economically viable compared to using virgin materials. Thermoset composites are more difficult to recycle but there are possible solutions. One way is to shred and ground the composite and use it as fillers or replacement for reinforcement, but the properties will be inferior to the prior material. As with the thermoplastics, the problem is that is more expensive than to use virgin materials. Fillers like sand or glass are less expensive, and then cost for grinding machines and extra transport is added. Sandwich structures are even more complicated to recycle, if a possibility of recycling should exist, it must be possible to separate the core from the face sheets.

Another way to dispose of the material is by chemical recycling where the material is conversed into chemicals and fuel. There are some different ways to do this. Pyrolysis is one example, where the material is separated into gas, oil, fibres and some carbon through heating the material without oxygen. The oil and the fibres could then be used in new FRP materials. As last resort, the material will go through incineration. FRP is considered to be cleaner than coal, but still leaves a lot of residue in the process. The method that the EuPC, EuCIA and ECRC recommend is the co-pressing, which is a mixture of incineration and material re-use (EuPC, EuCIA, ECRC, 2011). The resin is burnt for energy recovery and the glass fibers and fillers are used in the cement. It is assumed that approximately 70% of the material is used in the cement mixture and the rest 30% is burnt for energy. This process leaves no residue and is considered to be the most viable recycling method available on the market today. The problem being that to make it economically viable, there must be large quantities of FRP to process.

Research of ways to recycle FRP is carried out all over Europe and as the material becomes more common and regulations on waste management is getting stricter, new methods of recycling may appear and it may become more economically viable to recycle the material when there are larger quantities to dispose of.

2.2.7 Economical aspects

The economical aspect is important for all new projects, without a competitive cost the project will never be executed. This is especially important when there is a new material on the construction market and it is therefore important to show that FRP composites can have a competitive cost compared to the more traditional if it shall ever be included and used more frequently in the construction industry. There are LCC analyses that has been performed comparing FRP with other construction materials, that show that when investigating the cost of the whole life cycle, FRP is not more expensive than the traditional materials. One case study was performed by Nishizaki et al. (2006), which showed that for bridges that have a long life span and are exposed to a corrosive environment, an FRP bridge is the most efficient solution. Another study performed by Haghani and Yang (2016) shows that FRP was a more efficient choice than steel for culvert bridges when looking at the cost of the whole life cycle.

However, in the industry today it is not only the pure economical costs that matter. A project that is more expensive than other alternatives can still be executed if it can be proven to be the better alternative when looking at other aspects, such as environmental and social costs.

2.2.7.1 Price of materials

The cost of FRP mainly comes from the high price of the raw materials used in the production of FRP (Friberg, Olsson, 2014). Depending on the manufacturing process, the material cost consists of 40-90% of the total cost of the construction. A very automated process such as the pultrusion process is more cost efficient than a more labour intensive process such as hand lay up or RTM. In table 2.4 the price off FRP constituent materials are shown as reported by Haghani and Yang in *FRP Composites for Manufacturing of Culvert Bridges*.

Table 2.4: Price of FRP materials (Haghani, Yang, 2016).

Material	SEK/kg
Glass fibres	25
Carbon fibres	250
Polyester	20
Vinylester	60
Epoxy	100

2.2.7.2 Industrialization of bridge construction

In the thesis *Industrial Bridge Engineering, Structural developments for more efficient bridge construction* the author Peter Harryson recognizes the lack of efficiency and need for industrialization in the Swedish construction market. Harryson notes that that the main advantage to be gained from an industrialized bridge construction process would be to minimize the amount of waste produced. He also notes advantages such as a lowered cost, lowered construction time and increased quality.

FRP materials are often considered as expensive compared to traditional materials (Friberg, Olsson, 2014). However, as mentioned in chapter 2.2.3 *Production of FRP elements*, the manufacturing process of FRP structures are prefabrication in factories and then assembling on site as mentioned in chapter 2.2.4 *Assembly*.

Most usage of FRP in civil engineering practices regarding infrastructure and bridges have been heavily reliant on manufacturing methods that demands a high degree of manual labour. An EU funded project called TRANS-ind coordinated by Mostostal Warszawa SA was carried out during the years 2009 and 2013. The main objective was to develop an industrialized process for FRP elements in infrastructure projects such as bridges and thus lowering the cost of such projects. TRANS-ind was successfully completed and the result was that bridges made with FRP components can be made 10% cheaper than bridges in traditional materials.

2.2.7.3 Social costs

An eco-bridge will in many cases be built over an existing road. It is thus natural that the construction will in some way interfere with the operation of the road. When a road can not operate at its full capacity it affects other parts of society that is dependent on the road. Many connections can be hard to establish but a direct and important connection is the increased travel time for vehicles driving on the road as a result of a detour or lowered speed needed during the construction time. Mattias Nilsson identifies in the paper *Samverkansbroar ur ett samhällsekonomiskt perspektiv* five different costs for each vehicle that travels on the affected road. Costs for fuel, tire wear, reparations, general wear of the vehicle and value loss of the vehicle. Another cost identified is the user delay cost that is the cost of lost time for the increased travel time. These costs are all directly proportional to both the number of vehicles traveling on the road and the construction time which is significant in a project for an eco-bridge that crosses a motorway like E6 where a high amount of traffic is present.

2.2.8 Application of FRP in bridges

FRP composites appeared in the 1970's and has since then become more and more used in civil engineering, but it is only in the last two decades that a larger increase of FRP in civil engineering has been seen (Domone, Illston, 2010). In the beginning there was only one type of FRP, a polyester matrix with glass fibre reinforcement. Since then the material has been developed and new and improved matrices and fibres are used in the FRP used today.

FRP is also used in more and more bridges, both in new bridges and in rehabilitation of already existing bridges (Zoghi, 2014). For new projects, FRP are often not the only material used. Since it is such a light-weight material it is advantageous to use bridge decks in FRP to reduce the weight on the girders or foundation, which can be in steel or concrete. There are also some vehicular bridges that has been built which have girders of FRP with a concrete deck resting on the girders (Areiza Hurtado, 2012).

2.2.8.1 Girders

FRP girders are made in different cross sections, some examples are I-beam, U-beam and box sections (Zoghi, 2014). The girders can be produced by either of the production methods mentioned in section 2.2.3 *Production of FRP elements*, but for beams with smaller dimensions pultrusion is the most common method of production. There are several companies that mass produce smaller beams using pultrusion (Fiberline, Creative Pultrusions, Strongwell, Liberty Pultrusion), but there are also examples of larger beams that can be pultruded. *Strongwell* manufactures one type of larger beam using pultrusion which is a double web I-beam with the height of 900 mm that uses glass fiber in the web and carbon fibre in the top and bottom flanges (Strongwell). Larger beams that have been used in bridges in Europe up until now has often been produced with hand lay-up, which is explained in section 2.2.3.1 *Hand lay-up*, and the beams are customized and manufactured for the project for which they are intended to be used.

Some examples of bridges that have used larger beams like this are the Spanish bridges Asturias bridge and the bridge over M111, more information of these can be found in sections 2.2.10.2 *Asturias Bridge* and 2.2.10.3 *M111 freeway bridges* respectively and also a composite bridge by the construction company *Mostostal* in Poland (Mostostal, 2017). The bridge is a single span bridge with the span of 21 meters, which is the longest span in the world for bridges using FRP girders. FRP girders are not very common so far, mainly because of the low stiffness of the material which gives large deflections which leads to girders having excessive height, just to pass the limits of deflection (Zoghi, 2014).

2.2.8.2 Bridge Decks

FRP bridge decks mainly used today are either assembled pultruded shapes or sandwich panels. Pultruded decks are available in several different shapes (Bakis et al, 2002). The pultruded elements are produced in continuous lengths and the elements are then joined together and a top and bottom layer is added (Zoghi, 2014). This is often done by adhesion of the different parts but could as well be done with mechanical fastening or a combination of the two. The properties could vary depending on the fibre used in the FRP, the direction of the fibres and the pultrusion shape. Generally, the strength and stiffness are very high in the longitudinal direction. The transverse properties are more dependent on the geometrical shape. Trapezoidal and triangular shapes are the best at transfer the lateral forces. Smaller bridge decks are produced in different shapes and sizes for different loads and spans by several companies. One example of a bridge deck like this is the ASSET bridge deck by produced by Fiberline which is designed to carry trucks up to 60 tons. These bridge decks that are mass produced are often designed for spans of less than 10 metres. Some examples of bridge decks on the market today are presented in figure 2.7. Larger bridge decks are also possible to use for bridges but they then have to be made especially for that case and can not be produced as easy as the smaller bridge decks which makes them a more expensive alternative.

Sandwich panels offer a high structural efficiency and a low weight which have made them a good choice in for example the aerospace industry, the marine industry and the car industry where they so far have been used in greater extent than in the civil engineering industry (Bakis et al, 2002). Sandwich panels consists of outer layers, with strong and stiff properties that can handle the flexural load and a core with material that has low density and ensures composite action. The core is often a rigid foam of polyuretan or similar, or a thin-walled cellular FRP, for example a honeycomb structure. Thin webs for better structural properties can also be incorporated in the sandwich elements together with foam core. Sandwich panels are not mass produced but rather produced for the planned project which means that depending on the desired properties, different dimensions, shapes and materials can be used to achieve an optimal design.

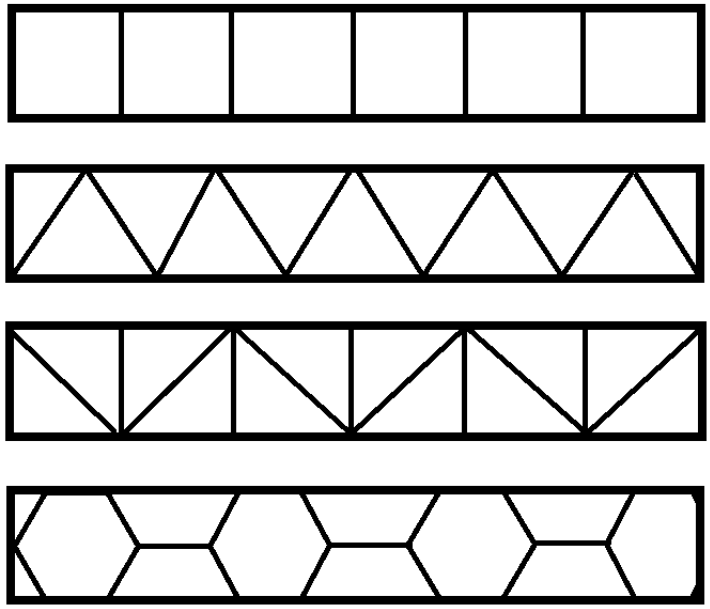


Figure 2.7: Examples of bridge decks available on the market.

2.2.8.3 Connections

The connections mainly used for FRP components are mechanically fasteners, adhesive bonding or a combination of the two (Zoghi, 2014). There are several factors affecting the choice of connection, for example service environment, lifetime of the structure, loads on the structure, geometry of the members and the option of disassembling. According to PGD, mechanical interlocking can also be used if the proper testing is done for the specific case. Figure 2.8 shows some examples of connections that can be done either with mechanical bonding, adhesive bonding or a combination.

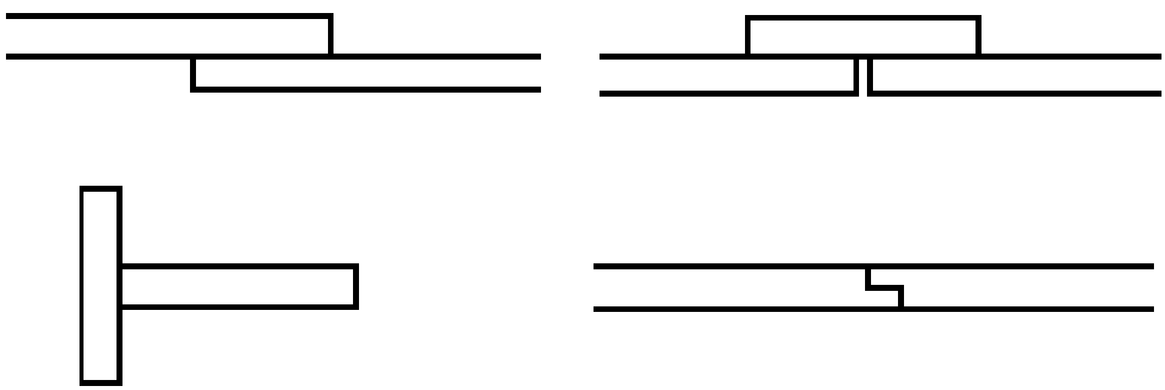


Figure 2.8: Examples of connections that can be bonded mechanically, adhesively or with a combination.

Mechanically fastened joints are most often bolts or rivets were bolts are the most common connection in civil engineering applications (Sadegh Khani, 2015). According to Sadegh Khani, bolts can be made either in steel or in FRP, but PGD only approves of steel bolts. These connections can fail either in the fastener or in the FRP material. Because of the anisotropic properties of FRP, the stress concentration can get really large around the holes. The failure in mechanical connections is not brittle, which means that the failure will not happen suddenly but rather develop during time which means that it can fixed before it is too late.

The adhesive bonded connection is the most common connection of FRP and are in general more stiff than mechanical joints (Sadegh Khani, 2015). It should be designed in such way that failure occurs in the adhesive or in the surrounding material and not in the interface (Zoghi, 2014). The adhesives could be a liquid, a paste or a film and are made of a thermoset or a thermoplastic and the properties of the connection is partly related to which type is chosen. The choice of adhesive depends on for example environmental conditions, the surrounding material, loads on the connection and cost. The adhesive connections are sensitive to environmental circumstances such as temperature and humidity (Sadegh Khani, 2015). The adhesive requires time to go through a chemical reaction after applied, it takes time for the connection to develop fully and be used for the intended cause. The adhesion bonding should be used with caution in critical structural connections, since the effect of long-term use is so far not investigated properly (Zoghi, 2014). In the guide PGD, adhesive connections of primary load bearing structures are also explicitly forbidden. Figure 2.9 shows examples of connections that can not be bolted and has to be adhesively bonded.

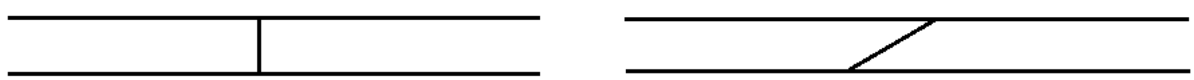


Figure 2.9: Example of connections that has to be bonded adhesively.

A combination of adhesive and mechanical bonding could also be used (Zoghi, 2014). The reasons to use a combination could be that the mechanical joints has been used to apply pressure during drying of the adhesive, that the two different methods take care of different stresses best which means that the best result will be to have both types or it could be done as an extra safety measure. Generally, it gives the connection a higher overall capacity to use a combination. In table 2.5 it is shown which properties the connection has depending on if it mechanical, bonded or a combined.

Table 2.5: Properties of the different connection categories (Clarke, 1996).

Properties	Mechanical	Bonded	Combined
Stress concentration at joint	high	medium	medium
Strength/weight ratio	low	medium	medium
Seal (water tightness)	no	yes	yes
Aesthetics (smooth joints)	bad	good	bad
Fatigue endurance	bad	good	good
Sensitive to peel loading	no	yes	no
Disassembly	possible	impossible	impossible
Inspection	easy	difficult	difficult
Tooling costs	low	high	low
Time to develop full strength	immediate	long	long

Connecting larger FRP structures is a bit different, even though the fundamentals are the same (Zoghi, 2014). It is the same three types that are used when connecting larger parts as it is when connecting smaller parts. Connecting FRP bridge panels to girders, in steel or FRP, could be done in different ways. It could be done with mechanical or adhesive connection, by letting the deck panel simply rest on the girders or to connect them with shear studs. A combination of some of these are also possible. Connecting FRP bridge decks to each other could either be done by tongue-and-groove ends, using interlocking ends, or pouring grout into the space between the decks to create a so called shear key.

2.2.9 Codes

There are today no European Standards for structural design regarding FRP since it is a relatively new material in the construction industry. There are however a few different guidelines or handbooks created during the years. One example of a handbook is the Eurocomp (Clarke, 1996), which consists of a design code part and a handbook part. Limitation with the code is that it only covers glass fibres. Another example is the dutch recommendation CUR96 (CUR, 2003), which has been revised to more resemble Eurocode. There have been requests to extend the existing European Standards to include new material, one of these being FRP. In 2016, PGD was published (Ascione et al., 2016). It is a design guide that may in the future develop into a European Standard amongst what is known as the *Eurocodes*.

2.2.10 Examples of existing FRP structures

The majority of the FRP bridges in the world are situated in the US, but there are some in Europe as well (Zoghi, 2014). The Netherlands is the country in Europe that so far has built the most FRP bridges. Most bridges of FRP are pedestrian and cycle bridges but there are also some examples of bridges for heavy traffic. In the following sections some examples of existing bridges are presented.

2.2.10.1 Aberfeldy Footbridge

Aberfeldy Footbridge is a cable-stayed pedestrian bridge spanning over a river at a golf course in Scotland (Skinner, 2009), see figure 2.10. According to Skinner, the Aberfeldy Footbridge was the first ever bridge built entirely of FRP when it was erected in 1992 and it is still today one of the FRP bridges with the longest span, the middle span is 64 meters.

The deck and the parapets are pultruded FRP sections (Composites UK, 2015). The FRP consists of polyester resin with fibres of E-glass. The cables are made of aramid fibres and are covered with a low density polyethylene. The only part of the bridge not made of FRP material are the connections, which are made of aluminium.

Figure 2.10: Aberfeldy Footbridge. Robert Cortright, Bridge Ink.

The erection could be performed without any cranes because of it being such a light-weight structure (Skinner, 2009). It was enough with a winch and a fork lift to erect the pylons. The cables were connected and cross beams for the bridge deck were then attached to these. The bridge deck was then hauled from one side of the river to the other, lowered onto the crossbeams and secured.

Another advantage of choosing a light-weight material for this bridge was that not much strengthening was required in the foundation, something that lowered the total cost of the project (Skinner, 2009). A problem with the bridge was the vibrations because of its light weight, relatively long span and slender structure. The problem was partly solved by adding concrete to increase the dead weight. There were also some experiments on the bridge with frictional joints to try and reduce the vibrations, but to no success. The problem was never really solved, but it was concluded that even though the bridge is prone to vibrate, it is acceptable since it is a pedestrian bridge.

During the life time of the bridge it has barely had any maintenance, according to Composites UK. The bridge has been strengthened in some places due to a change of the loads acting on the bridge. Some parts may have to be substituted in a foreseeable futures because there has been signs of weathering of the polymer which exposes the fibres. Due to lack of maintenance, mould and algae growth has developed which affects the aesthetics of the bridge.

2.2.10.2 Asturias Bridge

In 2002, the first FRP bridge for vehicles in Spain was built (Areiza Hurtado, 2012). The bridge is called Asturias Bridge and is made of concrete columns that carry continuous girders of carbon fibre with a total length of 46 meters, divided into four spans. The girders were manufactured using hand lay-up in a factory and then transported to the site. The whole girders were then lifted up and placed on the columns in just a couple of hours, because of its light weight.

2.2.10.3 M111 freeway bridges

The bridge over the M111 freeway near Madrid, Spain was built in 2007 (Areiza Hurtado, 2012). It has three spans, two outer spans with lengths of 10 meters and a middle span of 14 meters. Four FRP girders are simply supported on the columns which are made of concrete. The girders have an open cross section and are made out of a hybrid laminate with a mix of carbon and glass fibres to lower the cost in comparison to only using carbon fibres.

2.2.10.4 The Kolding Bridge

The Fiberline bridge in Kolding, Denmark is a pedestrian and bicycle bridge that crosses a railway (Fiberline). According to Fiberline, it was the first FRP bridge in Scandinavia when it was completed in 1997, a picture of the bridge can be seen in figure 2.11. It is a cable-stayed bridge entirely of FRP except for the bolts and some details at the supports. It has a long span of 27 meters and a shorter span of 13 meters, giving the bridge a total length of 40 meters. The width of the bridge is 3.4 meters and the height of the tower is 18.5 meters. It is designed to carry a load of 500 kg/m^2 or a vehicle of 5 tons.

Since it crosses a railway, an important reason that FRP was used was that the assembling of the bridge was very fast. It only took 18 hours in total, divided into three nights, to assemble the whole bridge. The final cost of the bridge was calculated to be around 5-10 % larger than if it would have been built in steel, but since the bridge in FRP does not require the same amount of maintenance as a steel bridge, it was argued that the life cycle cost would be smaller than the same bridge in steel (Zoghi, 2014). The expected life time is set to 100 years (Fiberline). According to

Fiberline, it should not require much maintenance. During the first half of the life time almost only aesthetic maintenance will be performed, like removing algae and graffiti, something that has been done continuously during the first 20 years.

Figure 2.11: The Fiberline Bridge. Fiberline.

2.2.10.5 Oosterwolde Lift Bridge

The lifting bridge in Oosterwolde in the Netherlands has a bridge deck entirely made of FRP (FiberCore Europe). It has a total length of 12 meters and a width of 11.2 meters and is designed to carry traffic load up to 60 ton. Figure 2.12 shows the bridge .

Figure 2.12: Oosterwolde bridge. FiberCore Europe.

3 Initial Design

The first objective of the study was to design an eco-bridge. To do this several demands on the structure were identified and concepts for main structural systems where produced. These concepts were then evaluated using an evaluation criteria matrix. In this chapter the demands on the structure and the different concepts are presented.

3.1 Design specifications

The eco-bridge have been designed primarily for wildlife but also for humans who wishes to use it as a passage across the road. No traffic is allowed on the eco-bridge. To not scare away wildlife it is important that the eco-bridge does not look like a man made structure but smells and feels like real nature. To accomplish this a layer of soil is placed on top of the bridge were vegetation can grow. This means that the eco-bridge will be in direct contact with nature which is a wet and generally degrading environment. Furthermore can the occurrence of vegetation on top of the eco-bridge potentially cause mechanical degradation of the top layer. Barriers should be placed at the edges to isolate the top from the sound and light coming from the road beneath and these should also be hidden from animals by covering them in vegetation.

3.1.1 Demands & Assumptions

The demands on this eco-bridge is the same as for the existing eco-bridge at Sandsjöbacka, which among other things entails a demand of a lifetime of 120 years. Furthermore should the eco-bridge fulfill the demands in TRVK Bro 11 (Swedish Transport Administration, 2011). This document gives an SLS deflection demand of $L/400$.

On the bridge there is 1 meter of soil mainly composed of sand which gives a load of 18 kN/m^2 on top of the eco-bridge. There is also a characteristic snow load of 1.5 kN/m^2 as stated in EN 1991. In addition to this there is also the dead load of the structure.

The bridge will rest on three concrete supports. The design of these supports are outside the scope of this project and are therefore initially assumed to be of the same dimensions as for the existing eco-bridge. If, however our design requires it there might be some changes made on the design of the supports. These supports should give two spans of 27 meters each. The free height between the eco-bridge and the road must be no less than 4.8 meters but it is assumed that the columns can be primarily used to reach this goal and thus not place any strict restraints on the deck.

3.1.2 Risk management

The main risk that can happen is the case of a collision between a vehicle and a column. The accidental load coming from the impact should be handled by the column and is thus outside the scope of the project. However, in the case of a road accident under the bridge there is a severe risk for fire. The fire risk is present due to the choice of using FRP as a material and can only be handled by the choice of main structural system to a small extent. This means that the fire risk will have to be handled by some kind of fire protection such as using fire retardant coatings or a protecting substructure regardless of choice and thus will not be incorporated in the evaluation of the structural systems, it will instead be solved afterwards.

3.2 Structural systems for the bridge

Some common structural systems that were considered where suspension bridges or cable stayed bridges. These were however discarded before the evaluation due to having big and distinctive structures visible on top of the bridge. It was believed that these structures would seem foreign to animals and thus reduce the efficiency of the wildlife bridge.

Another common structural system that was early discarded was the arch bridge system or similar systems heavily based on compression. FRP materials have a significantly higher tension strength than compression strength and using a system were the main load is carried in compression would thus be an inefficient use of material.

3.2.1 Glass fibre deck

The first system is a GFRP sandwich deck which is placed on the supports. As the width of the bridge is 32 meters it is necessary to divide the bridge deck into smaller parts and join them together. There are many designs readily available for FRP decks, some examples can be found in 2.2.8.2 *Bridge decks*. However, due to the size of the web the most practical would most likely be a straight web.

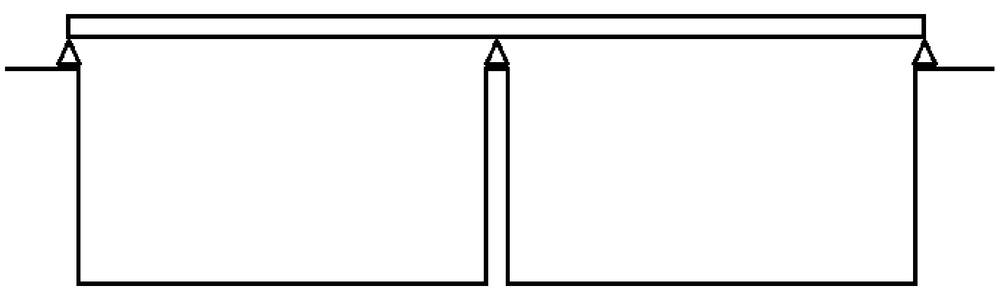


Figure 3.1: Schematic drawing of a longitudinal deck.

3.2.2 Truss system with deck

The second system is a bridge deck consisting of several smaller decks with a sandwich structure placed on top of a truss system. The truss system would consist of FRP rods and bolted connections. In critical parts of the structure carbon fibre rods could be used for stiffness while glass fibre rods could be used in the majority of the system to save money.

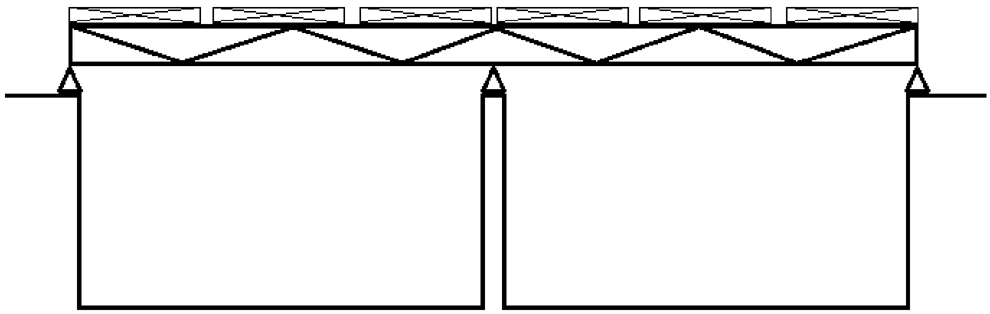


Figure 3.2: Schematic drawing of a truss system with a deck.

3.2.3 Beams with deck

The third system consists of beams placed across the road as the main load carrying elements. On these beams a bridge deck is placed consisting of several smaller plates with a sandwich structure. As the beams will have rather big dimensions either a U-section or Ω-section will be used to simplify production. Different combinations of fibres and polymers could be used. The beams could consist of a glass fibre epoxy composite and could be reinforced with carbon fibers to give extra stiffness while still being relatively cheap.

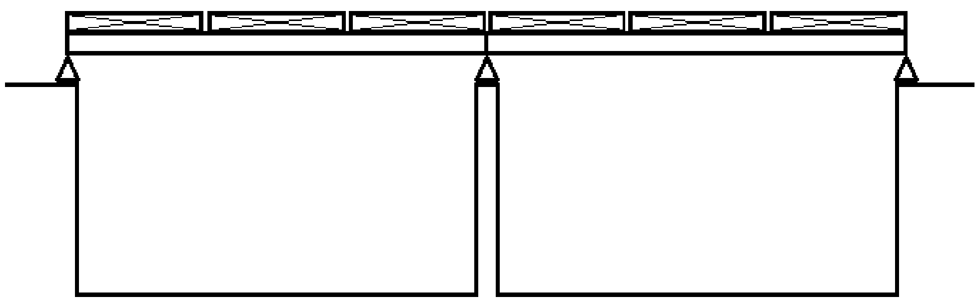


Figure 3.3: Schematic drawing of beam deck system.

3.2.4 Carbon fibre deck

The fourth system is the same as the 3.2.1 *Glass fibre deck*. In this concept however a generous use of carbon fibres could significantly lower the needed height of the deck due to its exceptional stiffness. This concept is expected to have a much higher initial cost than its GFRP counterpart but if deflections or creep rupture proves to be governing then this concept could be used.

3.2.5 Carbon fibre beams with glass fibre deck

The last system is just as the one used in 3.2.3 *Beams with deck*, but with carbon fibre beams and a glass fibre deck. This concept would also result in a higher initial cost but could be advantageous if deflections or creep rupture are important parameters.

3.3 Criteria

To choose one of the concepts to continue working with, an evaluation was performed using several criteria. These criteria was chosen to cover the subjects of cost, sustainability and constructability which are all important factors in civil engineering projects. After much consideration, 8 criteria were chosen and are presented here.

3.3.1 Transport

This criteria considers how easy the structural elements of a concept gets transported to the construction site. Small elements with regular shapes, such as straight box cross-section beams are preferred. These take up lesser space in a transport and are more flexible than big and irregular shapes such as curved beams or big quadratic plates.

3.3.2 Assembly

A shorter assembly time means a shorter interruption in the everyday life of motorists and other affected parties. It is therefore desirable to have a shorter assembly time. Concepts with fewer elements scores higher than concepts with more elements. However, the weight and size of the elements is also considered as this impacts how easily handled they are on the construction site.

3.3.3 Maintenance

This criteria includes the general maintenance of the eco-bridge as well as the ease of inspection of the different parts of the structure that needs to be checked periodically. Connections are especially critical members in this aspect and should be designed in a way to minimize the maintenance of these. Furthermore, the design of the eco-bridge should simplify the accessibility to all parts of the eco-bridge.

3.3.4 Cost

In most infrastructure projects the cost is of uttermost importance. FRP structures, especially structures heavily reliant on carbon fibres, often have a higher initial cost than structures in more traditional materials. This cost is most often payed back as the life cycle cost of FRP structures usually is lower but it is still desirable to keep it to a minimum. Concepts that minimizes the use of material and especially carbon fibre therefore ranks higher in this criteria.

3.3.5 Production

The main reasons why FRP could be a good alternative in projects like these is that it is prefabricated in a factory and only assembled in place. Therefore the production of the elements are an important criteria when choosing a design. Some shapes of elements is easier to manufacture, it is preferable if they could be produced using pultrusion rather than hand-lay or RTM. Since pultrusion is an automated process it saves time and does not require labour to the same extent as the other processes, especially hand-lay up. Pultrusion is, as mentioned in section 2.2.3.2 *Pultrusion*, suitable for mass production and is mostly used for standard elements with standard dimensions.

3.3.6 Durability

To fully utilize the inherent durability of FRP a structural concept that allows for these abilities to express themselves is needed. Therefore a good concept should minimize joints which are especially susceptible to degradation. It should also handle the effects of moisture in a good way and prevent water from reaching critical parts such as joints.

3.3.7 Risk

A good concept should handle risks such as accidental loads or fire in a good way that does not compromise the integrity of the structure. A good concept should also have a low risk of consequences stemming from unforeseen occurrences. It lies in the nature of such a risk that it is impossible to plan for it but by choosing a concept which is as simple as possible and where every part of the structure is fully understood, the chance of mitigating possible unforeseen risks is increased. A high grade in this category is therefore given to a concept which is as simple as possible while simultaneously handling known actions in a good way.

3.3.8 Environmental sustainability

Environmental sustainability is a factor that is getting increasingly important in new projects. To keep it simple, the environmental sustainability focuses on energy consumption and the emission of green house gasses. They are both seen as relatively easy to measure and a good factor to use in a comparison. The energy consumption includes the total energy consumed in the whole chain of production, from the production of the fibres and resin to the manufacturing of the elements themselves as well as the energy consumption during transportation and assembling.

3.4 Evaluation matrix

The criteria was put into an evaluation matrix, which can be seen in table 3.1. The concepts were rated using +,− and 0 were + means that it performs good in that aspect and − means that is has not so good qualities in that aspect. If the concept is neither good nor bad in that aspect it receives a 0.

Table 3.1: Evaluation matrix.

Criteria	Deck	Truss/deck	Beam/deck	CF deck	CF beam/GF deck
Transport	0	-	0	+	+
Assembly	+	0	0	+	0
Maintenance	+	-	0	+	+
Cost	0	0	0	-	-
Production	-	+	0	0	0
Durability	0	-	0	+	0
Risk	0	-	0	0	0
Environment	+	0	+	-	-

3.4.1 Deck

The criteria that a pure GFRP deck scored high in was assembly, maintenance and environmental sustainability. Glass fibres and polyester are two materials that neither produces much emissions nor requires much energy to produce and thus gained a good score in this category. The assembly is expected to be easy as there is one single structural element. This element of course must be divided into smaller parts for transport but these are expected to be easily transported and put in place due to their box shape and light weight. Furthermore does this concept minimize the amount of joints and will thus be both easier assembled and inspected than other concepts.

This concept scored badly in production mainly for the reason that most decks are constructed by the means of pultrusion due too their long shapes and closed cross sections and this might not be a viable production method for the big cross sections needed. The span of the bridge is 27 meters and a large cross sections is needed to carry the loads. If so is the case then a significant investment cost will be needed or another method will be needed for manufacturing such as VIP or RTM. It is however uncertain whether these two methods are capable of producing such large cross sections as is needed in this project.

3.4.2 FRP-Truss-deck

This concept got a high score in production. This is because a truss system consists of many smaller cross sections which without doubt could be fabricated through pultrusion and assembled in a factory into trusses. Another strength of this system that is not reflected in the matrix is the possibility of having different materials in different parts of the truss. For example could carbon fibres be used to a relatively high degree in lower parts of the truss to significantly increase the stiffness of the truss without impacting the cost of the system to much. This is a flexibility that the other concepts lack.

This concept scored very low in transport, maintenance, durability and risk. This is all because of the amounts of joints that a truss requires. Joints are places that must be regularly inspected and are weak points in the structure from a durability aspect. When there are many joints the risk of errors also increases and a truss system also needs much more careful handling during transport than solid structures.

3.4.3 Beam-deck

The beam-deck system is a kind of middle ground on the two more extreme concepts of either a deck or a truss. This is reflected in the matrix by scoring mostly zeroes. The positive thing that stands out from this evaluation is that this system scored no negative grades which means that there are no obvious flaws in the design and could thus be a valid design.

What gives this concept an edge over the deck system is the ease of production. Creating a relatively few amounts of beams with a U or omega section can be done by the help of the RTM manufacturing process. This is slower than production by pultrusion but is simpler and requires a lower investment in production equipment.

This design could just as the truss system, but to a lesser extent, be improved by using carbon fibres in critical places but to a higher cost. One problem with using both glass and carbon fibres is that the fibres have different thermal expansion coefficients which can lead to extra stress in the beam that need to be handled.

3.4.4 CF deck

Using a deck system just as the previous one but with a heavy use of carbon fibres have some advantages over a standard GFRP concept. The significant increase in stiffness means that the overall structure becomes much smaller. This eases both transport and assembly. Carbon fibres also have a somewhat better durability and thus scores higher in this category.

One drawback of this concept is the much higher usage of energy in carbon fibre production that leads to a worse climate impact. Another possible problem is the cost which might be higher than what would be acceptable.

3.4.5 CF beam/GF deck

This concept shares many of the advantages and drawbacks of the previous CF deck. It is somewhat more difficult to assemble but could possibly be cheaper due to only using carbon fibres in the beams and not in the deck. It will however come at a significantly higher cost than if all GFRP beams would have been used.

3.5 Chosen system

The truss system was deemed to require to much maintenance to still retain the selling point of FRP to be a low maintenance material and was as such ruled out. The alternatives were then the beam-deck system and the pure decks. The chosen system was the deck as it was believed to have the fastest assembly time on site and thus disturb the traffic on E6 as little as possible. Two designs was chosen to be made, one in GFRP and one in CFRP to get a comparison between the two different materials. The main problem with the eco-bridge is that the cross section of the deck will be large and thus can not the pultrusion production method be used for manufacturing. Another more labour intensive production method will be used and therefore it is good if the section is simple without any complex geometries to reduce the risk of man made errors and generally speed up the production and thus keep production costs to a minimum. Based on this the deck design was chosen to be a sandwich deck with straight webs, which arguably can be considered the simplest form of a deck cross section. This design can be seen in the schematic figure 3.4.

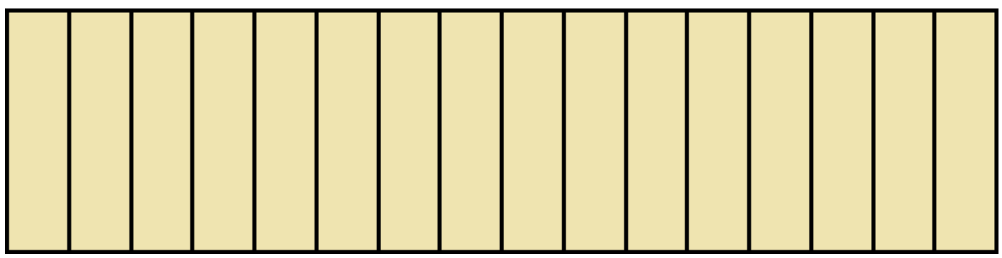


Figure 3.4: Schematic drawing of a sandwich deck cross section with straight webs.

4 Detailed design

The design of the deck was done primarily by using hand calculations supported by PGD and modelling of the deck in the commercially available FE-program Abaqus. Presented in this report are the last and final designs, however, the number of different versions of these decks are many and during the entire designing process an iterative work method has been used. It was early discovered that the deciding factor for the whole design was the deflection. It is allowed to pre-camber structures for permanent loads and thus has the main design task been to ensure that the creep deflection does not surpass the allowed limit of 68 mm while simultaneously not allowing the deck to fail due to buckling.

The figure 4.1 shows how the coordinate systems are defined. They both follow the right hand rule and have their first axis placed in the main direction. For the deck the main direction is defined as the direction of loading and for plies the main direction is the fibre direction. For global coordinates used in the deck, the letters x, y and z are used while the local axis for a ply has the numbering 1,2 and 3.

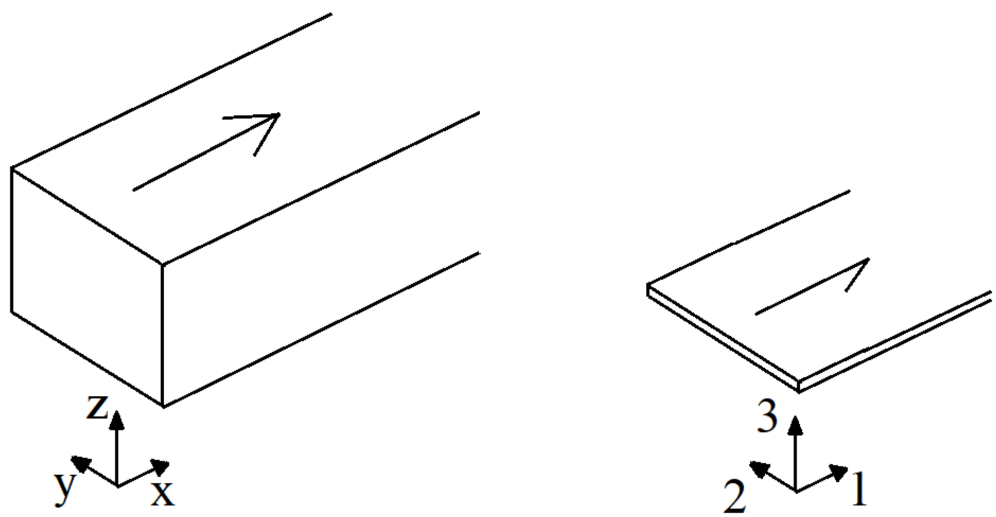


Figure 4.1: The left figure shows the definition of the global coordinate system with the main direction indicated on the deck. The left figure shows the definition of the local coordinate system for one ply with the fibre direction indicated on the ply.

4.1 Loads

Three different load combinations have been regarded in accordance with PGD and EN 1991. A ULS load combination, an SLS load combination and a quasi-permanent load combination.

The ULS combination is used for strength verification against failure due to stresses or strains but more primarily against buckling. The SLS combination is used for checks in the service state, in this case deflections. The quasi permanent load combination is used when verifying creep deflections.

The load combinations are:

$$Q_{ULS} = \gamma_g G_k + \gamma_g Q_{soil} + \psi_0 \gamma_q Q_{snow} \tag{4.1}$$

$$Q_{SLS} = G_k + Q_{soil} + \psi_0 Q_{snow} \tag{4.2}$$

$$Q_{quasi} = G_k + Q_{soil} + \psi_2 Q_{snow} \tag{4.3}$$

Where:
G_k: Self weight kN/m^2
Q_{soil}: Soil load = 18 kN/m^2
Q_{snow}: Snow load = 1.5 kN/m^2
γ_g: Partial safety factor = 1.35
γ_q: Partial safety factor = 1.5
ψ_0: Reduction factor for periodic loads = 0.6
ψ_2: Reduction factor for periodic loads = 0.1

The values of the three different loads are presented in table 4.1 were the self weight G_k is excluded.

Table 4.1: Values of different load combinations excluding the self weight G_k.

Case	Load [kN/m^2]
Q_{ULS}	25.38
Q_{SLS}	19.08
Q_{quasi}	18.18

4.2 Material properties

According to PGD an arbitrary design material property is calculated from a characteristic value as:

$$X_d = \eta_c \cdot \frac{X_k}{\gamma_M} \tag{4.4}$$

The factors γ_M and η_c are presented and discussed in section 4.3 *Partial factors* and 4.4 *Conversion factors* respectively while the formulas used to calculate the different characteristic values are presented in this section.

The stiffness properties of one FRP unidirectional (UD) ply is calculated according to 11.6.2

in PGD with the following formulas, where the index R stands for the resin and the index f stand for fibres. V_f is the fiber volume fraction.

$$E_1 = [E_R + (E_{f1} - E_R) \cdot V_f] \cdot \varphi_{UD} \tag{4.5}$$

$$E_2 = \left[\frac{(1 + \xi_2 \eta_2 V_f)}{(1 - \eta_2 V_f)} \cdot E_R\right] \cdot \varphi_{UD} \tag{4.6}$$

$$G_{12} = \left[\frac{(1 + \xi_G \eta_G V_f)}{(1 - \eta_G V_f)} \cdot G_R\right] \cdot \varphi_{UD} \tag{4.7}$$

$$\nu_{12} = \nu_R + (\nu_{f1} - \nu_R) \cdot V_f \tag{4.8}$$

where $\xi_2 = 1$ and $\xi_G = 1$. E_{f1} is Young's modulus in the longitudinal fibre direction and E_{f1} is Young's modulus in the transverse direction. $\varphi_{UD} = 0.97$ is an empirical reduction factor. Furthermore is:

$$\eta_2 = \frac{(\frac{E_{f2}}{E_R} - 1)}{(\frac{E_{f2}}{E_R} + \xi_2)} \tag{4.9}$$

$$\eta_G = \frac{(\frac{G_f}{G_R} - 1)}{(\frac{G_f}{G_R} + \xi_G)} \tag{4.10}$$

The basic theory behind FRP materials is that the ultimate strain of the fibres must be much lower than that of the matrix, which was mentioned in section 2.2 *Fibre Reinforced Polymers*. Applying this gives a formula for the failure stress in the fibre direction of one ply:

$$f_{ka} = \varepsilon_{f1a} \cdot E_{1a} \tag{4.11}$$

Where ε_{f1} is the fibre direction strain limit and a denotes either the tensile or compressive property.

The compressive failure stress perpendicular to the fibre direction can be calculated by instead using the E_2 and ε_2 properties in equation 4.11. The stiffness of the fibres perpendicular to the fibre direction, along with the shear strength of the fibres, is assumed to be insignificant and thus the tensile strength perpendicular to the fibre direction and the shear strength is that of the matrix material.

A UD ply placed with a fibre direction that deviates from the main direction of loading (the x-axis) still contributes to the bending stiffness in the main direction. The Young's modulus in the direction of loading of such a ply can be solved from equation 4.12 using the values given by the equations 4.5 - 4.8 (Bhagwan Agarwal, Lawrence Broutman, Chandashekhara, 2015). The main direction is $\theta = 0$.

$$\frac{1}{E_{x,ply}} = \frac{cos^4\theta}{E_1} + \frac{sin^4\theta}{E_2} + \frac{sin^2 2\theta}{4}\left(\frac{1}{G_{12}} - \frac{2v_{12}}{E_1}\right) \tag{4.12}$$

Using this equation it is a simple matter to compute an equivalent Young's modulus for a laminate by calculating the mean value of all plies making up the laminate.

The GFRP deck consists of E-glass fibre and polyester while the CFRP deck consists of HS carbon fibre and epoxy. Polyester is cheaper and more easily processed than other common alternatives and is therefore used together with the glass fibres. When using carbon fibre a higher-performance resin, epoxy, is used. It is the resin which is most often used in conjunction with carbon fibre and it provides strength and durability to the composite. The final mixes consists of 60% fibres and 40% resin. The foam core of the sandwich deck is the rigid foam PVC. It is relatively cheap and is suitable for outside conditions. Table 4.2 and 4.3 shows the characteristic values as well as the design values that should be used for ULS and SLS for the two materials. Table 4.4 presents the Poisson ratios and also the densities, which are calculated using the same principle as for equations 4.5 and 4.8. The density of the PVC is 40 kg/m^3. Table 4.5 and 4.6 show the design strength for a GFRP ply and a CFRP ply respectively.

Table 4.2: Stiffness properties for GFRP. Units in GPa.

Property	Characteristic	ULS	SLS	SLS creep
E_1	43.9	12.4	35.6	16.7
E_2	15.6	4.4	12.6	5.9
G_{12}	4.5	1.3	3.6	1.7

Table 4.3: Stiffness properties for CFRP. Units in GPa.

Property	Characteristic	ULS	SLS	SLS creep
E_1	139.7	39.4	113.2	53.2
E_2	11.0	3.1	8.9	4.2
G_{12}	4.9	1.4	4.0	1.9

Table 4.4: Densities and Poisson ratios of GFRP and CFRP.

Material	Density [kg/m^3]	Poisson ratio [-]
GFRP	2022	0.295
CFRP	1574	0.336

Table 4.5: Design strengths of one GFRP ply. Units in MPa.

Property	Characteristic	Design
f_{1t}	1669	471
f_{1c}	1054	297
f_{2t}	50	14
f_{2c}	373	105
f_s	50	14

Table 4.6: Design strengths of one CFRP ply. Units in MPa.

Property	Characteristic	Design
f_{1t}	2096	591
f_{1c}	1257	355
f_{2t}	80	23
f_{2c}	99	28
f_s	80	23

4.3 Partial factors

In PGD the uncertainty of material properties is taken cared of by using the *Partial Factors Method* found in the *Eurocode* to reduce the characteristic material properties. The partial factor for an arbitrary material property is:

$$\gamma_M = \gamma_{M1} \cdot \gamma_{M2} \tag{4.13}$$

The factor γ_{M1} is dependent on how the property is derived and γ_{M2} is dependent on what type of check is being performed and the manufacturing conditions. The values from PGD are shown in tables 4.7 and 4.8. For the calculations done in this project $\gamma_{M1} = 1.0$ has been used as it is assumed that a producer of the structural elements is certified by an EOTA member. In the case of Sweden this EOTA member would be RISE. Furthermore are the γ_{M2} values in the first row of table 4.8 used as it is also assumed that sufficient manufacturing certainty is achieved for this. For SLS checks $\gamma_M = 1.0$ have been used as per 2.3.4.1.(3) in PGD.

Table 4.7: Values of γ_{M1}.

Conditions	γ_{M1}
Manufacturing certified by EOTA-member	1.0
Test derived properties	1.15
Theoretical values	1.35

Table 4.8: Values of γ_{M2}. V_x is the variation coefficient according to EN1990 Annex D.

Conditions	ULS	Local stability	Global stability
$V_x \leq 0.10$	1.35	1.5	1.35
$0.10 < V_x \leq 0.17$	1.6	2.0	1.5

4.4 Conversion factors

To handle specific risks and problems that FRP materials have, The PGD uses conversion factors. These factors reduce the material properties to account for problems related to degradation and long term effects, for example creep. The conversion factor for an arbitrary material property is stated as:

$$\eta_c = \eta_{ct} \cdot \eta_{cm} \cdot \eta_{cv} \cdot \eta_{cf} \tag{4.14}$$

Where:
η_{ct} : Reduction due to high temperatures
η_{cm}: Reduction due to exposure to humidity and moisture
η_{cv} : Reduction due to creep
η_{cf} : Reduction due to fatigue

4.4.1 Humidity and moisture η_{cm}

The factor η_{cm} handles problems regarding moisture and humidity and should be chosen according to table 4.9 taken from 2.3.6.2 in PGD. In this project the value $\eta_{cm} = 0.9$ was used which is exposure class II. The argument for choosing this value is that while the top side of the deck is continuously exposed to water, neither strong UV exposure or service temperatures above 30 $°C$ are present. This means that the requirements for exposure class III is not met and thus would class II be used.

Table 4.9: The three different exposure classes and their respective η_{cm} values.

Exposure class	η_{cm}	Humidity
I	1.0	Dry goods, indoor climate
II	0.9	Outdoor climate, $T_s < 30°C$
III	0.7	Continuous exposure to water, strong UV exposure, $T_s = 30{-}40°C$

4.4.2 Creep η_{cv}

Due to the viscoelastic behaviour of the resins significant creep can occur in FRP structures. This is handled by the conversion factor η_{cv} which is determined by the formula:

$$\eta_{cv}(t_v) = (\eta_{cv,20})^T \tag{4.15}$$

Where:

$$T = 0.253 + 0.141 \cdot Log(t_v) \tag{4.16}$$

In which t_v is the accumulated load duration in hours [h].

The reference value $\eta_{cv,20}$ is a value of the needed property reduction for 20 years of creep. It is calculated by the formula:

$$\eta_{cv,20} = \frac{1}{2 - \delta} \tag{4.17}$$

Where δ is the fibre mass proportion in the direction of loading.

This formula is valid for a mixed laminate, that is a reinforcement layout which is a mix between different arranged fibre directions. In the design for the deck, the value $\eta_{cv} = 0.47$ was used. Compared to the other η-values, the creep represents the most significant reduction of the material properties.

4.4.3 Temperature η_{ct} and fatigue η_{cf}

The effects of temperature is handled by setting $\eta_{ct} = 0.9$ as per 2.3.6.1.(1) in PGD. The last conversion factor which is η_{cf}, handles fatigue. There are no cyclic loads acting on the structure and thus has this factor been disregarded completely.

4.4.4 Combinations of η

Depending on what type of check is being performed, only some of the η -values should be regarded. These different combinations are shown in table 4.10 and the values of the conversion factors that should be used for the checks are presented in table 4.11. Worth noting is that according to PGD, creep should not be regarded in buckling analyses. However, there are contradictory opinions if the creep effect should be included or not and therefore, to be on the safe side the creep will be included in the buckling analysis in this study and the creep effect is included in the conversion factor for the stability check in table 4.11.

Table 4.10: The different checks and which conversion factors should be used. A selective presentation of table 2.4 in PGD.

Conversion factor	Strength	Stability	Momentary deflection	Creep deflection
η_{ct}	x	x	x	x
η_{cm}	x	x	x	x
η_{cv}	x			x

Table 4.11: Conversion factors for the different checks.

Check	Conversion factor
Strength	0.381
Stability	0.81
Creep deflection	0.381
Momentary deflection	0.81

4.5 The design of the sandwich decks

With a design based on the loads from section 4.1 *Loads* and the partial and conversions factors for the materials, the dimensions of the deck could be calculated. The hand calculations can be found in appendix A and appendix B for GFRP and CFRP respectively. Using the input data presented earlier in this chapter, two designs for a sandwich deck is presented. One GFRP deck and one CFRP deck.

4.5.1 Deck cross sections

In figure 4.2 the two cross sections are presented and in figure 4.3 the length of the deck and the placement of vertical stiffeners can be seen. Table 4.12 presents the thicknesses of the cross section. Both decks have two longitudinal stiffeners running the entire length of the deck to handle the web buckling in the mid span. They also have two vertical stiffeners close to the support to handle the shear buckling of the webs.

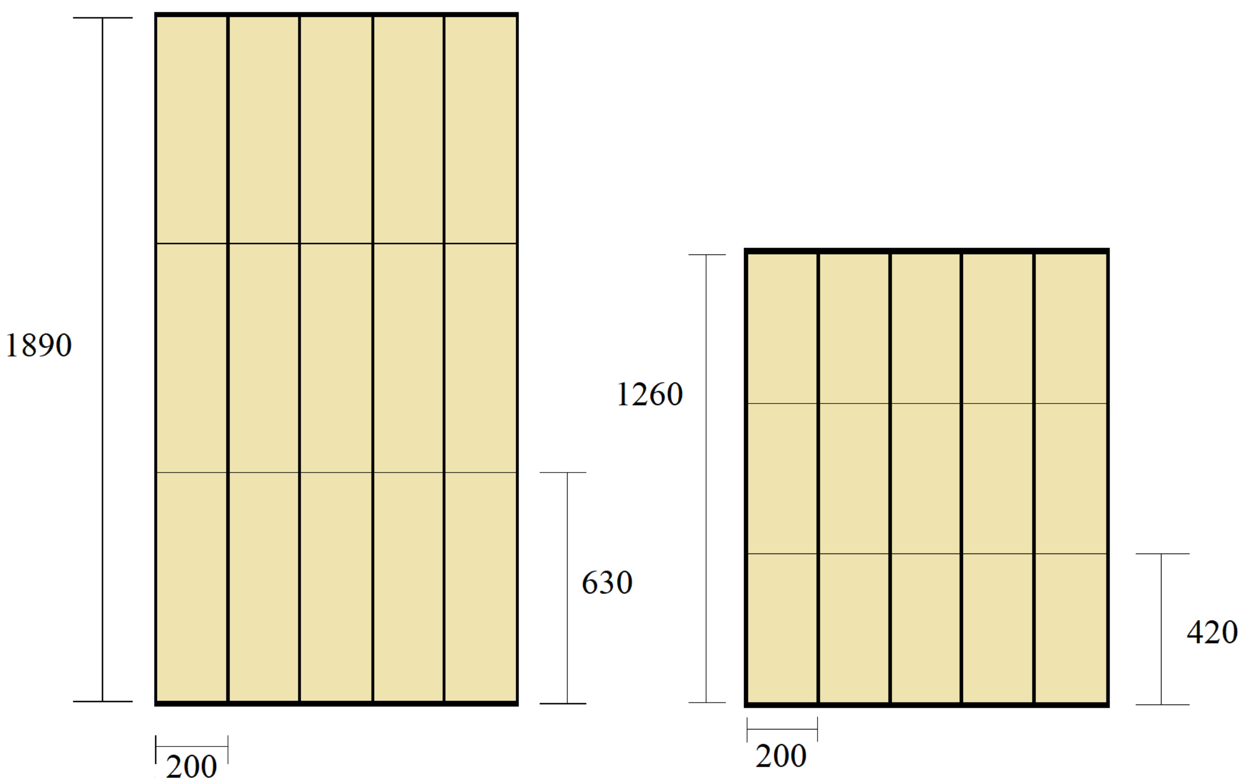


Figure 4.2: Cross sections of 1 meter of the final designs. GFRP to the left and CFRP to the right. Units in mm.

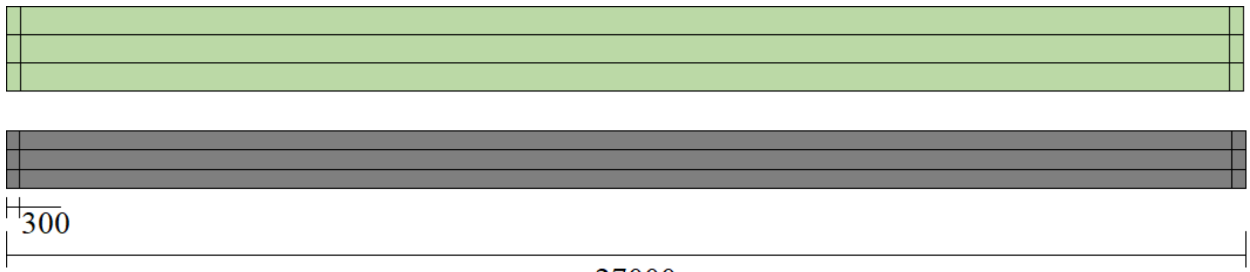


Figure 4.3: Longitudinal view of the decks. GFRP on top and CFRP below. Units in mm.

Table 4.12: Thickness of different plates in the designs. Units in mm.

Part	GFRP	CFRP
Flange	23.8	18.3
Web	16.4	11.4
Longitudinal stiffener	4.0	3.6
Vertical stiffener	5.6	6

The self-weights of the FRP decks with the chosen cross sections, including the foam are presented in table 4.13. To be able to make a comparison the self-weight of the superstructure of the existing concrete eco-bridge is presented as well. The supports and foundations are not included in these values for either of the alternatives.

Table 4.13: Self-weight of the decks of the two FRP designs and the concrete eco-bridge.

Material	Self-weight [ton]
GFRP	830
CFRP	392
Concrete	4300

4.5.2 Composite lay-up

When choosing the lay-up of the plies in the structure the main goal was to use the fibre directions in the most optimized way. In figure 4.4 the two placement directions used can be seen. In the flanges it was important to have the majority of the fibres in the 0° direction to handle the bending and minimize the deflections. Some plies with the direction 45° are added in between to get stability and to hold it together. For the webs, the most fibres should normally be in the ±45° direction to take care of the shear in an effective way. In this case, to decrease the buckling of the webs and to achieve smaller deflection, plies with 0° orientation was incorporated in the web as well. For both the longitudinal and vertical stiffeners, only ±45° plies were used. The final lay-up of the different parts of the GFRP deck is presented in table 4.14 with a thickness of each ply of 0.2 mm. The final lay-up of the CFRP deck is presented in table 4.15, where the thickness of one ply is 0.3 mm.

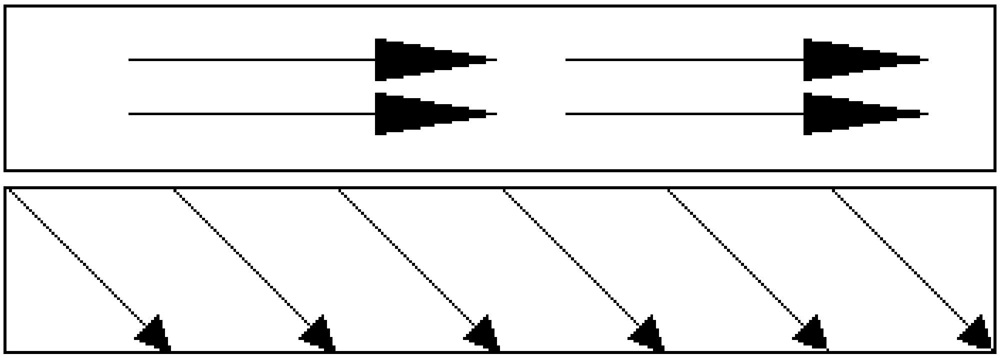


Figure 4.4: Schematic figure of how UD plies can be placed. 0 degrees first and 45 degrees second.

Table 4.14: Lay-up of the different parts of the GFRP deck.

Part	Lay-up
Web	$[\pm 45_5/0_{20}/\pm 45_5]_s$
Flange	$[\pm 45/0_{17}/\pm 45/0_{17}/\pm 45/\overline{0_{39}}]_s$
Longitudinal stiffener	$[\pm 45_5]_s$
Vertical stiffener	$[\pm 45_7]_s$

Table 4.15: Lay-up of the different parts of the CFRP deck.

Part	Lay-up
Web	$[\pm 45/0_8/\pm 45/0_7]_s$
Flange	$[\pm 45/0_{13}/\pm 45/0_8/\pm 45/\overline{0_7}]_s$
Longitudinal stiffener	$[\pm 45_3]_s$
Vertical stiffener	$[\pm 45_5]_s$

4.5.3 Checks

The ULS strength checks performed on the designs are presented in table 4.16 for the GFRP design and in table 4.17 for the CFRP design. In addition to the tensile, compressive and shear check against the maximum moment and shear force, the designs have also been verified against creep rupture. The demand 7.2.3 in PGD states that the axial stress of an FRP should be limited under quasi permanent load to prevent the risk of creep rupture. The demand is stated as follows:

$$\sigma_{t,quasi} \leq \eta_c \frac{f_{Rk,cr}}{\gamma_M} \tag{4.18}$$

Where:
$f_{Rk,cr} = 0.3 \cdot f_{1t}$ for GFRP
$f_{Rk,cr} = 0.9 \cdot f_{1t}$ for CFRP

Table 4.16: ULS strength checks of the GFRP deck.

Check	[MPa]	Utilization ratio
$\sigma_{t,max}$	31.0	6.6%
$\sigma_{c,max}$	31.0	10.5%
τ_{max}	2.1	14.7%
$\sigma_{t,quasi}$	22.4	7.5%

Table 4.17: ULS strength checks of the CFRP deck.

Check	[MPa]	Utilization ratio
$\sigma_{t,max}$	68.2	11.5%
$\sigma_{c,max}$	68.2	19.2%
τ_{max}	3.4	14.9%
$\sigma_{t,quasi}$	49.0	4.3%

4.6 FEM model

To verify the deflections in the decks, FE-models of the two decks were made. These FE-models also served the purpose of making buckling analyses of the decks to investigate the need of stiffeners and their dimensions. The FE analyses were performed using the software Abaqus.

4.6.1 Boundary conditions and loads

The eco-bridge is designed as a simply supported beam. One end has a pinned connection, the edge is locked in x-, y- and z-direction and in the other end there is a roller support which means it is locked in y-and z-direction which is shown in figure 4.5. The load is applied as a uniform load with the values given in table 4.1 in section 4.1 *Loads* together with a gravity component to include the self weight of the structure.

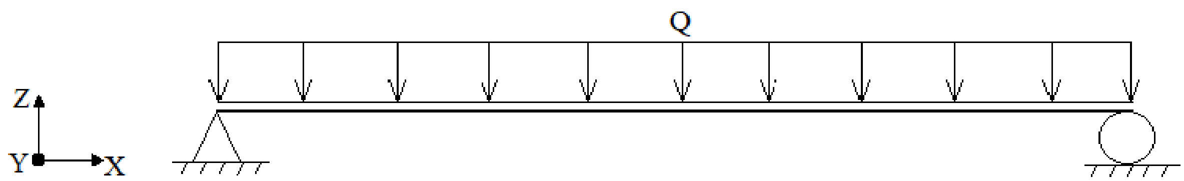


Figure 4.5: Structural system of the deck.

4.6.2 Mesh

A convergence study was made on the GFRP deck in order to find a good mesh that is neither too rough or too fine. The meshing was done using quad elements and the starting size was 1 meter. The mesh size was for every iteration divided by 2 and the results of the study can be found in figure 4.6. Up until the mesh size 0.0625 there is a slight change in results. At a size of 0.03125 the result from the previous step is hardly distinguishable and thus the size 0.0625 was chosen.

Convergence studies for the buckling model were also performed. The first mesh size was 0.1 and was thereafter reduced by 0.01 for every iteration. The results for the GFRP deck can be seen in figure 4.7. As can be seen in the figure there is no strict convergence between the tested mesh sizes but instead the lambda seems to get slightly smaller with the decrease of mesh size. However the difference for the three smallest mesh sizes is almost negligible. Furthermore is $\lambda > 3$ for the GFRP deck which means that the buckling is now far on the safe side. It was thus deemed sufficient to use the mesh size 0.05 for the GFRP deck as going below this size caused unnecessary long waiting times for the simulations.

The result from the convergence analysis of the CFRP deck can be seen in figure 4.8. A mesh size of 0.03 m was deemed sufficient, when decreasing the mesh size to 0.02 the computational time became too long.

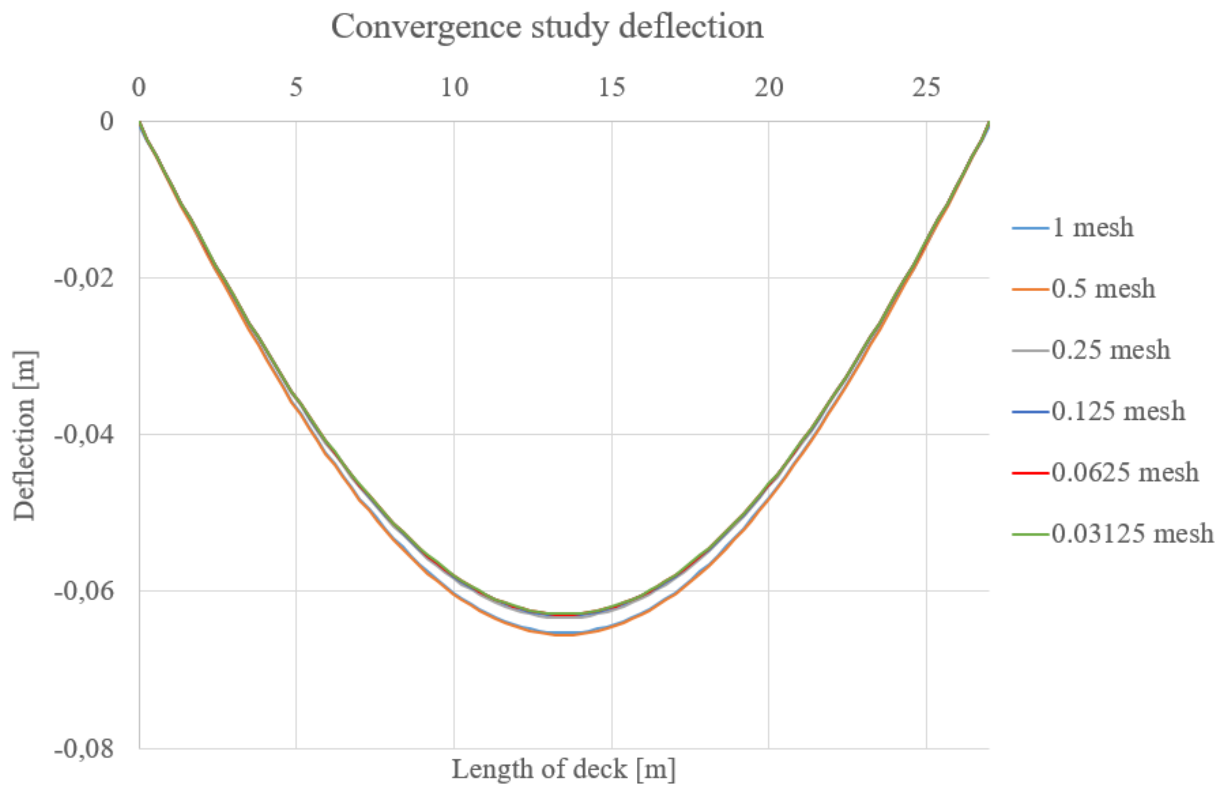


Figure 4.6: Convergence study of the FEM model.

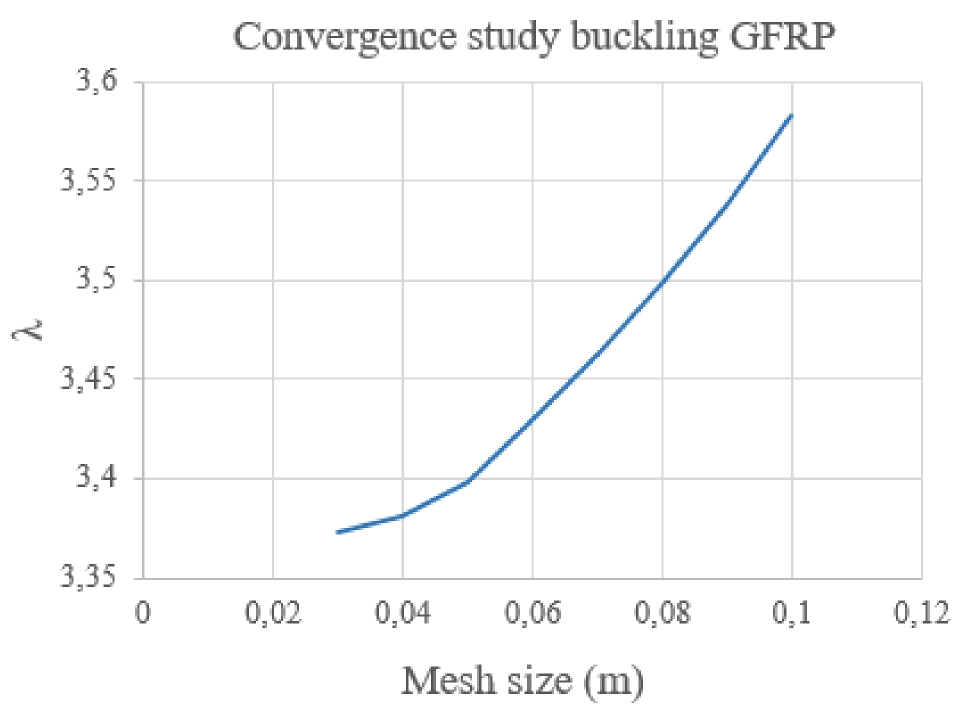


Figure 4.7: Convergence study of the buckling eigenvalue of the GFRP FEM model.

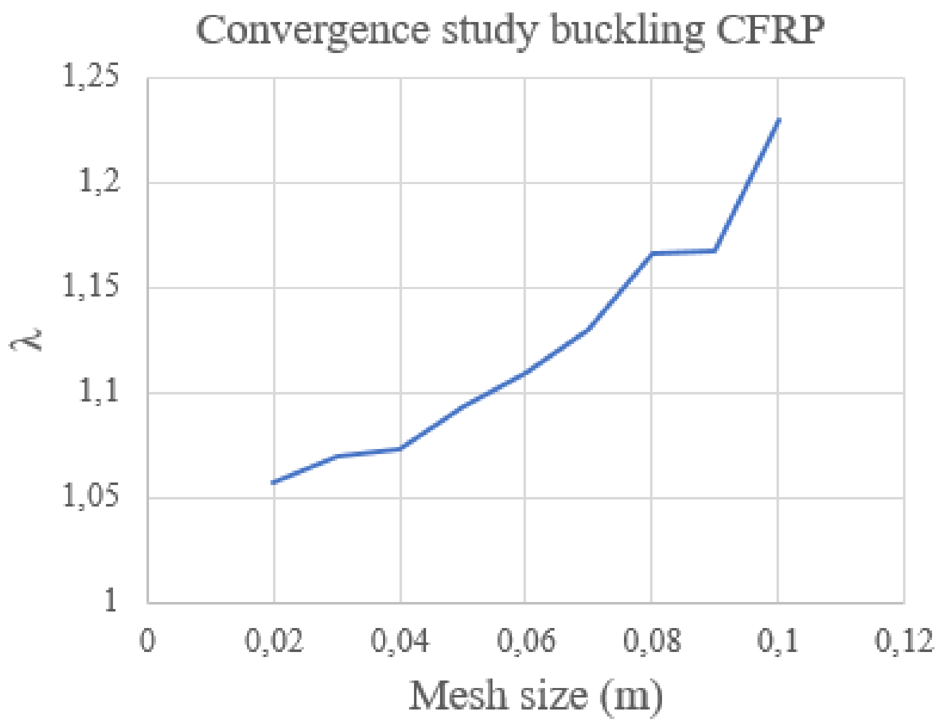


Figure 4.8: Convergence study of the buckling eigenvalue of the CFRP FEM model.

4.6.3 Elements

The FE-model consists of conventional shell elements. The elements themselves are two dimensional but can deform in three dimensions. These are preferable as they portray bending in a good way as well as being computationally efficient compared to a fully three dimensional element. The material properties have been entered into the model using the *Lay-up modeling tool* in Abaqus. This function allows for the design of laminate layups by placing each ply individually in the laminate.

4.6.4 Static analysis

The method to solve for deflections in Abaqus have been to use the Static, General step. This method can solve the designed FE-system without inertia effects and with only one load increment, thus producing the deflections quickly and correctly.

4.6.5 Linear analysis

For the linear buckling analysis the step Buckle, Linear perturbation was used. This method calculates a buckling eigenvalue λ for the structure from which the critical buckling load Q_{crit} can be computed according to the formula:

$$Q_{crit} = \lambda \cdot Q_{applied} \tag{4.19}$$

4.6.6 Static results

The static immediate deflection and the static creep deflection was obtained from the FEM analysis. These values was compared to hand calculations for static deflections based on an equivalent Young's modulus using the equation 4.12 to validate the FE model. The results from the FE analysis and associated hand calculated deflections are presented in table 4.18 and 4.19.

Table 4.18: Static deflections for the GFRP deck. Units in mm.

Type	FEM	Hand calculation
Immediate deflection	65	65
Creep deflection	68	68

Table 4.19: Static deflections for the CFRP deck. Units in mm.

Type	FEM	Hand calculation
Immediate deflection	64	66
Creep deflection	67	68

4.6.7 Buckling results

The results of the buckling analysis for the GFRP deck was that two buckling modes were identified as problematic. Buckling of the web in the mid span and at the supports. In figure 4.9 the buckling mode for the span buckling can be seen and in figure 4.10 the buckling mode for web buckling at the support can be seen. For one longitudinal stiffener the buckling eigenvalue was $\lambda = 0.97$ for the GFRP deck. With two stiffeners the buckling eigenvalue became $\lambda = 3.4$. This is an unnecessarily high value, however, after investigations it was found to be a more efficient use of materials to add a second stiffener than to increase the thickness of the webs until the point $\lambda = 1.0$ was reached. The buckling eigenvalue of the CFRP deck was early discovered to be < 1 for just one stiffener. In the final design presented here the lowest buckling mode is web buckling in the mid span for both decks. The lowest buckling eigenvalues are presented in table 4.20.

Table 4.20: Buckling eigenvalues λ of the final designs.

Material	λ [-]
GFRP	3.40
CFRP	1.16

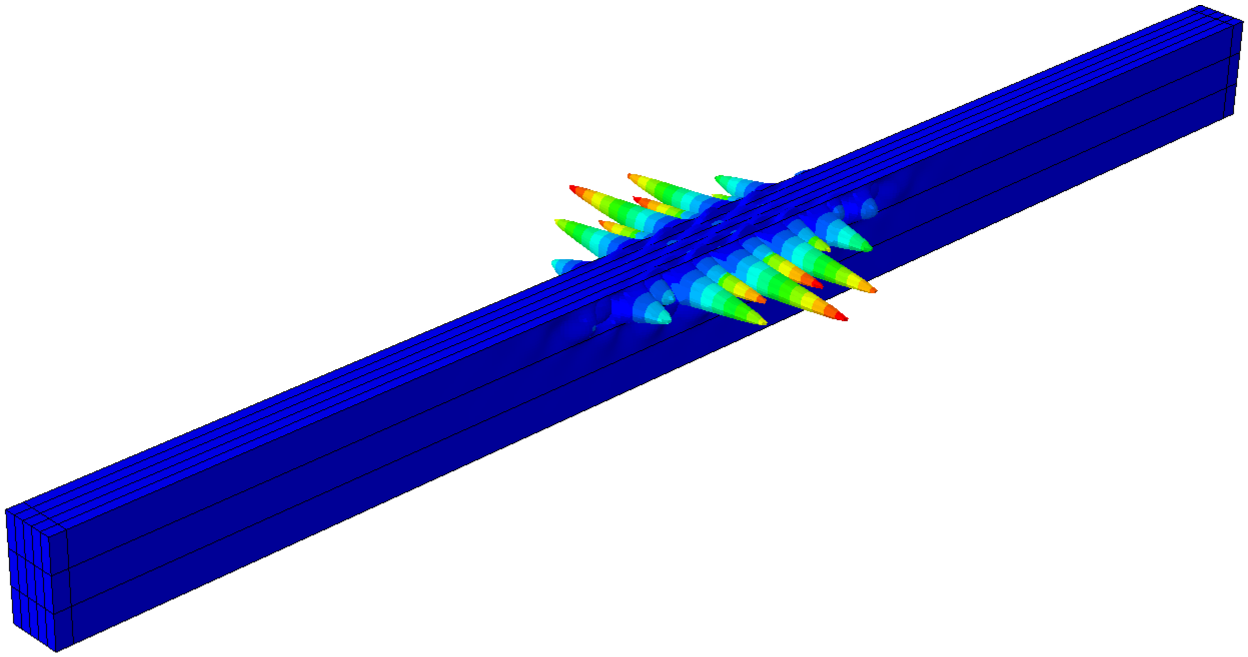


Figure 4.9: The span web buckling mode. Figure from Abaqus. The figure shows the lowest buckling mode for the GFRP design.

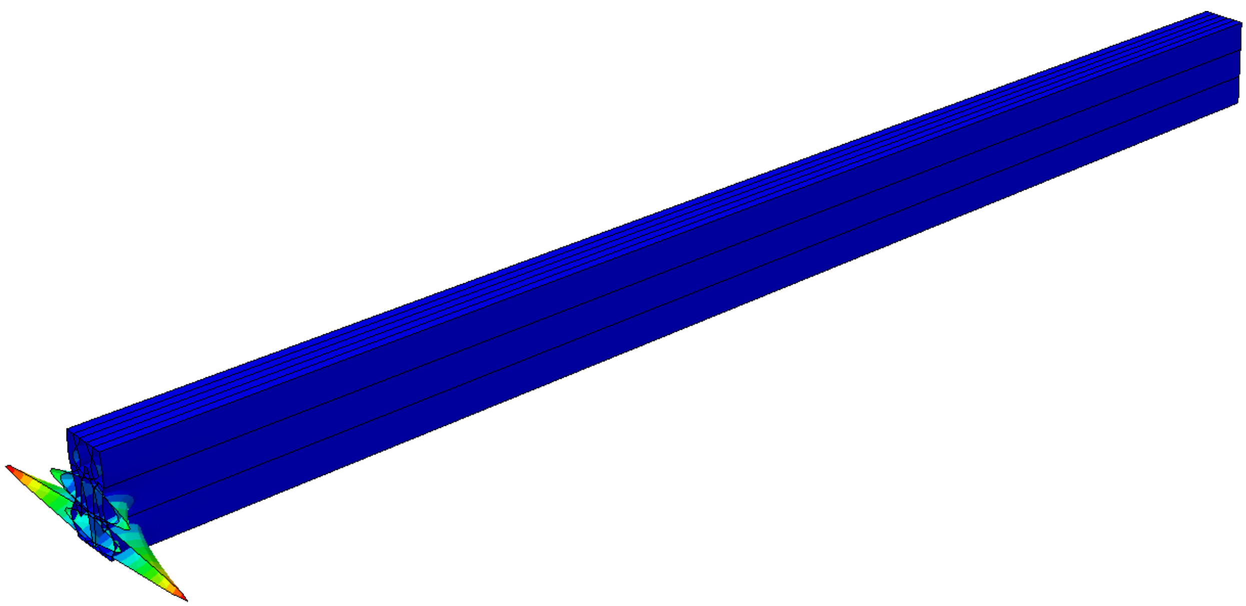


Figure 4.10: The support web buckling mode. Figure from Abaqus.

4.7 Production

One issue with the designed deck is the production method. Since FRP is not a common material used in Sweden so far there are not many companies that can produce the decks. Pultrusion is not seen as a possible manufacturing method since the deck has such large dimensions and since it is not allowed to use adhesion in the primary load bearing directions it is not possible to manufacture smaller elements and put together either. Hand-lay up is also difficult because of the hollow cross section. The production of the decks is a problem which needs more processing but in this section one production method is proposed.

The decks could be produced by using PVC foams as an internal mould around which the plies are wrapped thus forming the webs. This would then be used in either the RTM method or the VIP presented in section 3.3.5 *Production of FRP elements*. To form the longitudinal stiffeners the foam core could be divided into three cells thus forming a "natural" stiffener across the deck. First the cores would be wrapped around the x-axis with plies until the thickness of the stiffener is reached. Then wrapping will take place around all three cores until the proper web thickness is reached. The vertical stiffeners at the supports could be produced in the same way by cropping the ends of the PVC core and instead wrap around the z or y-axis. This is illustrated in figure 4.12. The flanges are attached to the webs by either a mechanic connection or adhesive connection.

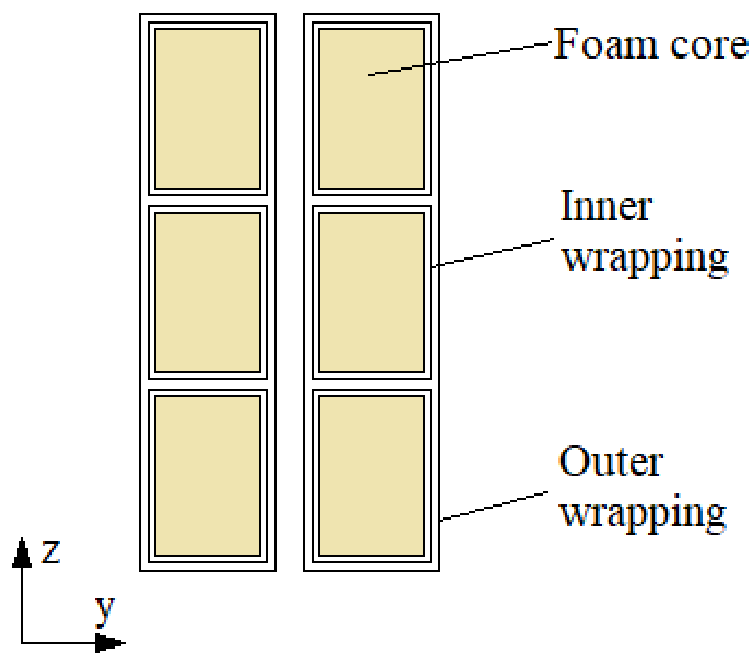


Figure 4.11: Schematic figure of how the plies can be placed around foam cores to produce the webs.

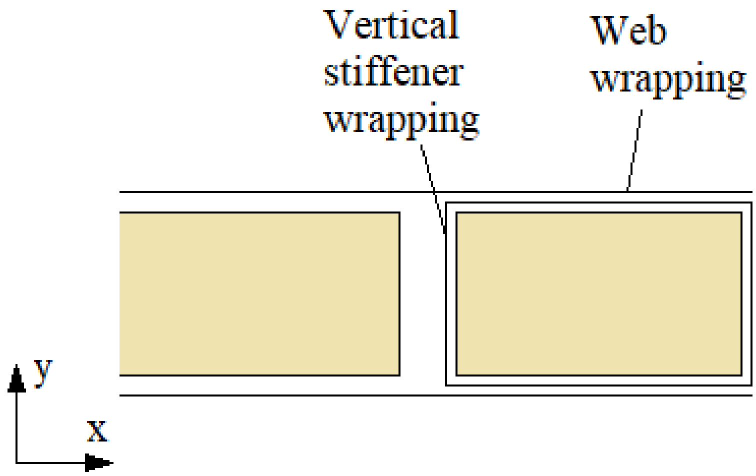


Figure 4.12: Schematic figure of how the plies can be placed around foam cores to produce the vertical stiffeners close to the supports.

By using this method the deck could be produced in sections with the size of $27m \times 3m \times h$. They can then be transported to the construction site for assembly.

4.7.1 Foundation and columns

The original plan was to assume that the foundation and the columns for the FRP decks would be the same as for the concrete, but after consideration some changes were made to better fit the new design. For the existing eco-bridge, the middle support consists of four columns that are higher than the edge supports since that eco-bridge is curved. Since the eco-bridge designed in this study is not curved all supports are assumed to have the same height, which will be the height of the middle support. The edge supports are except for the height, assumed to have the same dimensions as for the existing eco-bridge. It was further assumed that the middle support is continuous like the edge supports, instead of being columns. This is to avoid stress concentrations in the FRP deck. The width of this support was assumed to be the same as the width of the columns for the concrete eco-bridge since the design value for them are accident load which will be the same in the cases with FRP deck. Finally, the foundations below the supports were assumed to be the same as for the existing concrete eco-bridge. It was assumed that 60 days was spent on this part of the project.

4.7.2 On site assembly

When the foundation and columns are in place, the deck should be placed on the supports. The deck is, as aforementioned manufactured in segments of 3 metres and are then transported on trucks to the site. A crane is used to lift the parts upon the supports and they are then connected to each other using interlocking ends. It was assumed that 6 weeks are spent to place the FRP deck.

4.8 Other considerations

The environment in which the eco-bridge is built in entails other possible problems which need to be solved in order to ensure that the structure does not lose strength during its lifetime and to ensure the safety of the users. Some of these problems that need to be handled are the risk of fire and the risk of degradation due to the surrounding conditions.

4.8.1 Protection against fire

The eco-bridge needs to be able to pass the Swedish rules for how long a structure should be structurally stable in case of fire to ensure the safe evacuation of people and the safety of firemen and other involved parties. As mentioned in 2.2.5.6 *Fire*, FRP is a flammable material that needs to be protected. For the GFRP deck, the polyester resin could be substituted with phenol resin which has superior fire resistant and flame retardant properties compared to the other resin types. For the CFRP deck a protective coating is chosen as the best alternative. The measures taken is assumed to be enough to pass the time limit for how long the eco-bridge needs to be structurally bearing; however, in case of extensive fire the eco-bridge will most probably not be good enough to be used.

4.8.2 Protection against degradation

As mentioned in 2.2.5 *Durability*, FRP is a durable material but there are conditions in which the material needs to be protected to avoid degradation of the material. A gel coat will be used for the GFRP deck as a surface finish to protect the deck. The CFRP does not need any extra protection since it is so durable itself. It will protect against moisture and chemical degradation that can be caused by the soil as well as against the alkali environment caused by the vicinity of concrete.

5 LCC analysis

A life cycle cost (LCC) analysis is a method to calculate the total cost for the whole service-life (Fuller, 2010). It includes all parts, from the design and planning to the end of life of the structure. It is especially advantageous to use when there are alternatives with different initial construction costs as well as operation and maintenance costs. An LCC analysis can then be a tool to compare the alternatives and see which is more economically advantageous.

The life cycle costs are generally divided into two parts, agency costs and social cost (Mara, 2014). This is further presented in Figure 5.1. The agency costs include cost for construction, operation and maintenance and also the cost for the disposal. The social costs include costs for users and for the society.

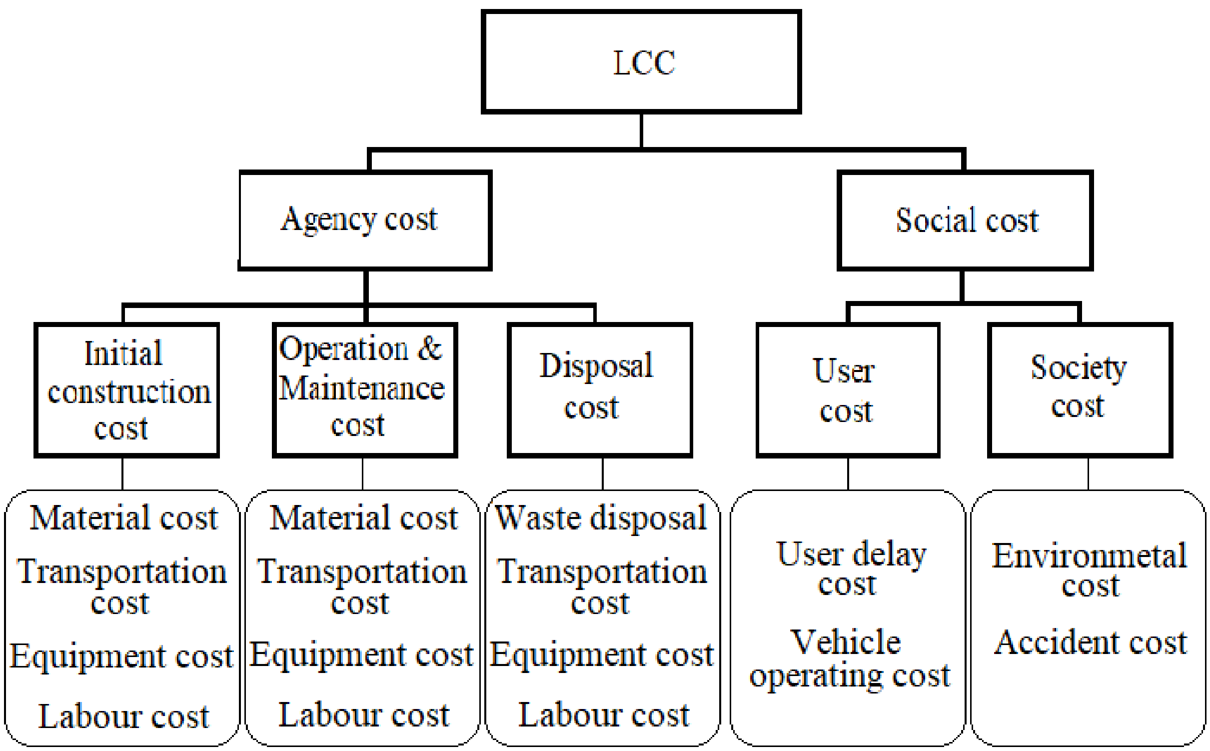


Figure 5.1: Life cycle costs divided into categories.

5.1 Case study

An objective of the project was to make a comparison between the produced designs and the actual constructed eco-bridge. To full fill this goal an LCC analysis was made for both the existing bridge and the new concepts. The LCC analysis done can be seen in its entirety in appendix C.

5.1.1 Assumptions

For a design to be built it must be proven to be economically viable. This have in this project been done by the means of an LCC analysis. As such an analysis includes many different costs and optimally all possible costs that could arise, it is also important to reference every number and assume as little as possible. Many costs can be hard to find and a good LCC analysis is best done by someone with solid experience in the field. To get an as reliable result as possible different LCC analyses done on FRP were studied and similar assumptions and costs where made. However, some new assumptions still had to be made.

5.1.2 Agency costs

Costs that are directly linked to the structure being built is called agency costs. These are initial costs such as price of materials and work force but also costs during operation and the cost of disposal at the end of the service life. Planning costs is also included and according to the Swedish Transport Administration this sum was 4 million SEK for the eco-bridge at Sandsjöbacka. It was assumed that the cost of this post is the same for the FRP alternatives as for the existing eco-bridge.

In order to evaluate future costs a Net Present Value (NPV) is calculated. The NPV is a way to calculate the present value of all future cash flows during the lifetime of the investment and will in this analysis be used for disposal costs and maintenance costs. A discount rate of 3,5 % was chosen for these calculations. The NPV value is calculated using the following formula:

$$NPV = \sum_{n=0}^{L_s} \frac{C_n}{(1+d)^n} \tag{5.1}$$

where:
L_s: Service life of the eco-bridge
n: The year
C_n: Cash flow for year n
d: Discount rate

5.1.2.1 Initial construction costs

The initial construction costs include costs for material, manufacturing, transport and assembly. For the existing bridge the initial cost has been taken as 57.4 million SEK, as presented by the Swedish Transport Administration. For the CFRP design the manufacturer Aston Harald has been consulted and has provided a price for the production of the CFRP deck. For the GFRP design an estimation have been made using typical costs found in different previously performed LCC analyses on FRP bridges. In table 5.1 the different initial costs are presented. The material costs are collected from section 2.2.7.1 *Price of materials*. For the cost of carbon fibre the price of 250 SEK/kg is mainly for small scale production of CFRP components and it was thus assumed that the price for carbon fibre could be reduced to as much as 150 SEK/kg when placing a large scale order such as an eco-bridge. The labour cost is gathered from the report *Lönerapport 2017* published by LO The Swedish Trade Union Confederation. In this report the average monthly wage of a Swedish industrial worker is

25 800 SEK. This divided into an hourly wage and multiplied with 1.3 to account for social costs ("Arbetsgivaravgift") gives a total of 208 SEK/h. The hours required for manufacturing the deck is difficult to assume but to be on the safe side 20 000 hours was assumed for the GFRP deck and 15 000 hours for the CFRP deck. Since it is such a difficult number to assume a sensitivty analysis was made which can be read more about in 5.3 *Sensitivity analysis*. The deck is assumed to be assembled in three days, when 6 people work 24 hours per day. The cost of equipment is assumed to be 10 000 SEK and is assumed to include a crane and different tools for assembly.

Table 5.1: Input data used to calculate the initial construction costs for both decks.

Materials	GFRP	CFRP
Fibre [SEK/kg]	25	150
Resin [SEK/kg]	20	100
Foam [SEK/kg]	60	60
Gel coat [SEK/m^2]	56	-
Production, transport and assembly		
Labour [SEK/h]	208	208
Equipment [SEK/day]	10 000	10000
Transportation [SEK/km·ton]	6	6
Man working hours manufacturing [h]	20 000	15 000
Assembly time [h]	72	72
Workers on site	6	6

5.1.2.2 Operation & Maintenance costs

The cost of maintenance for the eco-bridge is estimated by the Swedish Transport Administration to 20 000 SEK/year. This cost is assumed to include maintenance of the topside of the eco-bridge such as gardening and fence maintenance. It is assumed that inspection costs and larger repairs are not included in this and it will be the same for all three concepts.

Not much maintenance is needed for the FRP decks. Washing is assumed to be needed every 10 year for both decks. For the GFRP deck, repainting of the gel coat is assumed to be necessary once during its lifetime.

For the concrete eco-bridge it was assumed that the maintenance is 0,5% of the construction cost every year. This cost was also used for the concrete supports in both FRP alternatives. Generally 2% is used, but since there is no wear on the top of the eco-bridge as there is on normal car bridges this value is assumed to be significantly smaller for this case.

Another cost that falls under this category is the inspection of the bridge which is an important part of the maintenance aspect. A superficial inspection will be performed every year, a general inspection every third year and finally a major inspection of the eco-bridge every sixth year. For the FRP deck one important part to check in these inspections is the gel coat on the deck that is located on the top of the deck, underneath the soil and to make sure that it has not degraded.

5.1.2.3 Disposal costs

At the end of the service life the bridge will either have to be disposed of or reinforced for further service. As the eco-bridge over E6 is the first of its kind in Sweden it is not unreasonable to assume that it in 120 years might be regarded as a cultural and historical structure worth preserving. Thus would the assumption of reinforcement at the end of the service life also be valid. However, the goal of this thesis is to give guidance for future eco-bridge projects that will not enjoy the unique status of being first. This would thus be a bad assumption. Instead, the assumption of disposal has been made as this would probably be the fate of an arbitrary eco-bridge. The costs included in the disposal costs are demolition of the structure, transportation of the material to disposal or recycling site and the cost or profit of recycling the material. In table 5.2 the costs regarding the demolition of the eco-bridge and the recycling are presented.

Another assumption made for the disposal cost is the distance to the nearest disposal facility, which was assumed to 30 km which is the approximate distance from the eco-bridge to the centre of Gothenburg. It is naturally impossible to predict where the old bridge materials will be transported in 120 years and as such holds the assumption done in this study little ground. However, the transportation part of the disposal cost is relatively small and thus it is also of lesser importance. Worth noting is that the transportation cost will always favor the lightest material in the study regardless of the distance. For simplicity the demolition cost of the deck of the FRP alternatives was assumed to be the same as the assembly cost and for the concrete structures it was assumed that they were 10 % of the construction cost. The transportation cost is assumed to be the same as mentioned in table 5.1 in section 5.1.2.1 *Initial construction costs*, which was 6 SEK/km·ton. For the recycling costs, it was assumed that there is no profit from recycling FRP, even though there are companies that pay for FRP material. Instead the same recycling cost as for the concrete was assumed.

Table 5.2: Input data used for the calculations of disposal costs.

Recycling	Cost [SEK/ton]
FRP	1000
Concrete	1000
Reinforcement	-500

5.1.3 Social costs

The social costs are costs that affect other parts of the society. Further information about what the social cost is and what is included can be found in section 2.2.7.3 *Social costs*. The social costs are usually divided into two parts, user costs and society costs. The society costs consist of environmental costs and accident costs. As mentioned in the section 1.4 *Limitations* in the introduction chapter, the environmental costs are not included in this analysis. As for the accident costs, it is almost impossible to calculate the cost of an arbitrary accident and this post was thus disregarded.

5.1.3.1 User costs

The user costs are usually divided into user delay costs and vehicle operating costs. In this case, there are no vehicle operating costs since the erection of the eco-bridge does not result in any extra wear on the vehicles since reduction of speed is the only change. These costs were calculated using equation 5.2.

$$User\ delay\ costs = \left(\frac{L_r}{S_a} - \frac{L_r}{S_n}\right) \cdot ADT \cdot N \cdot w \tag{5.2}$$

where:
L_r: Length of the road which is affected
S_a: Reduced speed on the road
S_n: Normal speed on the road
ADT: Average daily traffic
N: Number of days with reduced speed
w: Hourly time value of drivers

The input data used to calculate these costs are presented in table 5.3 and 5.4. Table 5.3 presents the data that is the same for all three cases while table 5.4 presents the number of days with reduced speed, which are different for the cases with FRP and concrete. The accident resulted in more days with reduced speed and two values are therefore used, one including the accident and one excluding it. Furthermore was E6 closed completely for 27 hours directly after the accident forcing a rerouting of traffic. The information about length of detour, speed, average daily traffic and number of days with reduced speed during normal construction are from the Swedish Transport Administration. It have been assumed that the traffic have been rerouted according to figure 5.2 during the accident. The number of days with reduced speed for the FRP eco-bridge were estimated to be the same as the total erection time.

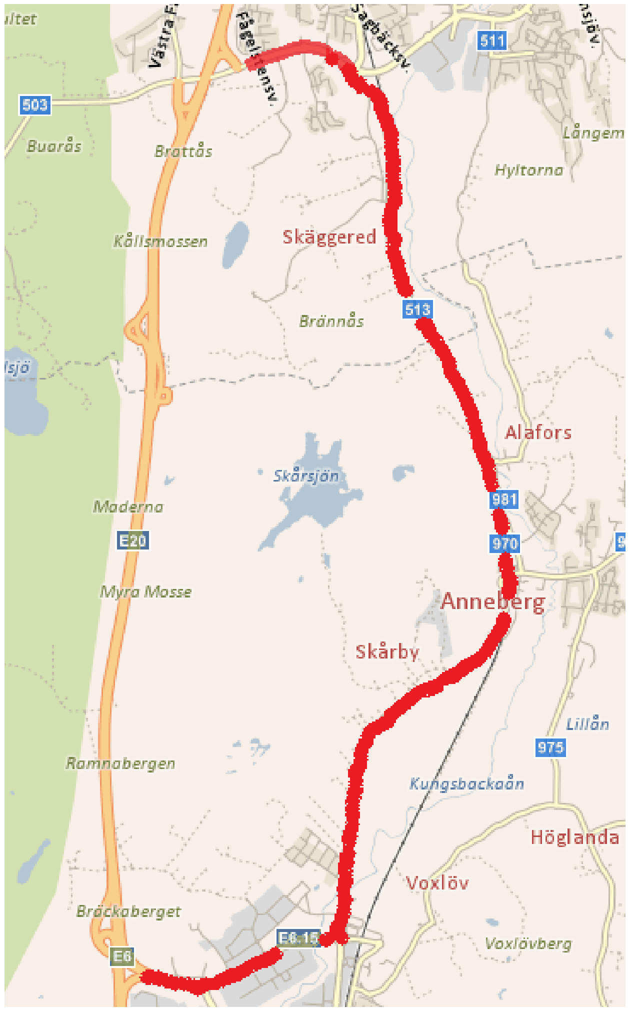


Figure 5.2: Rerouting of traffic during accident.

Table 5.3: Input data used for the user cost calculations that are same for all three cases.

Input data	Value
Length of detour L [km]	0.6
Normal speed S_n [km/h]	100
Reduced speed S_a [km/h]	70
Average daily car traffic ADT_c [cars/day]	46 000
Average daily truck traffic ADT_t [trucks/day]	5 600
Hourly time value of car drivers w_c [SEK/h]	280
Hourly time value of truck drivers w_t [SEK/h]	347

Table 5.4: Input data used for the number of days with reduced speed.

Case	Days
FRP	120
Concrete (excl. accident)	510
Concrete (incl. accident)	635

5.2 Results

The different costs for the alternatives are presented in table 5.5. In figure 5.3 and 5.4 it can be seen how big of a portion every post is in the total cost.

Table 5.5: Cost of the Sandsjöbacka eco-bridge and the two FRP alternatives. Units in SEK.

Cost	Concrete	GFRP	CFRP
Planning	4 000 000	4 000 000	4 000 000
Construction	57 400 000	35 600 000	62 200 000
Maintenance	9 800 000	3 800 000	3 000 000
Disposal	151 000	91 000	83 000
Social	19 400 000	2 400 000	2 400 000
Total	90 800 000	45 900 000	71 700 000

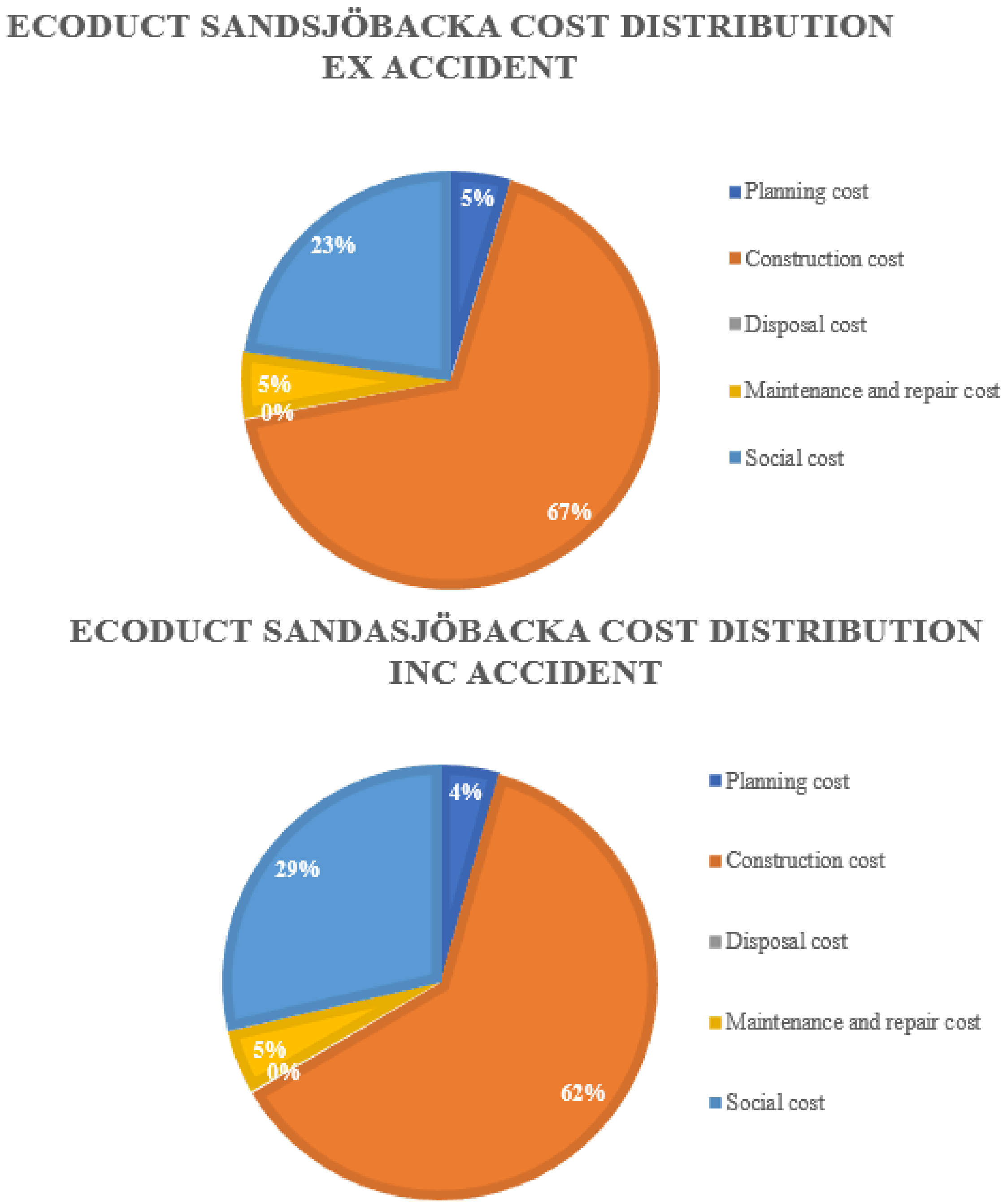
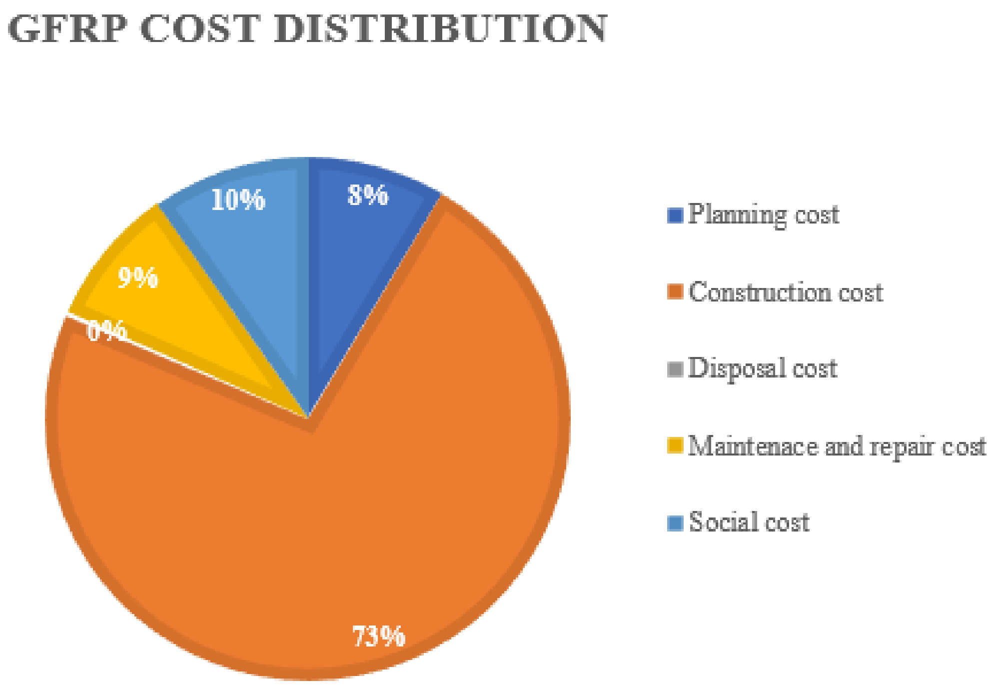


Figure 5.3: Cost distribution of Sandsjöbacka eco-bridge.



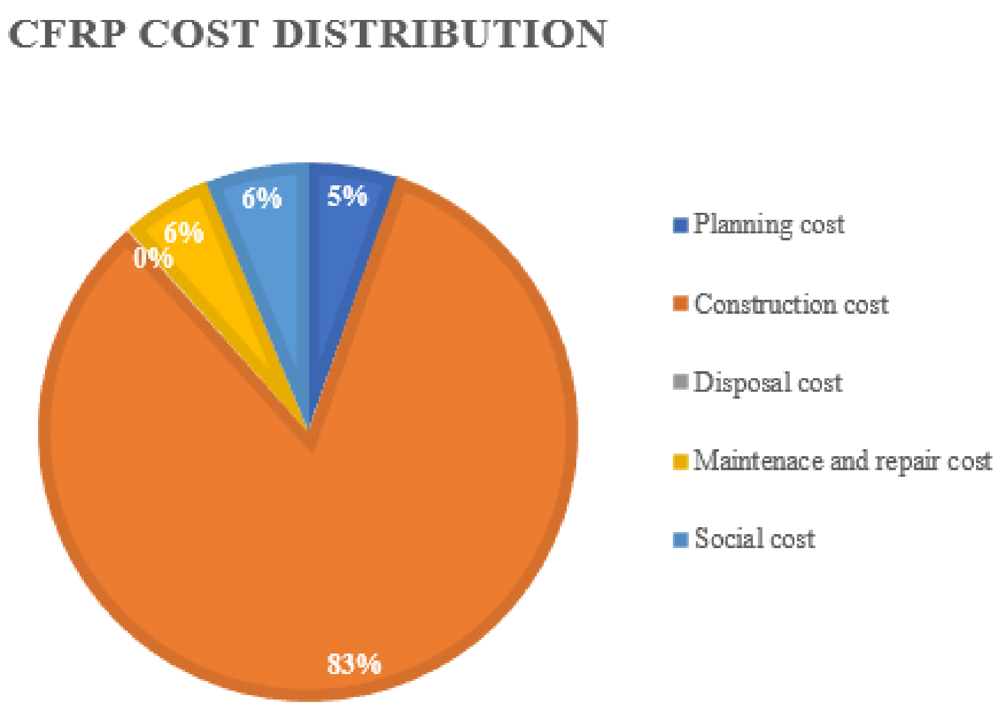


Figure 5.4: Cost distribution of FRP alternatives.

5.3 Sensitivity analysis

The assumption of how many working hours it takes to manufacture the decks is an important one. Thus have a sensitivity analysis been done on this to analyze how big of a difference it makes. In table 5.10 the result of this analysis can be seen. The analysis showed that the assumption of manufacturing was not as important as expected. It was in the end assumed to take 10 000 hours for the GFRP deck and 7 000 hours for the CFRP deck.

Table 5.6: Sensitivity analysis of working hours.

Working hours	Labour cost [SEK]
5 000	1 040 000
10 000	2 080 000
20 000	4 160 000
50 000	10 400 000
100 000	20 800 000
200 000	41 600 000

A sensitivity analysis were also done on the price of carbon fibre. At a price of 250 SEK/kg the cost of the CFRP deck was 85.7 million SEK and at 200 SEK/kg it was 73.9 million SEK. The breaking point for the price was at 179 SEK/kg were the construction cost of the project became the same as for the constructed concrete eco-bridge. It can thus be concluded that the price of carbon fibre is important. However, the full life cycle cost breaking point for carbon fibre is at 232 SEK/kg.

Table 5.7: Material costs.

Material	Cost [SEK/kg]
Glass fibre	25
Carbon fibre	150
Polyester	20
Epoxy	100
Foam	60

Table 5.8: Time assumptions.

Post	Cost
Manufacturing time GFRP	20 000 h
Manufacturing time CFRP	15 000 h
Assembly time FRP	3 days
Construction time concrete	510 days

Table 5.9: Time costs.

Post	Cost [SEK/h]
Labour cost	208
Car delay cost	280
Truck delay cost	347

Table 5.10: Time costs.

Post	GFRP	CFRP	Concrete
Height [m]	1.9	1.26	1.5
Weight [ton]	844	434	4300

6 Discussion

6.1 Structural design of the eco-bridge

On top of the eco-bridge a layer of 1 meter soil giving the load 18 kN/m^2 has been placed. Pre-cambering of the deck for permanent loads has been the solution to handle the immediate deflections. However, this high permanent load means that the designing factor has been the creep deflections and to compensate for the low elastic modulus the height of the deck has had to be high. This introduces another problem namely the risk of web buckling. The two designs presented in this thesis have both been designed for creep deflections and validated against buckling failure. While FRP composites traditionally have a lower elastic modulus they have very high strength. As can be seen in section 4.5.3 *Checks*, the utilization ratios are low and there would seem to be room for improvement to get these higher as low utilization ratios can be seen as a measure of inefficiency in the usage of materials. However, the decks are highly optimized towards the deflection and it would be hard to increase the utilization ratios without completely rethinking the concept. There is also an inherent safety in having a structure that is designed towards SLS rather than ULS in that an unexpected increase in load will only result in inconvenience for the users rather than a possible catastrophic failure of the entire structure.

The aesthetic part of the design has been completely disregarded in this project. It is possible that different government instances have an interest in that eco-bridges built in natural preserve areas have a visual appeal and this should then be considered. However, the aim of this project has not been to make a design but to evaluate FRP as a building material for eco-bridges. FRP is a material that allows for great freedom in what shape and form a structure can have and the designs presented in this report can easily be redesigned into for example an arch as the one used for the Sandsjöbacka eco-bridge. This would naturally change the structural performance and as a consequence the material usage but the final cost of such a design should have similar results in an LCC analysis.

6.2 Thoughts on *Prospect for New Guidance in the Design of FRP*

This project have tested out the PGD. As of now the PGD is a relatively easy to use design code compared to the Eurocodes. The way PGD handles different situations and service climates by the conversion factor method is reminiscent of how Eurocode 5 handles different service conditions for timber structures. However, the creep reduction conversion factor is a much simpler way to handle creep than how for example Eurocode 2 handles creep in concrete.

Regarding the creep, there is much uncertainty about the true creep behaviour of FRP composites. There is a lot of research to be found regarding this but it lays in the nature of creep, which is a long time phenomenon, that it also takes a long time to examine it. Outside of the lab environment the oldest FRP bridge as of today is only 25 years and there are much fewer FRP bridges than concrete. This uncertainty is reflected in the PGD as for this project the reduction of material strength via the conversion factor η_{cv} has been 0.47. This is a very severe reduction and this factor alone has been governing for the whole design. However table 2.4 in PGD states that creep should not be accounted for in the calculations of stability which in the case of the projects have been buckling and can thus help reduce the material usage significantly. This was tested out and it was shown that by excluding the creep the number of longitudinal stiffeners could be reduced from two to one in both designs. This exclusion however is nothing that was done for the final designs as buckling in this project is the governing ULS check and it is the authors beliefs that the decks out of safety reasons must be validated against creep in the ULS.

6.3 Economical aspects

The most noteworthy difference in the LCC analysis is the large difference in construction cost between the GFRP alternative and the concrete eco-bridge. As the Swedish Transport Administration payed PEAB for the construction of the eco-bridge ("utförandeentreprenad") no documentation on what the 57.4 million SEK have been used for have been available and only speculations can be done. One possible reason for the high price could be the many more hours on site it has taken to build the eco-bridge compared to manufacturing the GFRP deck as work have sometimes taken place during night as well as day. There has probably also been a greater need for workers than what is needed for the production of FRP structures. As this eco-bridge is the first of its kind in Sweden there is also the possibility that the lack of experience has increased the cost of construction.

The increase of social costs for the accident on 26th of January 2017 have been estimated to 6.9 million SEK. The first 27 hours directly after when the traffic had to be rerouted costed 2 million SEK. It was assumed that all traffic was rerouted the shortest way and that all vehicles could travel at maximum speed on this road. This assumption completely disregards that the reroute road is not dimensioned for the traffic load of 46 000 cars/day meaning that the estimated cost is the lowest possible cost for the accident. Any refinement of this model would thus result in an increase of social cost for the accident.

The sensitivity analysis done on the working hours shows that the breaking point when the GFRP alternative have a higher construction cost is approximately at 120 000 hours. The actual production time would most likely be significantly lower than this but it suggests that the GFRP design is rather insensitive to the amount of working hours required. However, there is another aspect to account for than just the purely economical one. 120 000 hours would mean a full working year of 64 workers and even though it might be economically defensible it could be regarded as impractical. It is thus out of importance to in an early stage of planning involve potential manufacturers and work closely with them to optimize the design towards production time.

7 Conclusion

Two decks to be used as an eco-bridges have been designed. One made out of glass fibre FRP and one in carbon fibre FRP. To verify the structural performance the design guide *Prospect for Guidance in the Design of FRP* (PGD) have been used. Both decks have in the ultimate limit state been verified against material strength failure and buckling failure. In the service limit state both decks fulfill the demand of a maximum deflection of $L/400 = 68$mm. The most noteworthy difference between the two materials is that CFRP have a high E_1 value while GFRP have a, relative to traditional building materials, low E_1 value. GFRP have, however, a significantly higher E_2 value than CFRP and combined with the need for thicker webs thus performs much better in buckling.

Comparing the FRP designs to the built concrete eco-bridge it can be noted that the actual eco-bridge has a design with 4 concrete T sections. A beam-deck system was also considered early in this project but was disregarded to get an overall lower height of the bridge. Designing an eco-bridge using FRP yields comparative dimensions to those of a concrete equivalent. The height of the actual eco-bridge is 1.5 m while the CFRP alternative manages to be lower than this with a height of 1.26 m. The GFRP design, however, is higher with a height of 1.89 m. Thus it can be concluded that FRP is a viable alternative to reinforced concrete out of a pure structural standpoint.

FRP has a distinct creep behaviour due to the viscoelasticity of polymers that constitutes the matrix. Using the PGD the conversion factor $\eta_{cv} = 0.47$ for a service life of 120 years. The load on the eco-bridge is also almost entirely a permanent soil load which results in a high quasi permanent load combination. It is thus suggested that in future projects where FRP intends to be used for eco-bridges that the creep should be regarded and thought of as early as possible in the planning phase.

To compare the produced designs with the built bridge economically an LCC analysis has been done. This analysis gave the expected total cost of the GFRP alternative to 47 million SEK and the CFRP alternative to 74.5 million SEK. It can from the LCC analysis be concluded that GFRP can be an economical alternative to concrete in the construction of eco-bridges and CFRP can be less expensive if the social costs are included. However, it is important to involve the manufacturers early in the project and work closely with them to optimize the production thus reducing both cost and manufacturing time. Especially for CFRP designs.

7.1 Further studies

As identified the creep of an FRP eco-bridge is important and it would thus be suggested that future studies focus on this. Furthermore must a structure be produced in some way. As this thesis have taken place on the division of Structural Engineering the actual production method of the deck have been handled briefly. This report presents only a theoretical way to produce the FRP decks and a suggestion for future studies would thus be to try to optimize a way for production and assembly of FRP eco-bridges.

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A Analytical calculations for the GFRP deck

Glass fibres

Calculations for a simply supported glass fibre deck as presented in the master thesis *Design of an FRP Ecoduct* (2018) by Emelie Hällerstål and Victor Sandahl. References written in paranthesis are referencing *Prospect for New Guidance in the Design of FRP* (2017) by Ascione et. al.

Contents

Partial and Conversion factors

Partial factors (2.3.4)

$\gamma_{M.sls} := 1.0$

$\gamma_{M1} := 1.0$

$\gamma_{M2.uls} := 1.35$

$\gamma_{M2.glo.stab} := 1.35$

Conversion factors (2.3.6)

$\eta_{ct} := 0.9$ Temperature effects

$\eta_{cm} := 0.9$ Humidity effects

$\eta_{cv} := 0.47$ Creep effects

Strength

$\eta_{c.str} := \eta_{ct} \cdot \eta_{cm} \cdot \eta_{cv} = 0.381$

Momentary deflection

$\eta_{c.md} := \eta_{ct} \cdot \eta_{cm} = 0.81$

Creep

$\eta_{c.cr} := \eta_{ct} \cdot \eta_{cm} \cdot \eta_{cv} = 0.381$

Geometry

Bridge geometry

$L := 27m$ Length of span

$B := 32m$ Width of bridge deck

Dimensions of section

$h_w := 1.9m$ Height of web

$t_w := 16.4 \cdot mm$ Thickness of web

$t_f := 23.8mm$ Thickness of flanges

Width of section (should always be 1m)

$t_{st} := 2mm$ Thickness av stiffener

Number of stiffeners

$t_{vs} := 5.6mm$ Thickness of stiffeners

Number of webs per meter

$cc_{web} := \frac{b}{n_w} = 0.2\,m$ CC distance of webs

Areas of section (width 1 meter)

$A_f := b \cdot t_f = 0.024\,m^2$ Area of one flange

$A_w := t_w \cdot h_w = 0.031\,m^2$ Area of one web

$A_{bc} := h_w \cdot (b - t_w) = 1.869\,m^2$ Area of cross section of 1 meter

$A_{st} := t_{st} \cdot (b - n_w \cdot t_w) = 1.836 \times 10^{-3}\,m^2$ Area of one stiffener

$A_b := 2A_f + n_w \cdot A_w + n_{st} \cdot A_{st} = 0.207\,m^2$ Total material area of section 1 meter

$V_{vs} := (h_w - 2 \cdot t_{st}) \cdot (cc_{web} - t_w) \cdot t_{vs} \cdot n_w = 9.747 \times 10^{-3} \cdot m^3$ Volume of 1 vertical stiffener of section 1 meter

Material input properties

Glass fibres (table 11.1 E-glass)

$E_{1f} := 73.1 GPa$ Young's modulus in direction 1

$E_{2f} := 73.1 GPa$ Young's modulus in direction 2

$\rho_f := 2570 \frac{kg}{m^3}$ Density

$G_f := 30 GPa$ Shear modulus

$v_f := 0.238$ Poisson's ratio

Resin (table 11.2 polyester)

$E_r := 3.55 GPa$ Young's modulus

$\rho_r := 1200 \frac{kg}{m^3}$ Density

$G_r := 1.35 GPa$ Shear modulus

$v_r := 0.38$ Poisson's ratio

Core material (table 11.3 PVC)

$\rho_{foam} := 40 \frac{kg}{m^3}$ Density

Characteristic FRP material properties

$V_f := 0.6$ Fibre fraction

$\varphi_{UD} := 0.97$ Empirical reduction factor (11.6.2.1.(1))

Young's modulus and Shear modulus

$$E_{1k} := \left[E_r + \left(E_{1f} - E_r\right)\cdot V_f\right]\cdot\varphi_{UD} = 43.922\cdot GPa$$

Young's modulus in 1 direction (11.6.2.1.(11.1))

$$\eta_2 := \frac{\left(\frac{E_{2f}}{E_r} - 1\right)}{\left(\frac{E_{2f}}{E_r} + 2\right)} = 0.867$$

$$\eta_G := \frac{\frac{G_f}{G_r} - 1}{\frac{G_f}{G_r} + 1}$$

$$E_{2k} := \left[\frac{\left(1 + 2\cdot\eta_2\cdot V_f\right)}{\left(1 - \eta_G\cdot V_f\right)}\cdot E_r\right]\cdot\varphi_{UD} = 15.558\cdot GPa$$

Young's modulus in 2 direction (11.6.2.1.(11.2))

$$G_{1k} := \left(\frac{1 + \eta_G\cdot V_f}{1 - \eta_G\cdot V_f}\right)\cdot\varphi_{UD}\cdot G_r = 4.489\cdot GPa$$

Shear modulus in 1 direction (11.6.2.1.(11.3))

$$G_{2k} := G_r$$

Shear modulus in 2 direction

$$v_{LT} := v_r - \left(v_r - v_f\right)\cdot V_f = 0.295$$

Poisson's ratio (11.6.2.1.(11.4))

Density

$$\rho_1 := \rho_r + \left(\rho_f - \rho_r\right)\cdot V_f = 2.022\times 10^3\,\frac{kg}{m^3}$$

Linear interpolation of the resulting density of the material

__**Tensile strength, Compressive strength and Shear strength**__

$\varepsilon_{f.t} := 0.038$ Ultimate tensile strain of fibre

$\varepsilon_{f.c} := 0.024$ Ultimate compressive strain of fibre in 1 direction (11.6.4.(8))

$\varepsilon_{f.2c} := 0.024$ Ultimate compressivesrain of fibre in 2 direction

Characteristic strengths

$f1_{kt} := \varepsilon_{f.t} \cdot E_{1k} = 1.669 \times 10^{3} \cdot MPa$ Tensile strength in 1 direction

$f1_{kc} := \varepsilon_{f.c} \cdot E_{1k} = 1.054 \times 10^{3} \cdot MPa$ Compressive strength in 1 direction

$f2_{kc} := \varepsilon_{f.2c} \cdot E_{2k} = 373.382 \cdot MPa$ Compressive strength in 2 direction

Design strengths

$$f1_{dt} := \eta_{c.str} \cdot \frac{f1_{kt}}{\gamma_{M1} \cdot \gamma_{M2.uls}} = 470.664 \cdot MPa$$

$$f1_{dc} := \eta_{c.str} \cdot \frac{f1_{kc}}{\gamma_{M1} \cdot \gamma_{M2.uls}} = 297.261 \cdot MPa$$

$$f_{2dc} := \eta_{c.str} \cdot \frac{f2_{kc}}{\gamma_{M1} \cdot \gamma_{M2.uls}} = 105.294 \cdot MPa$$

$$f1_{ds} := \eta_{c.str} \cdot \frac{50MPa}{\gamma_{M1} \cdot \gamma_{M2.uls}} = 14.1 \cdot MPa$$

Characteristic shear strength is that of polyester (Table 11.2)

Loads

Coefficients

Coefficients according to *Eurocode 1: Actions on structures*

$\mu_1 := 0.8$ $\quad \gamma_g := 1.35$ $\quad \gamma_q := 1.5$

$\psi_{0s} := 0.6$ $\quad \psi_{2s} := 0.1$

Characteristic loads

$$g_k := A_b \cdot \rho_1 \cdot g + \left(h_w - n_{st} \cdot t_{st}\right) \cdot \left(1m - n_w \cdot t_w\right) \cdot \rho_{foam} \cdot g = 4.789 \cdot \frac{kN}{m}$$ Self weight

$$q_k := 18 \frac{kN}{m^2}$$ Soil weight

$$S_k := 1.5 \frac{kN}{m^2}$$ Snow load

Load combinations

$$Q_{uls} := \gamma_g \cdot g_k + \gamma_g \cdot q_k \cdot b + \psi_{0s} \cdot \left(\gamma_q \cdot \mu_1 \cdot S_k \cdot b\right) = 31.845 \cdot \frac{kN}{m}$$ ULS-combination

$$Q_{sls} := g_k + q_k \cdot b + \psi_{0s} \cdot \left(\gamma_q \cdot \mu_1 \cdot S_k \cdot b\right) = 23.869 \cdot \frac{kN}{m}$$ SLS-combination

$$Q_{quasi} := g_k + q_k \cdot b + \psi_{2s} \cdot \left(\gamma_q \cdot \mu_1 \cdot S_k \cdot b\right) = 22.969 \cdot \frac{kN}{m}$$ Quasi permanent combination

Loads without self weight

$$Q_{uls.a} := Q_{uls} - \gamma_g \cdot g_k = 25.38 \cdot \frac{kN}{m}$$

$$Q_{sls.a} := Q_{sls} - g_k = 19.08 \cdot \frac{kN}{m}$$

$$Q_{quasi.a} := Q_{quasi} - g_k = 18.18 \cdot \frac{kN}{m}$$

Moment and Shear force

$$M_{uls} := \frac{Q_{uls} \cdot L^2}{8} = 2.902 \cdot MN \cdot m$$

$$M_{uls.quasi} := \frac{Q_{quasi} \cdot L^2}{8} = 2.093 \cdot MN \cdot m$$

$$V_{uls} := \frac{Q_{uls} \cdot L}{2} = 429.906 \cdot kN$$

$$V_{uls.quasi} := \frac{Q_{quasi} \cdot L}{2} = 310.079 \cdot kN$$

Moment of inertia

$$tp_t := A_f \cdot \left(\frac{t_f}{2}\right) + n_w \cdot A_w \cdot \left(t_f + \frac{h_w}{2}\right) + A_f \cdot \left(t_f + h_w + \frac{t_f}{2}\right) + A_{st} \cdot \left(t_f + \frac{h_w}{3}\right) + A_{st} \cdot \left(t_f + \frac{2 \cdot h_w}{3}\right)$$

$$tp := \frac{tp_t}{A_b} = 0.974\,\mathrm{m}$$

Rotation centre of cross section

$$I_f := \frac{b \cdot t_f^{\,3}}{12} + A_f \cdot \left(\frac{t_f}{2} + \frac{h_w}{2}\right)^2 = 0.022\,\mathrm{m}^4$$

Moment of inertia of flanges

$$I_w := \frac{t_w \cdot h_w^{\,3}}{12} = 9.374 \times 10^{-3}\,\mathrm{m}^4$$

Moment of inertia of webs

$$I_b := 2 \cdot I_f + n_w \cdot I_w = 0.091\,\mathrm{m}^4$$

Total moment of inertia

ULS

Material properties in ULS

$$E_{1d.uls} := \eta_{c.str} \cdot \frac{E_{1k}}{\gamma_{M1} \cdot \gamma_{M2.uls}} = 12.386 \cdot GPa$$

$$E_{2d.uls} := \eta_{c.str} \cdot \frac{E_{2k}}{\gamma_{M1} \cdot \gamma_{M2.uls}} = 4.387 \cdot GPa$$

$$G_{d.uls} := \eta_{c.str} \cdot \frac{G_{1k}}{\gamma_{M1} \cdot \gamma_{M2.uls}} = 1.266 \cdot GPa$$

Global ULS

$$\sigma_{maxC.global} := \frac{M_{uls}}{I_b} \cdot \left(t_f + h_w + t_f - tp\right) = 31.082 \cdot MPa$$ Max compressive stress

$$\sigma_{maxT.global} := \frac{M_{uls}}{I_b} \cdot tp = 31.082 \cdot MPa$$ Max tensile stress

$$\tau_{max} := \frac{V_{uls}}{A_b} = 2.076 \cdot MPa$$ Max shear stress

Creep rupture

$$\sigma_{maxC.cr} := \frac{M_{uls.quasi}}{I_b} \cdot \left(t_f + h_w + t_f - tp\right) = 22.419 \cdot MPa$$ Max creep rupture compressive stress

$$\sigma_{maxT.cr} := \frac{M_{uls.quasi}}{I_b} \cdot tp = 22.419 \cdot MPa$$ Max creep rupture tensile stress

$$f_{Rd.t.cr} := \eta_{ct} \cdot \eta_{cm} \cdot \frac{0.3 \cdot f1_{kt}}{\gamma_{M2.uls}} = 300.424 \cdot MPa$$ Creep rupture tensile strength

$$f_{Rd.c.cr} := \eta_{ct} \cdot \eta_{cm} \cdot \frac{0.9 \cdot f1_{kc}}{\gamma_{M2.uls}} = 569.224 \cdot MPa$$ Creep rupture compressive strength

Utilization ratios

$\frac{\sigma_{maxT.global}}{f1_{dt}} = 0.066$ Tensile stress

$\frac{\sigma_{maxC.global}}{f1_{dc}} = 0.105$ Compressive stress

$\frac{\tau_{max}}{f1_{ds}} = 0.147$ Shear stress

$\frac{\sigma_{maxT.cr}}{f_{Rd.t.cr}} = 0.075$ Tensile creep rupture stress

$\frac{\sigma_{maxC.cr}}{f_{Rd.c.cr}} = 0.039$ Compressive creep rupture stress

SLS

Young's modulus for SLS

$E_{e1\_md} := \eta_{c.md} \cdot \frac{E_{1k}}{\gamma_{M.sls}} = 35.576 \cdot GPa$ Young' modulus for instant deflections in 1 direction

$E_{e2\_md} := \eta_{c.md} \cdot \frac{E_{2k}}{\gamma_{M.sls}} = 12.602 \cdot GPa$ Young' modulus for instant deflections in 2 direction

$E_{e\_cr} := \eta_{c.cr} \cdot \frac{E_{1k}}{\gamma_{M.sls}} = 16.721 \cdot GPa$ Young's modulus with creep effects in 1 direction

Shear modulus for SLS

$G_{e\_md} := \eta_{c.md} \cdot \frac{G_{1k}}{\gamma_{M.sls}} = 3.636 \cdot GPa$ Shear modulus for instant deflections

$G_{e\_cr} := \eta_{c.cr} \cdot \frac{G_{1k}}{\gamma_{M.sls}} = 1.709 \cdot GPa$ Shear modulus with creep effects

E for one ply

$$E_{0k} := \left[\left[\frac{(\cos(0))^4}{E_{1k}}\right] + \left[\frac{(\sin(0))^4}{E_{2k}}\right] + \left(\frac{1}{G_{1k}} - \frac{2\cdot v_{LT}}{E_{1k}}\right)\cdot\frac{1}{4}((\sin(2\cdot 0)))^2\right]^{-1}$$

$$E_{45k} := \left[\left[\frac{\left(\cos\left(45\cdot 2\cdot\frac{\pi}{360}\right)\right)^4}{E_{1k}}\right] + \left[\frac{\left(\sin\left(45\cdot 2\cdot\frac{\pi}{360}\right)\right)^4}{E_{2k}}\right] + \left(\frac{1}{G_{1k}} - \frac{2\cdot v_{LT}}{E_{1k}}\right)\cdot\frac{1}{4}\left[\sin\left[2\cdot\left(45\cdot 2\cdot\frac{\pi}{360}\right)\right]\right]^2\right]^{-1}$$

$E_{0k} = 43.922\cdot GPa$ Characteristic Young's modulus of 0 degree ply

$E_{45k} = 13.496\cdot GPa$ Characteristic Young's modulus of 45 degree ply

$n_{45f} := 12$ Number of 45 degree plies in flange

$n_{45w} := 42$ Number of 45 degree plies in web

$n_{0f} := 107$ Number of 0 degree plies in flange

$n_{0w} := 40$ Number of 0 degree plies in web

$$E_{ply.k.f} := \frac{\left(n_{45f}\cdot E_{45k} + n_{0f}\cdot E_{0k}\right)}{n_{45f} + n_{0f}} = 40.853\cdot GPa$$ Characteristic Young's modulus of flanges

$$E_{ply.k.w} := \frac{\left(n_{45w}\cdot E_{45k} + n_{0w}\cdot E_{0k}\right)}{n_{45w} + n_{0w}} = 28.338\cdot GPa$$ Characteristic Young's modulus of webs

$$E_{ply.k} := \frac{\left(E_{ply.k.f}\cdot 2\cdot I_f + E_{ply.k.w}\cdot I_w\cdot n_w\right)}{I_b} = 34.401\cdot GPa$$ Equivalent characteristic Young's modulus of cross section

$$E_{ply.d} := \eta_{c.md}\cdot\frac{E_{ply.k}}{\gamma_{M.sls}} = 27.865\cdot GPa$$ Young's modulus for instant deflections

$$E_{ply.cr} := \eta_{c.cr}\cdot\frac{E_{ply.k}}{\gamma_{M.sls}} = 13.096\cdot GPa$$ Young's modulus with creep effects

Deflections

$$\delta_{md.bE} := Q_{sls} \cdot \frac{5 \cdot L^4}{384 \cdot E_{ply.d} \cdot I_b} = 0.065\,m$$

Instant deflection

$$\delta_{cr.bE} := Q_{quasi} \cdot \frac{5 \cdot L^4}{384 \cdot E_{ply.cr} \cdot I_b} - \delta_{md.bE} = 0.068\,m$$

Creep deflections after precambring for the instant deflections

B Analytical calculations for the CFRP deck

Carbon fibres

Calculations for a simply supported carbon fibre deck as presented in the master thesis *Design of an FRP Ecoduct* (2018) by Emelie Hällerstål and Victor Sandahl. References written in paranthesis are referencing *Prospect for New Guidance in the Design of FRP* (2017) by Ascione et. al.

Contents

Conversion and Partial factors

Partial factors (2.3.4)

$\gamma_{M.sls} := 1.0$

$\gamma_{M1} := 1.0$

$\gamma_{M2.uls} := 1.35$

$\gamma_{M2.glo.stab} := 1.35$

Conversion factors (2.3.6)

$\eta_{ct} := 0.9$ Temperature effects

$\eta_{cm} := 0.9$ Humidity effects

$\eta_{cv} := 0.47$ Creep effects

Strength

$\eta_{c.str} := \eta_{ct} \cdot \eta_{cm} \cdot \eta_{cv} = 0.381$

Momentary deflection

$\eta_{c.md} := \eta_{ct} \cdot \eta_{cm} = 0.81$

$\eta_{c.cr} := \eta_{ct} \cdot \eta_{cm} \cdot \eta_{cv} = 0.381$

Geometry

Bridge geometry

$L := 27m$ Length of span

$B := 32m$ Width of bridge deck

Dimensions of section

$h_w := 1.26m$ Height of web

$t_w := 11.2 \cdot mm$ Thickness of web

$t_f := 18.3mm$ Thickness of flanges

$b := 1m$ Width of section (should always be 1m)

$t_{st} := 3.6mm$ Thickness av stiffener

$n_{st} := 2$ Number of stiffeners

$t_{vs} := 6mm$ Thickness of vertical stiffeners

$n_w := 5$ Number of webs per meter

$cc_{web} := \frac{b}{n_w} = 0.2\,m$ CC distance of webs

Areas of section (width 1 meter)

$A_f := b \cdot t_f = 0.018\,m^2$ Area of one flange

$A_w := t_w \cdot h_w = 0.014\,m^2$ Area of one web

$A_{bc} := h_w \cdot (b - t_w) = 1.246\,m^2$ Area of cross section of 1 meter

$A_{st} := t_{st} \cdot (b - n_w \cdot t_w) = 3.398 \times 10^{-3}\,m^2$ Area of one stiffener in 1 m

$A_b := 2A_f + n_w \cdot A_w + n_{st} \cdot A_{st} = 0.114\,m^2$ Total material area of section 1 meter

$V_{vs} := (h_w - 2 \cdot t_{st}) \cdot (cc_{web} - t_w) \cdot t_{vs} \cdot n_w = 7.096 \times 10^{-3} \cdot m^3$ Volume of 1 vertical stiffener of section 1 meter

Material input properties

Carbon fibres (table 11.1 HS Carbon fibre)

$E_{1f} := 238GPa$ Young's modulus in 1 direction

$E_{2f} := 15GPa$ Young's modulus in 2 direction

$\rho_f := 1790 \frac{kg}{m^3}$ Density

$G_f := 30GPa$ Shear modulus

$v_f := 0.3$ Poisson's ratio

Resins (table 11.2 epoxy)

$E_r := 3.10GPa$ Young's modulus

$\rho_r := 1250 \frac{kg}{m^3}$ Density

$G_r := 1500MPa$ Shear modulus

$v_r := 0.39$ Poisson's ratio

Foam

$\rho_{foam} := 40 \frac{kg}{m^3}$

Characteristic FRP material properties

$V_f := 0.6$ Fibre fraction

$\varphi_{UD} := 0.97$ Empirical reduction factor (11.6.2.1.(1))

Young's modulus and Shear modulus

$$E_{1k} := \left[E_r + \left(E_{1f} - E_r\right)\cdot V_f\right]\cdot\varphi_{UD} = 139.719\cdot GPa$$

Young's modulus in 1 direction (11.6.2.1.(11.1))

$$\eta_2 := \frac{\left(\frac{E_{2f}}{E_r} - 1\right)}{\left(\frac{E_{2f}}{E_r} + 2\right)} = 0.561$$

$$\eta_G := \frac{\frac{G_f}{G_r} - 1}{\frac{G_f}{G_r} + 1}$$

$$E_{2k} := \left[\frac{\left(1 + 2\cdot\eta_2\cdot V_f\right)}{\left(1 - \eta_G\cdot V_f\right)}\cdot E_r\right]\cdot\varphi_{UD} = 11.009\cdot GPa$$

Young's modulus in 2 direction (11.6.2.1.(11.2))

$$G_{1k} := \left(\frac{1 + \eta_G\cdot V_f}{1 - \eta_G\cdot V_f}\right)\cdot\varphi_{UD}\cdot G_r = 4.911\cdot GPa$$

Shear modulus in 1 direction (11.6.2.1.(11.3))

$$G_{2k} := G_r$$

Shear modulus in 2 direction

$$v_{LT} := v_r - \left(v_r - v_f\right)\cdot V_f = 0.336$$

Poisson's ratio (11.6.2.1.(11.4))

Density

$$\rho_1 := \rho_r + \left(\rho_f - \rho_r\right)\cdot V_f = 1.574\times 10^3\,\frac{kg}{m^3}$$

Linear interpolation of the resulting density of the material

Tensile strength, Compressive strength and Shear strength

$\varepsilon_{f.t} := 0.015$ Ultimate tensile strain of fibre

$\varepsilon_{f.c} := 0.009$ Ultimate compressive strain of fibre in 1 direction (11.6.4.(8))

$\varepsilon_{f.2c} := 0.009$ Ultimate compressivesrain of fibre in 2 direction

Characteristic strengths

$f1_{kt} := \varepsilon_{f.t} \cdot E_{1k} = 2.096 \times 10^3 \cdot MPa$ Tensile strength in 1 direction

$f1_{kc} := \varepsilon_{f.c} \cdot E_{1k} = 1.257 \times 10^3 \cdot MPa$ Compressive strength in 1 direction

$f2_{kc} := \varepsilon_{f.2c} \cdot E_{2k} = 99.077 \cdot MPa$ Compressive strength in 2 direction

Design strengths

$$f1_{dt} := \eta_{c.str} \cdot \frac{f1_{kt}}{\gamma_{M1} \cdot \gamma_{M2.uls}} = 591.011 \cdot MPa$$

$$f1_{dc} := \eta_{c.str} \cdot \frac{f1_{kc}}{\gamma_{M1} \cdot \gamma_{M2.uls}} = 354.606 \cdot MPa \qquad f2_{dc} := \eta_{c.str} \cdot \frac{f2_{kc}}{\gamma_{M1} \cdot \gamma_{M2.uls}} = 27.94 \cdot MPa$$

$$f1_{ds} := \eta_{c.str} \cdot \frac{80MPa}{\gamma_{M1} \cdot \gamma_{M2.uls}} = 22.56 \cdot MPa$$

Characteristic shear strength is that of epoxy (Table 11.2)

Loads

Coefficients

Coefficients according to *Eurocode 1: Actions on structures*

$\mu_1 := 0.8$ $\quad\gamma_g := 1.35$ $\quad\gamma_q := 1.5$

$\psi_{0s} := 0.6$ $\quad\psi_{2s} := 0.1$

Characteristic loads

$g_k := A_b \cdot \rho_1 \cdot g + \rho_{foam} \cdot (h_w - n_{st} \cdot t_{st}) \cdot (1m - n_w \cdot t_w) \cdot g = 2.223 \cdot \frac{kN}{m}$ Self weight

$q_k := 18 \frac{kN}{m^2}$ Soil weight

$S_k := 1.5 \frac{kN}{m^2}$ Snow load

Load combinations

$Q_{uls} := \gamma_g \cdot g_k + \gamma_g \cdot q_k \cdot b + \psi_{0s} \cdot (\gamma_q \cdot \mu_1 \cdot S_k \cdot b) = 28.381 \cdot \frac{kN}{m}$ ULS-combination

$Q_{sls} := g_k + q_k \cdot b + \psi_{0s} \cdot (\gamma_q \cdot \mu_1 \cdot S_k \cdot b) = 21.303 \cdot \frac{kN}{m}$ SLS-combination

$Q_{quasi} := g_k + q_k \cdot b + \psi_{2s} \cdot (\gamma_q \cdot \mu_1 \cdot S_k \cdot b) = 20.403 \cdot \frac{kN}{m}$ Quasi permanent combination

Loads without self weight

$Q_{uls.a} := Q_{uls} - \gamma_g \cdot g_k = 25.38 \cdot \frac{kN}{m}$

$Q_{sls.a} := Q_{sls} - g_k = 19.08 \cdot \frac{kN}{m}$

$Q_{quasi.a} := Q_{quasi} - g_k = 18.18 \cdot \frac{kN}{m}$

Moment and Shear force

$M_{uls} := \frac{Q_{uls} \cdot L^2}{8} = 2.586 \cdot MN \cdot m$ $\quad M_{uls.quasi} := \frac{Q_{quasi} \cdot L^2}{8} = 1.859 \cdot MN \cdot m$

$V_{uls} := \frac{Q_{uls} \cdot L}{2} = 383.143 \cdot kN$

Moment of inertia

$$tp_t := A_f \cdot \left(\frac{t_f}{2}\right) + n_w \cdot A_w \cdot \left(t_f + \frac{h_w}{2}\right) + A_f \cdot \left(t_f + h_w + \frac{t_f}{2}\right) + A_{st} \cdot \left(t_f + \frac{h_w}{3}\right) + A_{st} \cdot \left(t_f + \frac{2 \cdot h_w}{3}\right)$$

$$tp := \frac{tp_t}{A_b} = 0.648\,\text{m}$$

Rotation centre of cross section

$$I_f := \frac{b \cdot t_f^{\,3}}{12} + A_f \cdot \left(\frac{t_f}{2} + \frac{h_w}{2}\right)^2 = 7.476 \times 10^{-3}\,\text{m}^4$$

Moment of inertia of flanges

$$I_w := \frac{t_w \cdot h_w^{\,3}}{12} = 1.867 \times 10^{-3}\,\text{m}^4$$

Moment of inertia of webs

$$I_{st} := \frac{\left(b - n_w \cdot t_w\right) \cdot t_{st}^{\,3}}{12} + A_{st} \cdot \left(\frac{h_w}{6} + \frac{t_{st}}{2}\right)^2 = 1.525 \times 10^{-4}\,\text{m}^4$$

Moment of inertia of stiffeners

$$I_b := 2 \cdot I_f + n_w \cdot I_w + n_{st} \cdot I_{st} = 0.025\,\text{m}^4$$

Total moment of inertia

ULS

Material properties in ULS

$$E_{1d.uls} := \eta_{c.str} \cdot \frac{E_{1k}}{\gamma_{M1} \cdot \gamma_{M2.uls}} = 39.401 \cdot GPa$$

$$E_{2d.uls} := \eta_{c.str} \cdot \frac{E_{2k}}{\gamma_{M1} \cdot \gamma_{M2.uls}} = 3.104 \cdot GPa$$

$$G_{d.uls} := \eta_{c.str} \cdot \frac{G_{1k}}{\gamma_{M1} \cdot \gamma_{M2.uls}} = 1.385 \cdot GPa$$

Global ULS

$$\sigma_{maxC.global} := \frac{M_{uls}}{I_b} \cdot \left(t_f + h_w + t_f - tp\right) = 68.177 \cdot MPa$$ Max compressive stress

$$\sigma_{maxT.global} := \frac{M_{uls}}{I_b} \cdot tp = 68.177 \cdot MPa$$ Max tensile stress

$$\tau_{max} := \frac{V_{uls}}{A_b} = 3.362 \cdot MPa$$ Max shear stress

Creep rupture

$$\sigma_{maxC.cr} := \frac{M_{uls.quasi}}{I_b} \cdot \left(t_f + h_w + t_f - tp\right) = 49.012 \cdot MPa$$ Max creep rupture compressive stress

$$\sigma_{maxT.cr} := \frac{M_{uls.quasi}}{I_b} \cdot tp = 49.012 \cdot MPa$$ Max creep rupture tensile stress

$$f_{Rd.t.cr} := \eta_{ct} \cdot \eta_{cm} \cdot \frac{0.9 \cdot f1_{kt}}{\gamma_{M2.uls}} = 1.132 \times 10^{3} \cdot MPa$$ Creep rupture tensile strength

$$f_{Rd.c.cr} := \eta_{ct} \cdot \eta_{cm} \cdot \frac{0.9 \cdot f1_{kc}}{\gamma_{M2.uls}} = 679.033 \cdot MPa$$ Creep rupture compressive strength

Utilization ratios

$\frac{\sigma_{maxT.global}}{f1_{dt}} = 0.115$ Tensile stress

$\frac{\sigma_{maxC.global}}{f1_{dc}} = 0.192$ Compressive stress

$\frac{\tau_{max}}{f1_{ds}} = 0.149$ Shear stress

$\frac{\sigma_{maxT.cr}}{f_{Rd.t.cr}} = 0.043$ Tensile creep rupture stress

$\frac{\sigma_{maxC.cr}}{f_{Rd.c.cr}} = 0.072$ Compressive creep rupture stress

SLS

Young's modulus for SLS

$E_{e1.md} := \eta_{c.md} \cdot \frac{E_{1k}}{\gamma_{M.sls}} = 113.172 \cdot GPa$ Young' modulus for instant deflections in 1 direction

$E_{e2.md} := \eta_{c.md} \cdot \frac{E_{2k}}{\gamma_{M.sls}} = 8.917 \cdot GPa$ Young' modulus for instant deflections in 2 direction

$E_{e.cr} := \eta_{c.cr} \cdot \frac{E_{1k}}{\gamma_{M.sls}} = 53.191 \cdot GPa$ Young's modulus with creep effects in 1 direction

Shear modulus for SLS

$G_{e1.md} := \eta_{c.md} \cdot \frac{G_{1k}}{\gamma_{M.sls}} = 3.978 \cdot GPa$ Shear modulus for instant deflections

$G_{e.cr} := \eta_{c.cr} \cdot \frac{G_{1k}}{\gamma_{M.sls}} = 1.869 \cdot GPa$ Shear modulus with creep effects

E for one ply

$$E_{0k} := \left[\left[\frac{(\cos(0))^4}{E_{1k}}\right] + \left[\frac{(\sin(0))^4}{E_{2k}}\right] + \left(\frac{1}{G_{1k}} - \frac{2\cdot v_{LT}}{E_{1k}}\right)\cdot\frac{(\sin(2\cdot 0))^2}{4}\right]^{-1}$$

$$E_{45k} := \left[\left[\frac{\left(\cos\left(45\cdot 2\cdot\frac{\pi}{360}\right)\right)^4}{E_{1k}}\right] + \left[\frac{\left(\sin\left(45\cdot 2\cdot\frac{\pi}{360}\right)\right)^4}{E_{2k}}\right] + \left(\frac{1}{G_{1k}} - \frac{2\cdot v_{LT}}{E_{1k}}\right)\cdot\frac{\left[\sin\left[2\cdot\left(45\cdot 2\cdot\frac{\pi}{360}\right)\right]\right]^2}{4}\right]^{-1}$$

$E_{0k} = 139.719\cdot GPa$ Characteristic Young's modulus of 0 degree ply

$E_{45k} = 13.476\cdot GPa$ Characteristic Young's modulus of 45 degree ply

$n_{45f} := 12$ Number of 45 degree plies in flange

$n_{45w} := 8$ Number of 45 degree plies in web

$n_{0f} := 48$ Number of 0 degree plies in flange

$n_{0w} := 30$ Number of 0 degree plies in web

$$E_{ply.k.f} := \frac{\left(n_{45f}\cdot E_{45k} + n_{0f}\cdot E_{0k}\right)}{n_{45f} + n_{0f}} = 114.47\cdot GPa$$

Characteristic Young's modulus of flanges

$$E_{ply.k.w} := \frac{\left(n_{45w}\cdot E_{45k} + n_{0w}\cdot E_{0k}\right)}{n_{45w} + n_{0w}} = 113.141\cdot GPa$$

Characteristic Young's modulus of webs

$E_{ply.k.st} := E_{45k}$ Characteristic Young's modulus of stiffeners

$$E_{ply.k} := \frac{\left(E_{ply.k.f}\cdot 2\cdot I_f + E_{ply.k.w}\cdot I_w\cdot n_w + E_{ply.k.st}\cdot n_{st}\cdot I_{st}\right)}{I_b}$$

$E_{ply.k} = 112.714\cdot GPa$ Equivalent characteristic Young's modulus of cross section

$$E_{ply.d} := \eta_{c.md}\cdot\frac{E_{ply.k}}{\gamma_{M.sls}} = 91.298\cdot GPa$$

Young's modulus for instant deflections

$$E_{ply.cr} := \eta_{c.cr}\cdot\frac{E_{ply.k}}{\gamma_{M.sls}} = 42.91\cdot GPa$$

Young's modulus with creep effects

Deflections

$$\delta_{md} := Q_{sls} \cdot \frac{5 \cdot L^4}{384 \cdot E_{ply.d} \cdot I_b} = 0.066\,m$$

Instant deflection with "real" E

$$\delta_{cr} := Q_{quasi} \cdot \frac{5 \cdot L^4}{384 \cdot E_{ply.cr} \cdot I_b} - \delta_{md} = 0.068\,m$$

Creep deflections after precambring for the instant deflections

C LCC analysis of a GFRP deck, a CFRP deck and Sandsjöbacka eco-bridge

GLASS FIBRE REINFORCED POLYESTER

Total cost of project	
Excluding social costs	**42 441 624**
Including social costs	**47 015 640**

Reference guide
Assumptions
Haghani, Yang
Yang, Kalabuchova
Friberg, Olsson
LO
San mianto bridge
Trafikverket

Planning cost	**Cost [SEK]**
Total cost	**4 000 000**

Construction cost			**Cost [SEK]**
FRP Deck			
Material cost			
Glass fiber	25	SEK/kg	10 625 000
Polyester	20	SEK/kg	5 666 000
Foam	60	SEK/kg	7 236 000
Gel coating	56	SEK/m^2	207 200
			23 734 200
Production			
Labour	208	SEK/h	2 080 000
			2 080 000
Assembly			
Labour	9984	SEK/day	599 040
Equipment	10000	SEK/day	600 000
			1 199 040
Transportation			
Truck	6	SEK/(km*ton)	226 290
			226 290
Foundation and columns			
Material cost			
Concrete	1500	SEK/m^3	1 794 000
Reinforcement	10	SEK/kg	4 664 400
			6 458 400
Construction			
On site casting	9984	SEK/day	599 040
			599 040
Total cost			**34 296 970**

Disposal cost					
Material cost					**NPV**
FRP	1	SEK/kg		828 900	13 356
Concrete	1	SEK/kg		2 990 000	48 176
Steel	-0,5	SEK/kg	-	233 220	- 3 758
Transportation truck	6	SEK/(km*ton)		771 361	12 428
				4 357 041	**70 202**
Demolition					
Labour	9984	SEK/day		1 198 080	19 304
Equipment	10000	SEK/day		1 200 000	19 335
				2 398 080	**38 639**
Total cost				**6 755 121**	**108 841**

Maintenace and repair cost					
Maintenance	Interval	m^2	SEK/m^2	SEK	**NPV**
Washing & painting	10	1728	250	639 200	1 531 668
Reparation of supports	60	437	14000	6 118 000	776 584
					2 308 252
Inspections					
Superficial inspection	1	1728	12	20 736	582 911
General inspection	3	1728	40	69 120	625 530
Major inspection	6	1728	70	120 960	519 120
					1 727 562
Total cost					**4 035 814**

Social cost				
User delay cost				
Cars	280	SEK/h	33 120	
Trucks	347	SEK/h	4 997	
			38 117	**SEK/day**
Total cost			**4 574 016**	**SEK**

Materials in bridge		
Glass fibre	425 000	kg
Polyester	283 300	kg
Foam	120 600	kg
Concrete	1 196	m^3
Steel	466 440	kg
FRP total weight	828 900	kg
Foundation total weight	3 456 440	kg
Area to be painted	3 700	m^2

Assumed times, distances and workers		
Production time FRP deck	10000	h
Assembly time FRP deck	60	days
Construction time foundation	60	days
Demolition time	120	days
Number of workers at site	6	st
Distance to construction site	45,5	km
Disposal distance	30	km

Assumed traffic load		
ÅDT cars	46000	cars/day
ÅDT trucks	5600	trucks/day
Length of affected road	0,6	km
Normal speed	100	km/h
Reduced speed	70	km/h

Other		
Discount rate	3,50%	
Life time	120	

CARBON FIBRE REINFORCED EPOXY

Reference guide
Assumptions
Haghani, Yang
Yang, Kalabuchova
Friberg, Olsson
LO
San mianto bridge
Trafikverket

Total cost of project	
Excluding social costs	**69 999 603**
Including social costs	**74 573 619**

Planning cost	Cost [SEK]
Total cost	**4 000 000**

Construction cost			Cost [SEK]
FRP Deck			
Material cost			
Carbon fibre	150	SEK/kg	35 190 000
Epoxy	100	SEK/kg	11 730 000
Foam	60	SEK/kg	4 904 400
Gel coating	56	SEK/m^2	207 200
			52 031 600
Production			
Labour	208	SEK/h	1 456 000
			1 456 000
Assembly			
Labour	9984	SEK/day	599 040
Equipment	10000	SEK/day	600 000
			1 199 040
Transportation			
Truck	6	SEK/(km*ton)	118 384
			118 384
Foundation and columns			
Material cost			
Concrete	1500	SEK/m^3	1 794 000
Reinforcement	10	SEK/kg	4 664 400
			6 458 400
Construction			
On site casting	9984	SEK/day	599 040
			599 040
Total cost			**61 862 464**

Disposal cost				
Material cost				**NPV**
FRP	1	SEK/kg	433 640	6 987
Concrete	1	SEK/kg	2 990 000	48 176
Steel	-0,5	SEK/kg	- 233 220	- 3 758
Transportation truck	6	SEK/(km*ton)	700 214	11 282
			3 890 634	**62 687**
Demolition				
Labour	9984	SEK/day	1 198 080	19 304
Equipment	10000	SEK/day	1 200 000	19 335
			2 398 080	**38 639**
Total cost			**6 288 714**	**101 326**

Maintenace and repair cost					
Maintenance	Interval	m^2	SEK/m^2	SEK	**NPV**
Washing & painting	10	1728	250	639 200	1 531 668
Reparation of supports	60	437	14000	6 118 000	776 584
					2 308 252
Inspections					
Superficial inspection	1	1728	12	20 736	582 911
General inspection	3	1728	40	69 120	625 530
Major inspection	6	1728	70	120 960	519 120
					1 727 562
Total cost					**4 035 814**

Social cost				
User delay cost				
Cars	280	SEK/h	33 120	
Trucks	347	SEK/h	4 997	
			38 117	**SEK/day**
Total cost			**4 574 016**	**SEK**

Materials in bridge		
Glass fibre	234 600	kg
Polyester	117 300	kg
Foam	81 740	kg
Concrete	1 196	m^3
Steel	466 440	kg
FRP total weight	433 640	kg
Foundation total weight	3 456 440	kg
Area to be painted	3 700	m^2

Assumed times, distances and workers		
Production time FRP deck	7000	h
Assembly time FRP deck	60	days
Construction time foundation	60	days
Demolition time	120	days
Number of workers at site	6	st
Distance to construction site	45,5	km
Disposal distance	30	km

Assumed traffic load		
ÅDT cars	46000	cars/day
ÅDT trucks	5600	trucks/day
Length of affected road	0,6	km
Normal speed	100	km/h
Reduced speed	70	km/h

Other		
Discount rate	3,50%	
Life time	120	

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Total cost of project	
Excluding social costs	**65 884 762**
Including social costs without accident	**80 977 708**
Including social costs with accident	**87 924 612**

Reference guide
Assumptions
Haghani, Yang
Yang, Kalabuchova
Friberg, Olsson
LO
San mianto bridge
Trafikverket

Planning cost	
Total cost	**4 000 000**

Construction cost	
Total cost	**57 400 000**

Disposal cost				
Material cost			**SEK**	**NPV**
Concrete	1	SEK/kg	6 702 500	107 993
Steel	-0,5	SEK/kg	- 522 795	- 8 423
Transportation truck	6	SEK/(km*ton)	1 394 656	22 471
			7 574 361	**122 041**
Demolition cost				
Labour	9984	SEK/day	499 200	8 043
Equipment	10000	SEK/day	500 000	8 056
			999 200	**16 099**
Total cost			**7 574 361**	**138 140**

Maintenance and repair cost					
Maintenance	Year of action	m^2	SEK/m^2	SEK	**NPV**
Reparation of bridge	60	1728	8400	14 515 200	1 842 477
Reparation of supports	60	437	14000	6 118 000	776 584
					2 619 061
Inspections	Interval				
Superficial inspection	1	1728	12	20 736	582 911
General inspection	3	1728	40	69 120	625 530
Major inspection	6	1728	70	120 960	519 120
					1 727 562
Total cost					**4 346 623**
Social cost					

User delay cost				
Cars	280	SEK/h	33 120	
Trucks	347	SEK/h	4 997	
			38 117	**SEK/day**
Total cost ex accident			**19 439 568**	**SEK**

Social cost for accident				
User delay cost during clean up				
Cars	280	SEK/h	1 717 333	SEK/day
Trucks	347	SEK/h	259 093	SEK/day
			2 182 304	**SEK**
User delay cost due to prolonged project				
Cars	280	SEK/h	33 120	
Trucks	347	SEK/h	4 997	
			38 117	**SEK/day**
Total cost inc accident			**26 386 472**	**SEK**

Materials in bridge		
Concrete	2 681	m^3
Steel	1 045 590	kg
Total weight	7 748 090	kg
Assumed times and distances		
Construction time ex accident	510	days
Demolition time	50	days
Disposal distance	30	km
Assumed traffic load		
ÅDT cars	46000	cars/day
ÅDT trucks	5600	trucks/day
Length of affected road	0,6	km
Normal speed	100	km/h
Reduced speed	70	km/h
Accidental information		
Re route extra time	8	min/vehicle
Closed time	1,104166667	days
Construction time inc accident	635	days
Other		
Discount rate	3,50%	
Life time	120	

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