



INNOVATIVE MATERIAL SOLUTIONS FOR ECONOMICAL COMPOSITE
BRIDGES WITH LARGE SPANS AND CONSTRAINED SLENDERNESS

Alwin P. Wilken

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“INNOVATIVE MATERIAL SOLUTIONS FOR ECONOMICAL COMPOSITE
BRIDGES WITH LARGE SPANS AND CONSTRAINED SLENDERNESS”

ALWIN WILKEN

JANUARY 2016

Delft University of Technology
Faculty of Aerospace Engineering
Department of Aerospace Structures and Materials
Section Structural Integrity and Composites
Delft, The Netherlands
www.tudelft.nl



Thesis committee

Prof. dr. ir. Rinze Benedictus

Professor at Delft University of Technology, Faculty of Aerospace Engineering, Head of Department of Aerospace Structures and Materials

Dr. ir. Wim Bierbooms

Assistant Professor at Delft University of Technology, Faculty of Aerospace Engineering, Department of Aerodynamics, Wind Energy and Propulsion

Dr. ir. Otto Bergsma

Assistant Professor at Delft University of Technology, Faculty of Aerospace Engineering, Department of Aerospace Structures and Materials, Section Structural Integrity and Composites

Dr. ir. Martijn Veltkamp

Head of Engineering Department at FiberCore Europe B.V.



Abstract

FiberCore Europe is a Dutch company, specialized in the design and manufacturing of composite, load-bearing structures for architecture and infrastructure. The company's main focus is on bridges and lock gates made from glass fiber reinforced polymer (GFRP). The price for currently produced GFRP bridges longer than approximately 26 meter is often higher than the price for bridges made from conventional steel or reinforced concrete. FiberCore Europe is looking for ways to lower the material costs for longer composite bridges to expand their market. This research focusses on two solutions to lower the material costs. These solutions are based on the implementation of stiffer material in the current GFRP bridge concept. Doing so yields a hybrid composite structure. The two materials addressed in this study are structural steel and standard modulus carbon fibers. Combining glass fibers, polyester and fully embedded steel or carbon fibers in large, load-bearing civil engineering structures is a new topic. This requires research on material behavior and design modelling.

Tests are performed to assess the corrosion characteristics of steel embedded in GFRP and the strength of the adhesive bond between GFRP and steel. A comparison of 14 different carbon fiber fabrics was made to determine the most suitable carbon fabric in combination with a polyester matrix. Hybrid carbon-glass-polyester laminates were built and tested. A design model has been created to compare different hybrid design sub-concepts with each other and with the reference GFRP bridge. The model is implemented in a Microsoft Excel design tool. The tool shows that it is possible to lower the material costs, the mass and the design height of a GFRP bridge simultaneously by embedding steel. Carbon fibers can lower the mass and the design height of the bridge even more, but only at increased material costs. Initial concerns with respect to the interfacial bond strength between carbon fibers and polyester were confirmed. Taking the total costs of ownership into account, hybrid composite bridges are cheaper than bridges from conventional materials. This is mainly due to the savings on maintenance costs over a design lifetime of 100 years.



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List of Abbreviations

AADT	Annual average daily traffic
CLC	Combined loading compression
COV	Coefficient of variation
CTE	Coefficient of thermal expansion
CFRP	Carbon fiber reinforced polymer
DASM-lab	Delft Aerospace Structures and Materials Laboratory
FAW	Fabric areal weight
FEA	Finite elements analysis
FRP	Fiber reinforced polymer
GFRP	Glass fiber reinforced polymer
ILSS	Inter-laminar shear strength
LCC	Life-cycle costs
PU	Polyurethane
SBS	Short-beam strength
SLS	Serviceability limit state
TCO	Total cost of ownership
TDS	Technical data sheet
UD	Unidirectional
ULS	Ultimate limit state
UP	Unsaturated polyester



Nomenclature

Note: some symbols are used more than once for different physical quantities. This is done mainly to retain the nomenclature as used in the respective test standards. From the context in this report it should be clear which quantity is meant.

A	Surface area
b	Specimen width
b	Width of the bridge
E	Stiffness
EI	Flexural rigidity
F	Short-beam strength
f	Frequency
g	Gravitational acceleration
h	Specimen thickness
h	Height of the bridge
I	Second moment of area
K	Harmonic constant
L	Length of the bridge
L	Bonded overlap length
m	Mass of the bridge
P	Applied force
p	Pressure
q	Distributed load
T	Temperature
t	Thickness
w	Width of a test specimen
w	Weight of the bridge
w^*	Pedestrian adjusted bridge weight



Greek letters

α	Coefficient of thermal expansion
γ	Reduction factor
Δ	Change or difference of a quantity
δ	Deflection
ν_f	Fiber-volume fraction
ρ	Density
σ	Normal stress
τ	Shear stress

Subscripts

0	design or initial value
<i>c</i>	composite
<i>con</i>	contraction
<i>css</i>	conversion, short, strength
<i>csv</i>	conversion, short, vibrations
<i>exp</i>	expansion
<i>f</i>	failure
<i>f</i>	fiber
<i>m</i>	matrix
<i>m</i>	material
<i>m1</i>	related to material uncertainties
<i>m2</i>	related to manufacturing uncertainties
<i>max</i>	maximum
<i>min</i>	minimum
<i>n</i>	natural or related to the mode of vibration
<i>o</i>	related to the bonded overlap
<i>sls</i>	serviceability limit state
<i>uls</i>	ultimate limit state
<i>x</i>	in longitudinal or 0° direction
<i>y</i>	in transverse or 90° direction



1

Introduction

In the 60s and 70s of the previous century, many steel and concrete bridges and overpasses have been built in the Netherlands. With the knowledge available at that time about materials, building methods, traffic densities and loads, the structures were supposed to perform their function for at least 60 to 80 years. Over time, the annual average daily traffic (AADT) has increased more than initially expected and the mass of the passing vehicles has increased considerably as well. On top of this, applicable design standards nowadays are often stricter than before. As a result, many bridge and overpass structures in the Netherlands are currently in dire need of repairs or even complete replacement.

Fiber reinforced polymers (FRP) can play an important role in this. These types of materials are best-known for their high strength and high stiffness over weight ratios. This makes them very suitable for structures where weight reductions have a direct benefit. While this aspect can certainly be of interest for (moveable) bridges, FRP materials have other properties that make them very interesting candidates for static, civil engineering structures. When implemented well, the low-maintenance and fatigue-resistant properties of FRP can make them superior building materials when compared to steel or concrete.

FiberCore Europe is a Dutch company specialized in the design and manufacturing of composite¹, load-bearing structures for architecture and infrastructure. The main focus lies currently on bridges and lock gates. The bridges are self-supporting sandwich structures with a foam core and glass fiber reinforced polymer (GFRP) shear webs and face sheets. A typical cross-section of FiberCore Europe's composite bridges is shown in Figure 1.1.

¹ In the aerospace industry the term "composite" refers in general to a fiber reinforced polymer (FRP) material. In the civil engineering world this term is often used to refer to a combination of steel and concrete. Any mention of the term "composite" in this report refers to the fiber reinforced polymer material.



1. Introduction

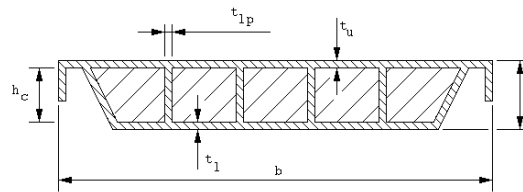


Figure 1.1: cross-section of a GFRP bridge as built by FiberCore Europe

The longest single-span, all-composite bridge manufactured by FiberCore Europe so far has a length of 26 meter. This bicycle bridge is installed in Rozenburg, the Netherlands and shown in Figure 1.2.



Figure 1.2: a 26 meter long all-GFRP bicycle bridge near Rozenburg, the Netherlands

FiberCore Europe perceives an increasing market demand for longer composite bridges. From a technical perspective it is possible to manufacture bridges with longer spans and without intermediate supports from the same material as used now. However, to meet the prevailing stiffness requirements, this requires the design height of the bridge to increase. An increased bridge height poses three disadvantages:

- The costs for the construction materials increase quickly with increasing height. For bridges longer than approximately 26 meter, bridges made from conventional materials are more likely to be cheaper than all-GFRP bridges.
- A higher bridge poses restrictions on the clearance underneath the bridge. The maximum height of traffic over water, roads or railroads going underneath the bridge decreases. As an alternative, the bridge can be placed higher. This, however, requires



steeper and/or longer slopes towards the bridge. Even if the space to achieve this is available, extra costs have to be made.

- The slenderness of a bridge is defined as the length of the bridge divided by its height. A less-slender bridge can be perceived as less appealing to the eye. This is purely a subjective matter of aesthetics, but can still play a decisive role in tender procedures.

From the above it is clear that preference will be given to more slender bridge designs, which leads to the problem definition of this thesis work.

1.1 Problem statement

FiberCore Europe is currently manufacturing single-span composite bridges up to a length of 26 meter. The company is looking to expand its market share by offering longer composite bridges, still without intermediate supports. The currently used materials and production methods can be used to do this. However, the height of the bridge then increases rapidly with increasing span. An increased height results in an increase in costs. Longer bridges made from conventional materials become more interesting and all-GFRP bridges are much harder to sell.

1.2 Proposed solution and goal

The main contributor to the rapid rise in costs is the increase in required design height of the bridge. With the currently used materials, this height is necessary to fulfill the stiffness requirements. A solution to this challenge is the use of stiffer materials. Replacing some parts of the currently used GFRP material by materials with a higher stiffness can reduce the required design height. The newly introduced materials need to become an integral part of FiberCore Europe's current manufacturing process. Two materials are proposed as potential candidates: structural steel and standard modulus carbon fibers. The argumentation for these specific choices and restrictions on their implementation will be given in the next chapter. With a possible solution to the problem given, the main aim of this thesis project can be described as follows:

The goal of this study is to find a combination of hybrid composite materials and design concepts in order to yield a technical and commercially applicable solution for composite bridges with a span longer than 26 meter.

1.3 Research questions

FiberCore Europe uses vacuum infusion for the production of their composite bridges. Polyester resin is used as matrix material to hold the glass reinforcement fibers in place. Adding steel or carbon fibers to this system poses a number of new challenges. For large, load-bearing civil engineering structures, these challenges are completely new and require in-debt research. The aim of the research, combined with the proposed solution, results in the main research question:



Is it technically feasible to make bridges of hybrid composite material which are commercially more attractive than conventional steel or reinforced concrete bridges as the length of the span increases beyond 26 meter?

This question can only be answered by dividing the design challenge into smaller sub-problems. By doing so, the following sub-questions arise:

- What boundary conditions are applicable for a representative bridge design?
- Which (combination of) composite materials have the largest potential to be successfully implemented?
- How can these hybrid composite materials be implemented in a bridge design so that it performs its function efficiently and can still be manufactured?
- Which carbon fiber performs the best in combination with polyester (combination of price and stiffness)?
- What are the material properties of the most suitable carbon with polyester?
- What are the material properties of polyester, glass fiber and carbon fiber combined?
- What is the strength of the adhesive bond between steel and GFRP?
- How corrosion resistant is steel embedded in GFRP?
- Can a conceptual design model be developed which determines the most suitable combination of construction materials as a function of the bridge's span and thickness?

All these sub-questions have been studied and are addressed in their respective chapters in this report. An overview of the work done and of the structure of this report is shown in the work breakdown structure in Figure 1.3. In this diagram all work packages and their interdependencies are visualized. At the start of the thesis project a literature research has been conducted in order to establish a firm theoretical base on which the rest of the study is built. This literature review is attached to this report and can be found in Appendix A. It must be noted that, due to time constraints for the entire project, the long-term behavior of the proposed hybrid concepts is not addressed in this thesis work. Fatigue, creep and durability of bond strengths are therefore not addressed.

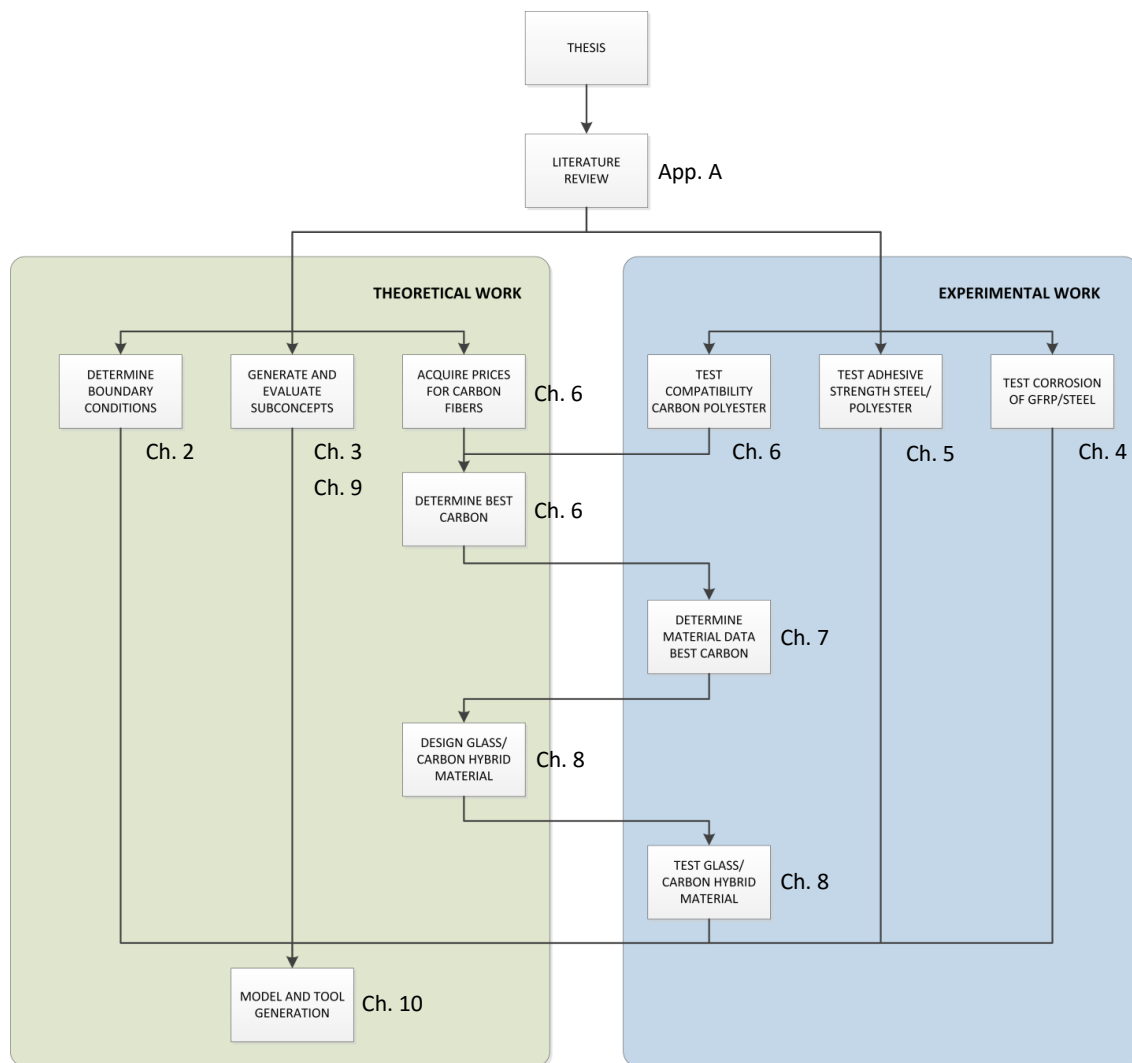


Figure 1.3: the work breakdown structure



2

Design boundary conditions

FiberCore Europe manufactures composite bridges that can compete in price with bridges made from conventional materials as timber, concrete and steel. At the time of writing, more than 500 composite bridges are built and installed by FiberCore Europe all over the world, showcasing the success of this still relatively young product. The largest of these fully composite bridges without intermediate supports has a length of 26 meter. Bridges with a longer span can still be built from GFRP from a structural point of view. The price, however, increases rapidly with increasing span. This is mainly due to an increase in bridge height as a result of stiffness requirements. In FiberCore Europe's current design concept, a higher bridge requires more relatively expensive core material. Purely looking at the costs for building materials, bridges made from conventional materials become more interesting when the span increases.

To overcome this challenge and be able to manufacture competitive composite bridges, means to lower the price are needed. Using the GFRP bridge as a starting point, and retaining FiberCore Europe's building principles for composite bridges, a number of options present themselves:

- The glass reinforcement fibers can (partially) be replaced by other, stiffer types of fibers.
- Other polymers for the matrix than the currently used polyester can be looked at.
- Lighter and/or cheaper core materials might be investigated.
- Adding other materials to increase stiffness and/or lower the price.
- Redesign of the bridge or manufacturing process which leads to a cheaper product due to lower costs of labor and/or material.

From the start of this project it became clear that FiberCore Europe's engineering department already spent some time and thoughts on the issues above. It was decided that the focus of this thesis project should be on the implementation of either carbon fibers or steel in the existing GFRP structure. Other fiber materials are too experimental, too expensive or not easily available in large quantities from reliable suppliers to be considered as serious candidates.



Polyester is cheap compared with alternatives as vinyl ester or epoxy and should be used as starting point. Only when compatibility with the carbon fibers turns out to be really problematic, other resin materials could be investigated. In consultation with the project coordinators, it is decided that a redesign in which the core material is replaced or made obsolete falls outside the scope of this thesis project.

Steel is known as “cheap stiffness” compared with composite material. Weight increase is the penalty, which should be investigated. Bridge structures with composite decks placed on steel girders (slab-on-girder bridges) already exist and are not innovative. Also, to benefit from the low-maintenance characteristics of fiber-reinforced polymer (FRP) materials, one of the most important advantages of composites in civil engineering structures, the steel should be embedded inside the polyester structure.

A comparison of the structural properties of steel, GFRP and CFRP in the context of bridge design is made in Appendix B. In the following sections the most important boundary conditions for all hybrid composite bridge designs are described.

2.1 Design and manufacturing

From the chapter’s introduction, the following general, design-related boundary conditions for a hybrid FRP composite bridge design can be formulated:

- Comply to FiberCore Europe’s proprietary manufacturing process
- Consider steel and carbon fibers as potential candidates
- Embed the steel inside the structure

2.2 Geometry

Other than the previous generic boundary conditions with respect to the design philosophy, some more practical, numerical boundary conditions are imposed to aid in the design of a hybrid composite bridge. An actual customer inquiry serves as the basis for the following restraints:

- Bridge type: pedestrian / bicycle bridge
- Length: 45 meter
- Width: 4.7 meter

These numbers will be used initially as input for the hybrid composite bridge designs. In a later stage, the length and width of the bridge can be changed to see what the effects are on parameters as costs and mass. Constraints on individual elements of design sub-concepts (e.g., the maximum thickness of steel flanges in a box girder or the minimum width of a bar-element) are too specific for this chapter and will be discussed in a later stage, after the sub-concepts are defined and described.

2.3 Deflection

When a composite bridge is manufactured by vacuum infusion, the whole structure is supported by a mold, giving it its initial shape. After curing in this form, the bridge is hoisted



from the mold and installed on location. For a single-span bridge, the structure is no longer supported over its entire span, but only at its ends. The weight of the bridge, which can be seen as a distributed load acting on the structure, will cause vertical deflections. Once the bridge is taken into use, there will be additional deflections as a result of traffic loads. For a pedestrian/bicycle bridge, the following restraint on the deflection is defined:

- Static load: 5000 N/m² (NEN [1])
- Maximum deflection due to static load: $\text{Length} / 100 = 45$ centimeter

The reasoning behind this load case needs some clarification. In previously applicable standards, the maximum deflection of a bridge was prescribed as follows:

- If the eigenfrequency of a bridge is larger than 4.6 Hz, the maximum deflection at mid-span has to be smaller than or equal to the length of the bridge divided by 150.
- If the eigenfrequency of a bridge is smaller than 4.6 Hz, but larger than or equal to 2.3 Hz, the maximum deflection at mid-span has to be smaller than or equal to the length of the bridge divided by 250.

Currently, Dutch laws no longer prescribe limits for the maximum deflection of composite bridges. FiberCore Europe adopted the regulatory rules above as design guidelines and kept using them. However, in practice it turned out that bridges designed in compliance with these guidelines were much stiffer and with that, more expensive than bridges offered by competing companies. Some tenders have been lost for this reason. After numerous debates within the company a compromise was reached; an upper limit for the maximum deflection of the bridges is still maintained, but this restriction is loosened to a value equal to the length of the bridge divided by 100.

2.4 Eigenfrequency

The frequency of a pedestrian walking over a bridge lies somewhere between 1.4 and 2.0 Hz. (Pachi, et al. [2]) To prevent excitation of the bridge at its eigenfrequency, with the accompanying increasing vertical accelerations, a lower limit of 2.3 Hz on the eigenfrequency is imposed. This is mainly a comfort-related restraint and does not follow from a safety point-of-view. Tests at FiberCore Europe have shown that deliberate attempts to excite a composite bridge into infinite deflections failed as soon as the acceleration exceeded just over 1 g. At that point the test subjects lost physical contact with the bridge and no more energy could be transmitted into the bridge. The structural integrity of the bridge was not harmed in any way. When more than two people utilize the bridge, the frequency of walking is always out of phase, resulting in damping of any excitation.

To characterize the eigenfrequency behavior of a bridge, loads according to the EUR23984 design guideline (Heinemeyer, et al. [3]) are used. This document advises to incorporate the weight of pedestrians in the determination of the eigenfrequency. For the calculations, the weight of one person is assumed to be 800 N and the density of the traffic is set according to traffic class 3. The latter is defined as “dense traffic” with a pedestrian density of 0.5 P/m²,



where P stands for pedestrian. A load of 0.5 times 800 = 400 N/m² is added to the weight of the bridge for the determination of the eigenfrequency.

- Load for eigenfrequency analysis: weight bridge + 400 N/m²
- Minimum required eigenfrequency: 2.3 Hz

2.5 Costs

The final boundary condition results from the premise of this thesis project; the total costs of ownership (TCO) of the hybrid composite bridge should be lower than the TCO of a bridge with the same characteristics as above, built from conventional construction materials.

2.6 References

- [1] NEN-EN 1991-2+C1 - Eurocode 1: Actions on structures - Part 2: Traffic loads on bridges, NEN, 2011
- [2] Pachi, A. and Ji, T., *Frequency and velocity of people walking*. The Structural Engineer, 2005. 83(3).
- [3] Heinemeyer, C., et al., *Design of Lightweight Footbridges for Human Induced Vibrations Background document in support to the implementation, harmonization and further development of the Eurocodes*. Editors: G. Sedlacek, Chr. Heinemeyer, Chr. Butz together with M. G rardin JRC, 2009.



3

Design sub-concepts

The focus of this study is to find ways to build long composite bridges in a cheaper way than building bridges from conventional materials. FiberCore Europe already makes competitive bridges from glass fiber reinforced polyester up to a length of approximately 26 meter. This upper boundary for a glass fiber reinforced polyester bridge is not directly prescribed from a structural point of view; it is more an economical limit. The amount of material needed to meet the stiffness requirements for these large bridges increases rapidly with length. This is the reason that these bridges are no longer able to compete on initial costs alone with bridges from conventional materials. The material increase is mainly due to the required increase in bridge height. This height can be restricted when materials with a higher stiffness are incorporated.

Two materials are proposed: structural steel and standard modulus carbon fibers. These materials possess approximate Young's moduli of 210 GPa and 240 GPa respectively. This is up to three times stiffer compared to glass fibers with a Young's modulus of 79 GPa. The fibers, both carbon and glass, however, are combined with a polyester resin to perform their load-carrying function. Depending on the mixing ratio, the overall material stiffness drops significantly due to the relatively low stiffness of the polyester resin (3.8 GPa). For a fiber volume fraction of 50%, the theoretical stiffnesses of unidirectional GFRP and CFRP laminates are 41 GPa and 123 GPa respectively.

In this chapter an overview is given of a number of conceptual designs in which either steel or carbon is added to the pre-existing InfraCore Inside bridges. Per sub-concept the design philosophy and the specific advantages and disadvantages are outlined.

3.1 InfraCore inside technology

In order to understand the design philosophy of the sub-concepts in which either steel or carbon is implemented, it is important to understand the current way FiberCore Europe is building bridges and the reasoning behind this way of manufacturing.



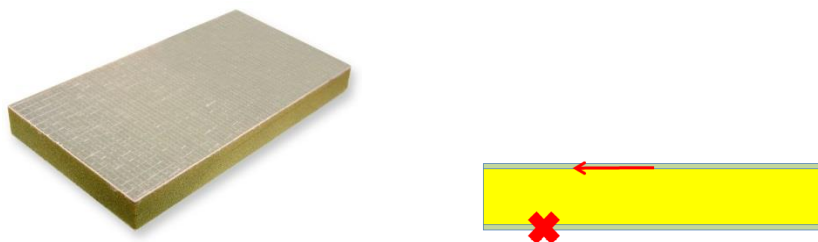
FiberCore Europe's general design philosophy with respect to composite materials is as follows:

"Do not use composite materials in infrastructure, unless these materials and structures are robust and damage tolerant."

This statement might seem very obvious, but numerous examples can be found where things have gone wrong simply because this advice is not followed. Unfortunately not only examples from the past are known, but also nowadays flawed bridge structures reach the market where problems are eventually inevitable.

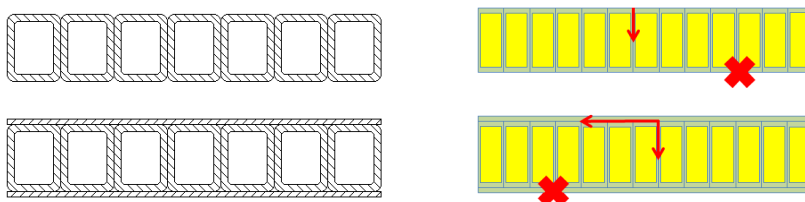
Where it comes to composite bridges, three techniques or designs are often seen: classic sandwich structures, multi-beam plates and pultrusions. All these concepts have their own inherent weaknesses of cracking, delamination or debonding, making them unsuitable for bridges with dense traffic.

3.1.1 Classic sandwiches



The bending resistance of a classical sandwich panel relies for a very large part on the bond strength between the load-bearing skins or face sheets and the lightweight core material. After local impact damage, debonding of the skin from the core occurs when the panel is frequently loaded by for example the wheels of passing vehicles. An initial crack can grow unhindered between the skin and the core until the structure fails completely. Failed structures in the field have exposed numerous parts where, during the production process, the core material was not even bonded over its entire surface to the face sheets.

3.1.2 Multi-beam plates

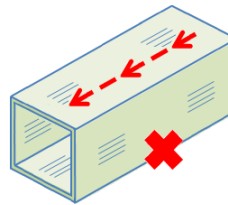


Multi-beam plates consist of a series of box-beams, joined together. In some cases additional close-out skins are added for extra structural coherence. Also in these structures initial cracks and delaminations can grow unhindered between the box-beams and between these beams and the skin panels. These defects can eventually lead to catastrophic failure. The fatigue-life



after impact reduces significantly and in-situ repairs have to be carried out. However, the need for these repairs requires detection of the damage in time.

3.1.3 Pultrusions

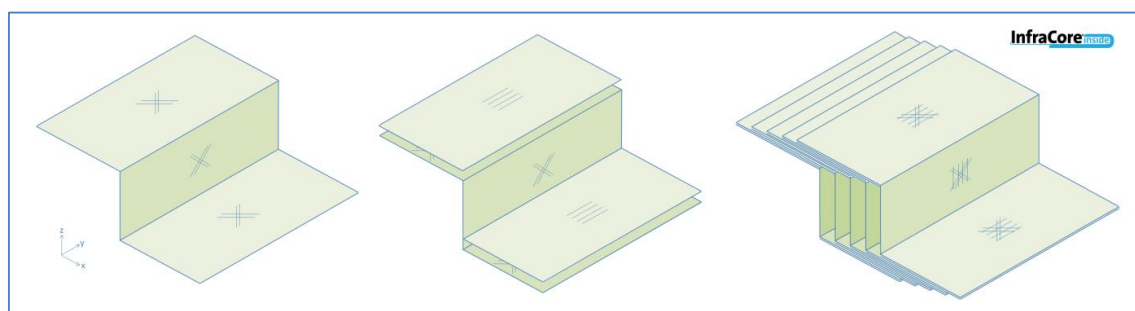


In spite of research and improvements in the field of pultrusion techniques, the direction of the reinforcement fibers in these kind of elements are currently still mainly in the longitudinal direction (>90%). Due to the small amount of fibers in off-axis direction, their function as crack arrestors is minimal; cracks between the fibers can propagate easily in longitudinal direction after initiation. Many examples of failed pultruded elements in bridge structures can be found in practice. These elements have to be replaced in almost all cases, rather than repaired. Bonded repairs have shown new crack initiation and growth, likely due to the brittle nature of the bond.

3.1.4 InfraCore Inside

FiberCore Europe developed an innovative way to manufacture composite bridges so that the inherent weaknesses of the structures above are overcome. Due to the application of a proprietary technique with the name InfraCore Inside, structures become very robust and keep performing their function under continuous fatigue loading, even after impact damage.

An InfraCore Inside bridge is built up from lightweight foam core cells, wrapped in dry fabric of glass reinforcement fibers. Between, over and under these core cells, one or more so-called Z-layers are draped. The core cells and Z-layers are placed alternately in a mold in the width direction of the product. For added strength or stiffness, extra fabrics can be placed between the Z-layers in longitudinal direction. The integrity of the PU foam core is not guaranteed over a design life of 100 years and it is therefore assumed that this material has no structural function. The contribution to stiffness or stability of the core material is ignored in any structural analysis. Figure 3.1 shows the basic build-up of the fabrics.



source: FiberCore Europe BV

Figure 3.1: the build-up principle of InfraCore inside bridges



The combination of multi-axial fabrics, wrapped around core cells and in Z-layers, provides adequate crack-arresting properties. Even if a crack is able to propagate between two plies, the structural integrity of the product as a whole is not compromised.

Once the vacuum infusion process is finished, the core cells and glass fiber fabrics are captured and hold in place by a polyester resin. Figure 3.2 shows a typical cross-sectional view in the transverse direction of a bridge, built according to the InfraCore concept. This cross section with flanges and sloping sides is simplified in Figure 3.3, which will function as the basis for the hybrid composite sub-concepts.

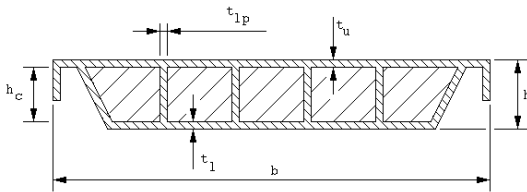


Figure 3.2: cross-section of a typical InfraCore inside bridge

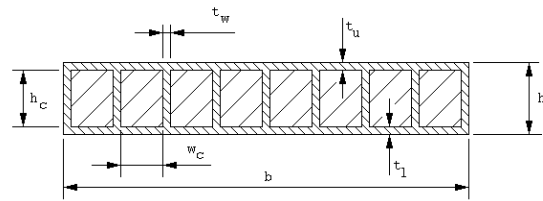


Figure 3.3: simplified cross-section of an InfraCore bridge

3.2 Glass fiber reinforced polyester and steel

The first sub-concepts to be addressed are the ones where steel is added to the existing GFRP structure. When comparing steel with GFRP one can distinguish general advantages and disadvantages; the most relevant ones are summarized in Table 3.1.

Table 3.1: advantages and disadvantages of steel compared with GFRP

Advantages of steel	Disadvantages of steel
- Higher stiffness	- Higher specific mass
- Recyclable	- Corrosive nature

For bridges with large spans, the high specific mass of steel results in heavy parts. In contrast to an all-FRP bridge where all building elements can be handled manually, a crane will always be needed for positioning when large and heavy steel elements are used. Extra time and expertise will be required, adding costs to the process. These extra costs have to be considered for every concept with steel. Another aspect that requires special attention is the vacuum infusion process. Care has to be taken that the steel elements do not hinder the flow of the resin through the rest of the product. However, when properly addressed in the design phase, this should not pose an insurmountable threat to the overall production process. The consequences of the corrosive nature of steel and how to deal with this are described in Chapter 4.

As explained in the previous section, all sub-concepts have to be compatible with FiberCore Europe's InfraCore Inside technology to assure a robust and damage-tolerant structure. Furthermore, all sub-concepts should be manufactured within FiberCore Europe's manufacturing framework. This means that the current production facilities should be taken



into account and major, often costly, modifications should be avoided. Even when large adjustments are justified, they will not be implemented on short notice. In the following sections the sub-concepts with steel will be presented and described.

3.2.1 Sub-concept S1 – Steel I-beams

Maybe the most obvious sub-concept for incorporating steel in a bridge structure is the usage of I-beams. These elements are used abundantly in load-bearing steel structures. The reason for this is the relatively high second moment of area with respect to its (symmetrical) surface area. The most material is located at the top and bottom of the profile, where the stresses due to bending are at their highest. Figure 3.4 shows the basic InfraCore Inside profile, combined with two steel I-beams. The spaces between the flanges of the steel beams need to be filled with standard core material to prevent resin from flowing in during the infusion process.

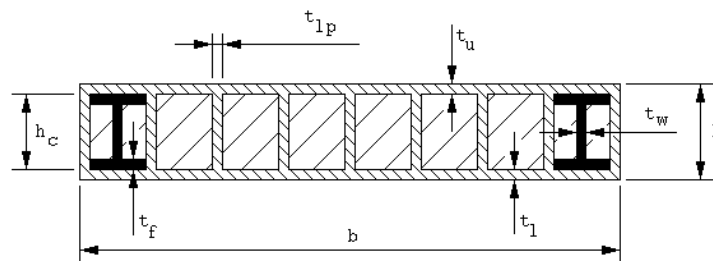


Figure 3.4: sub-concept S1 – steel I-beams

Advantages:

- The I-beams are integral structures where the load-carrying top and bottom flanges are attached to each other through vertical webs. The neutral axes of the steel elements are at the mid-plane, as is the neutral axis of the FRP structure without steel. Therefore, when the adhesive bond between the steel and the GFRP fails, the steel still maintains its high contribution to the flexural rigidity of the complete structure. The structure's resistance to bending does not rely on the adhesive bond strength between steel and the GFRP.

Disadvantages:

- Stress concentrations will occur around the steel beams. This needs special attention.
- The contribution to the flexural rigidity of the vertical steel webs of standard I-beams is less than 10% of the total contribution. Yet, for a typical IPE beam, the vertical webs contribute more than 25% to the mass of the I-beams. The steel is not used as optimal as possible.
- The mold on which the bridge is built has a preset radius in the span direction. The steel I-beams run over the full length of the bridge and need to be given this pre-camber as well.



- Fiber fabrics cannot be folded tightly around sharp, orthogonal corners without damaging the fibers. For this reason, any orthogonal corners of the steel elements need to be chamfered.
- As soon as standard IPE profiles do not suffice, customized profiles are required. These are more expensive and have longer lead-times.

The parameters that can be changed in this concept are listed in Table 3.2.

Table 3.2: the variable design parameters of sub-concept S1

Sub-concept S1 – design variables
Height of the bridge
Number of I-beams
Height of the I-beam
Width of the I-beam
Thickness of the horizontal flanges
Thickness of the vertical web
Thickness of the GFRP skins
Thickness of the vertical shear webs
Number of foam core profiles

In this sub-concept PU-foam core material is partly replaced by steel beams for added stiffness. The rest of the structure remains unchanged. At places where there is no steel in the structure, local loads due to traffic need to be carried as usual. The required longitudinal and transverse stiffness of the GFRP skins and shear webs can be assumed to be unaltered. The laminate build-up is therefore not a variable in this design sub-concept.

3.2.2 Sub-concept S2 – Steel box girders

Rather than using steel I-beams as in the previous sub-concept, this time steel box girders are added to the basic design. Figure 3.5 shows the result. Most of the advantages and disadvantages of the previous sub-concept apply here as well.

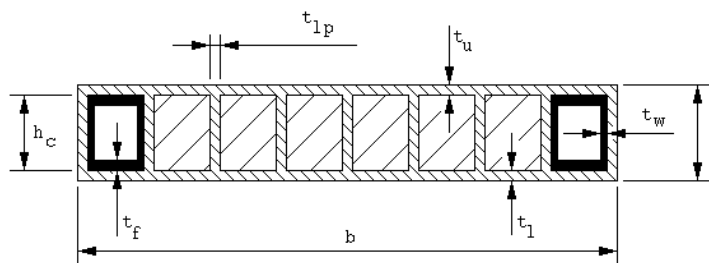


Figure 3.5: sub-concept S2 – steel box girders

Advantages:

- Similar to the previous sub-concept with the I-beams, this sub-concept is also independent of the adhesive bond between the steel and the GFRP.



- This sub-concept can be lighter than sub-concept S1 with the I-beams, because the space inside the box girders can remain empty. This saves both the costs and the weight of the PU foam and its processing time.
- The box girders can aid in increasing the torsional rigidity of the structure, if required.

Disadvantages

- Stress concentrations will occur around the beams.
- Special care needs to be taken to assure resin does not flow into the open space of the box girder. The ends need to be closed. Pressure release valves might be necessary for each box girder to prevent large distortions as a result of pressure differences over the girders' sides during the infusion process.
- Similar to the previous sub-concept, the webs of the embedded steel are not optimally located to resist bending.
- The box girders have to be pre-cambered to follow the radius of the mold.
- Orthogonal corners have to be rounded to facilitate fabric folding around them and prevent breaking of the fibers.
- Unless a standardized profile can be used, the box girders have to be composed from sheet metal. This is more expensive and requires more time. An added benefit is that different thicknesses can be used for the horizontal flanges and vertical webs.

The parameters that can be changed in this sub-concept are listed in Table 3.3.

Table 3.3: the variable design parameters of sub-concept S2

Sub-concept S2 – design variables
Height of the bridge
Number of box girders
Height of the box girders
Width of the box girders
Thickness of the horizontal flanges
Thickness of the vertical web
Thickness of the GFRP skins
Thickness of the vertical shear webs
Number of foam core profiles

3.2.3 Sub-concept S3 – Vertical steel sheets

In this sub-concept steel sheets are placed in a vertical manner, next to the foam core cells. In geometrical terms, this is similar to the first two sub-concepts, when the thickness of the horizontal flanges is reduced to zero. The result is depicted in Figure 3.6.

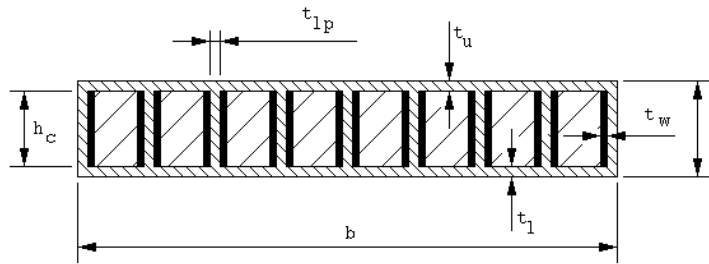


Figure 3.6: sub-concept S3 – vertical steel sheets

Advantages:

- Again, the function of the steel as contributor to the total flexural rigidity is not dependent on the adhesive bond strength between the steel sheets and the GFRP.

Disadvantages:

- The contribution of the steel sheets to the total flexural rigidity is far from optimal. For the best result, the relatively stiff steel should be located as far as possible from the neutral axis. In this concept, this is not the case
- The steel sheets somehow need to be pre-cambered to follow the radius of the mold. Cutting the sheets in the proper shape is an option, but yields additional costs and waste material.
- Long, heavy steel parts need to be fixed in place (vertically) during the build-up of the bridge on the mold. This might pose challenges for manufacturing.
- The integrity of the core material is not guaranteed over the design life of the bridge structure. If the foam core disintegrates and the adhesive bond between the steel and the adjacent GFRP fails, the steel sheets might fall inward.

The parameters that can be changed in this sub-concept are listed in Table 3.4.

Table 3.4: the variable design parameters of sub-concept S3

Sub-concept S3 – design variables
Height of the bridge
Number of steel sheets
Height of the steel sheets
Thickness of the steel sheets
Thickness of the GFRP skins
Thickness of the vertical shear webs
Number of foam core profiles

3.2.4 Sub-concept S4 – Horizontal steel sheets

Again, the implementation of horizontal steel sheets is a variation of the first two sub-concepts where this time the thickness of the vertical webs is reduced to zero. The resulting lay-out is depicted in Figure 3.7.

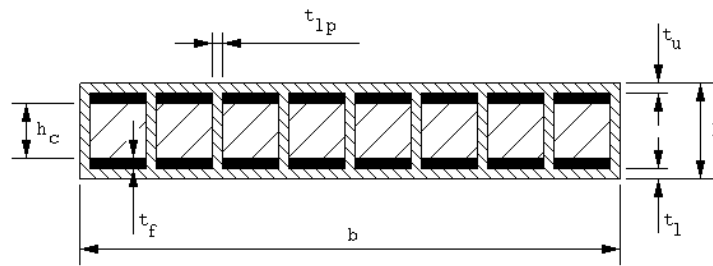


Figure 3.7: sub-concept S4 – horizontal steel sheets

Advantages:

- The stiff steel is better spread out over the width of the bridge than in previous sub-concepts. The stress concentrations are likely to be less.
- Disregarding a protective GFRP outer layer, the steel sheets are located as far away as possible from the neutral axis. At this location, the steel is most efficient in its contribution to the total flexural rigidity.
- Both the upper and the lower metal sheets can be placed relatively easy in the mold during the build-up. The steel will easily follow the camber of the mold.

Disadvantages:

- The contribution of the steel sheets to the total flexural rigidity reduces almost to zero as soon as the sheets can move freely in span direction with respect to the adjacent GFRP skins. Fatigue loading by traffic and deterioration over time pose high risks for the adhesive bond strength. Extra measures have to be taken to remove the structural dependency on the adhesive bond strength. Mechanical interlocking connections can solve this.
- Sharp, orthogonal corners have to be chamfered in order to fold fiber fabrics around them.
- Extra measures are required to prevent the top metal sheets to fall down if the core material happens to deteriorate over time.

The parameters that can be changed in this sub-concept are listed in Table 3.5.

Table 3.5: the variable design parameters of sub-concept S4

Sub-concept S4 – design variables
Height of the bridge
Number of steel sheets
Width of the steel sheets
Thickness of the steel sheets
Thickness of the GFRP skins
Thickness of the vertical shear webs
Number of foam core profiles



3.2.5 Sub-concept S5 – Steel bars

In this sub-concept, solid steel bars are placed inside the existing foam core cells, as far away as possible from the neutral axis. It is a variation on sub-concept S4 with the horizontal steel sheets. Figure 3.8 shows the steel bars added to the original design.

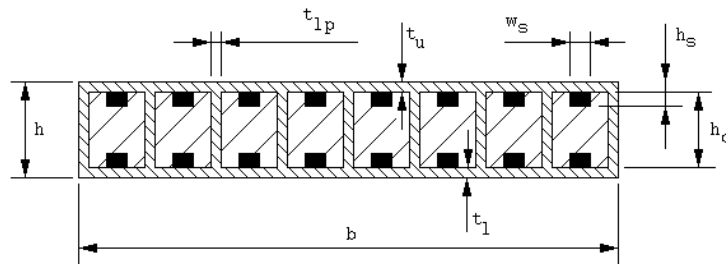


Figure 3.8: sub-concept S5 – steel bars

Advantages:

- This relatively simple sub-concept requires the least amount of alterations to the existing design concept. The bars are placed inside the foam core cells and other than that, the build-up remains completely similar to FiberCore's current production process.
- The steel bars can be placed almost as efficient as the steel sheets in sub-concept S4. Far away from the neutral axis for maximum efficiency.
- Orthogonal corners of the steel bars do not require additional chamfering if the bars can be placed directly in the foam core material.

Disadvantages:

- This design, like sub-concept S4, relies heavily on a fixed position of the steel bars in span direction with respect to the adjacent GFRP skins. Since the reliability of the adhesive bond strength between the GFRP and the steel bars is not high to begin with and even decreases over time, this sub-concept also requires additional mechanical measures to ensure fixation in longitudinal direction.
- The location of the top bars should be guaranteed over time, if the core material happens to deteriorate.

The parameters that can be changed in this sub-concept are listed in Table 3.6.



Table 3.6: the variable design parameters of sub-concept S5

Sub-concept S5 – design variables
Height of the bridge
Number of steel bars
Width of the steel bars
Thickness of the steel bars
Thickness of the GFRP skins
Thickness of the vertical shear webs
Number of foam core profiles

3.2.6 Sub-concept S6 – Transverse composite deck on steel girders

In contrast to all previous design sub-concepts, the longitudinal axis of an all-GFRP composite bridge deck is oriented in the transverse direction of the bridge. Steel girders are used to carry the loads in the bridge's span direction. If the bridge span increases, these steel girders either increase in size or the number of girders increases. If the width of the bridge increases, the height of the composite deck increases accordingly. This sub-concept is shown in Figure 3.9.

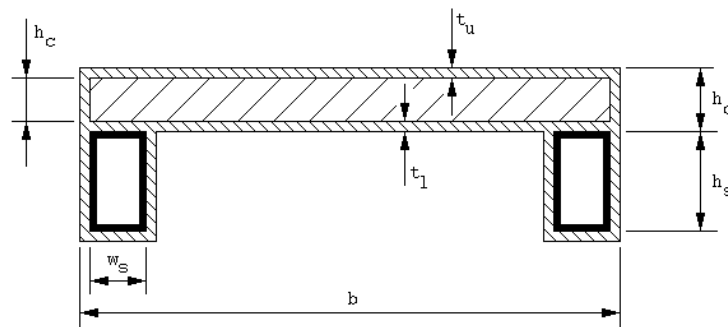


Figure 3.9: sub-concept S6 – transverse composite deck on steel girders

Advantages:

- The steel girders with their relatively cheap stiffnesses are responsible for carrying most of the loads in span direction, while the composite deck only carries loads in transverse direction. The GFRP bridge deck can be made thinner, making it lighter and cheaper.

Disadvantages:

- This sub-concept is higher than the previous concepts, reducing clearance under the bridge.
- When box girders are used, additional measures are required to prevent the hollow spaces from filling up with resin during infusion
- The girders require a pre-camber to fit in the mold.
- Sharp, orthogonal corners require chamfering to facilitate fiber folding.

The parameters that can be changed in this sub-concept are listed in Table 3.7.



Table 3.7: the variable design parameters of sub-concept S6

Sub-concept S6 – design variables
Height of the GFRP bridge deck
Thickness of the GFRP skins
Number of steel girders
Geometry of the steel girders
Dimensions of the steel girders

From a manufacturing point of view it can be argued that the production of sub-concept S6 as one integral part through vacuum infusion is not very cost-effective. The only function of a polyester layer around the steel parts is to protect them against a harmful environment. From a structural point of view, reinforcement fibers are not really necessary around the steel girders and only add unnecessary costs. Extra effort is required to place the girders in the right position with respect to the bridge prior to infusion. Holding glass fabrics in place with I-beams or preventing resin from flowing into box girders also have to be addressed properly. It makes far more sense to produce an all-GFRP bridge deck separately and place this after curing on top of the steel girders. The girders themselves can be coated beforehand with a protective layer of any kind. As mentioned in the previous chapter, these so-called slab-on-girder bridges fall outside the scope of this thesis project. Therefore sub-concept S6 will not be implemented in the design model.

3.2.7 Sub-concept S7 – composite deck on steel girders

Sub-concept S7 is a more aesthetical variation of sub-concept S6; a classic InfraCore composite bridge deck is placed on top of steel girders. Again, the steel elements can be I-beams, box girders or any other typical steel profile. The steel parts are packed in a thin protective layer, which has as main function to protect the steel against the environment. The thin layer only carries its own weight and does not contribute to the load-carrying capabilities of the bridge itself. The concept is schematically depicted in Figure 3.10. Similar to sub-concept S6, this sub-concept is also of the type slab-on-girder and therefore disregarded in this thesis project.

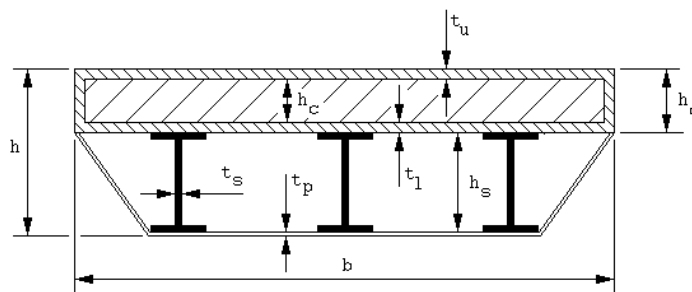


Figure 3.10: sub-concept S7 – a composite deck on steel girders (slab-on-girder)



3.3 Glass and carbon fiber reinforced polyester

The second concept for a hybrid composite bridge comprises the default glass fiber reinforced polyester structure, combined with carbon fibers. In general, one can state that the implementation of carbon fiber adds stiffness to the structure and reduces the mass for a higher price. FiberCore currently uses polyester as matrix material. The interfacial bond strength between carbon fibers and polyester is known to be relatively weak. This issue needs to be addressed thoroughly and is the topic of Chapters 6 and 7. The advantages and disadvantages of CFRP in comparison with GFRP are summarized in Table 3.8.

Table 3.8: advantages and disadvantages of CFRP compared with GFRP

Advantages	Disadvantages
- Higher specific stiffness - Lower specific mass	- High price - Weaker fiber-resin interfacial strength ¹⁾ - Extra protective measures required for dust control

¹⁾ based on polyester resin

One of the major advantages of the concepts with carbon fibers over the concepts with steel is the much smaller impact on the production process. Carbon fabrics can be handled more or less in the same manner as glass fiber fabrics. No heavy elements are present and therefore no cranes are required during the build-up of the bridge on the mold. Carbon fiber dust can cause short-circuiting in electrical devices and this is an issue that can be avoided, but needs to be addressed. Since glass fiber fabrics can be replaced almost one-on-one with carbon fiber fabrics, the number of variations on FiberCore's current design concept is limited when not looking as deep as the ply-levels. The latter topic is addressed in more detail in Chapter 8. Two sub-concepts are worked out and described in the following sections.

3.3.1 Sub-concept C1 – carbon fibers in the top and bottom skins

Since carbon fibers are stiffer than glass fibers, but also more expensive, it makes sense to replace the glass fibers only at locations where the stiffness benefit is the largest. For bending, this location is as far away from the neutral axis as possible. Figure 3.11 shows the carbon fibers in the top and bottom skins. The exact ratio between glass fibers and carbon fibers and the lay-up of the individual plies is too specific for this conceptual design phase. This issue will be addressed in more detail in Chapter 8.

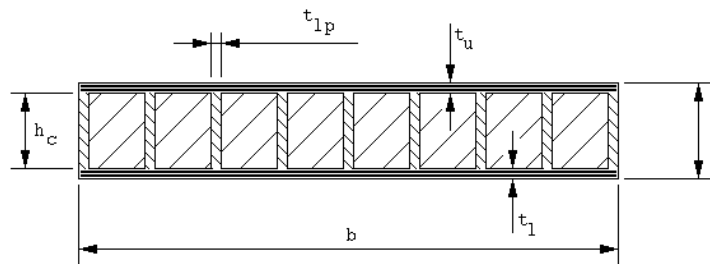


Figure 3.11: concept C1 – carbon fibers in the top and bottom skins

Advantages:

- The carbon fibers are located as far away from the neutral axis as possible, where their contribution to the total flexural rigidity is maximal.

Disadvantages:

- No sub-concept specific disadvantages.

The parameters that can be changed in this sub-concept are listed in Table 3.9.

Table 3.9: the variable design parameters of sub-concept C1

Sub-concept C1 – design variables
Height of the bridge
Ratio of carbon vs. glass in the top skin
Ratio of carbon vs. glass in the bottom skin
Thickness of the hybrid composite skins
Thickness of the vertical shear webs
Number of foam core profiles

The orientation of the individual glass fiber and carbon fiber plies is analyzed and described in Chapter 8. This orientation is not implemented as variable in the design model.

3.3.2 Sub-concept C2 – carbon fibers in the Z-layers

When looking for variations in FiberCore Europe's current concept, complemented with carbon fibers, it might seem appropriate to replace the glass fabric Z-layers with carbon fabric. This is done in this sub-concept and depicted in Figure 3.12. From previous discussions, however, it should already be clear that the more expensive carbon should be placed as far away from the neutral axis as possible for maximum efficiency. In this sub-concept, this is not the case.

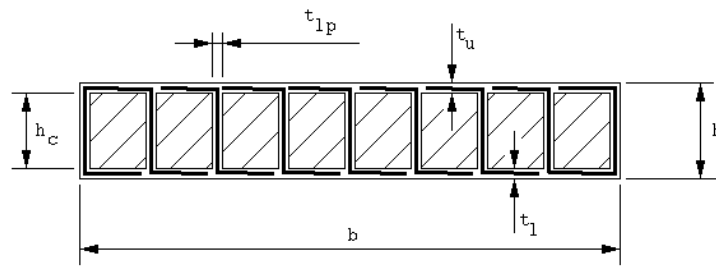


Figure 3.12: concept C2 – carbon fibers in the Z-layers

Advantages:

- No advantages with respect to the previous sub-concept C1, where the carbon fibers are placed in the outer skins.

Disadvantages:

- The expensive carbon material is partially placed in locations where its effect is not optimal.

The parameters that can be changed in this sub-concept are listed in Table 3.10.

Table 3.10: the variable design parameters of sub-concept C2

Sub-concept C2 – design variables
Height of the bridge
Ratio of carbon vs. glass in the Z-layers
Thickness of the hybrid composite skins
Thickness of the vertical shear webs
Number of foam core profiles

Since sub-concept C2 does not possess any advantages when compared to sub-concept C1 and based on the qualitative analysis that sub-concept C1 will perform better than sub-concept C2, the latter sub-concept is not implemented in the design model.

3.4 Results

In chapter 2 it was made clear that certain design rules should be followed during the design and production of composite bridges to guarantee a robust and damage tolerant structure. When incorporating new materials in FiberCore Europe's current design, whether this is steel or carbon fiber, these design rules still apply. Seven hybrid sub-concepts with steel are introduced and two with carbon fibers, all compatible with FiberCore Europe's InfraCore Inside technology. From a first qualitative analysis potentially more successful candidates per concept can already be distinguished. However, a more objective approach will be used to choose the design sub-concept with the greatest potential to become an economically viable counterpart



3. Design sub-concepts

of current conventional bridges. To quantify the efficiency with respect to one another, all sub-concepts will be modelled in a design tool. In this tool the design variables as identified in this chapter can be changed to optimize the sub-concept for costs, mass and height. The modeling of the sub-concepts will be the topic of Chapter 10. First, the more specific challenges that arise when adding new materials to a GFRP structure will be addressed in the next chapters.



4

Corrosion of steel embedded in GFRP

Structural steel is a material that is well known for its degradation over time under the influence of moisture and oxygen. This phenomenon is known as corrosion. FiberCore Europe manufactures low-maintenance, high-durability bridges with a design life of at least 100 years. While contributing stiffness at a low €/GPa ratio, embedding steel inside a GFRP bridge raises questions about the long-term behavior of the structure. In order to warrant the structural performance over the life time, the corrosive behavior of steel should be known. Since the combination of steel inside large, load-bearing GFRP structures is new and undocumented, corrosion tests have to be performed to make statements about the long-term behavior.

4.1 Test standards

Over the years, many different standards for accelerated corrosion tests have been developed. Carlsson, et al. [4] give an overview of the most common standards and their recommended fields of application. From this overview it is clear that it is not possible to draw conclusions about the long-term behavior of products from accelerated corrosion tests alone. A real-time reference test is always required, where (part of) a product is, as realistically as possible, exposed to the same circumstances as in practical use. This reference test should last a minimum of one year, preferably two. The degradation of test specimens in an accelerated test can only then be compared to the non-accelerated degradation. From this comparison it is known how much time it takes during an accelerated test to achieve the same amount of degradation as in real-life. These data can then be extrapolated to make predictions about future corrosion behavior.

It is clear that in the time-frame of a master thesis project it is impractical to perform the real-time corrosion reference test. All tests according to the relevant standards can only be used for either quality control or comparative testing when reference test data are not available. To still be able to make qualitative statements about the corrosion behavior of steel embedded in GFRP, a practical approach is used. A Liebis[®] S 1000 A-TR Constamatic[®] salt spray cabinet is available at the Delft Aerospace Structures and Materials Laboratory (DASM-lab). In this cabinet accelerated corrosion tests can be performed according to the ISO 9227 standard (ISO



[2]). It is specifically noted that this test cannot be used to draw conclusions about the long-term behavior of products or their protective coatings. The reason for this is that the corrosion stresses that occur during the test are significantly different from the stresses that occur in an actual use case. However, the test can be used to analyze discontinuities, pores and damages in coatings. It is the only accelerated corrosion test that is available within the time-frame and budget of the thesis project.

4.2 Production of test specimen

Goal of the performed accelerated corrosion test is to demonstrate the protective nature of the reinforced polyester. In practice, the polyester outer skin of every bridge is covered in extra layers of protective gelcoat and a finishing topcoat. For the test, four specimens are manufactured in order to compare the influence of the different protective layers in practice. The specimens before the test are depicted in Figure 4.1. The used materials for specimen production are specified in Table 4.1.

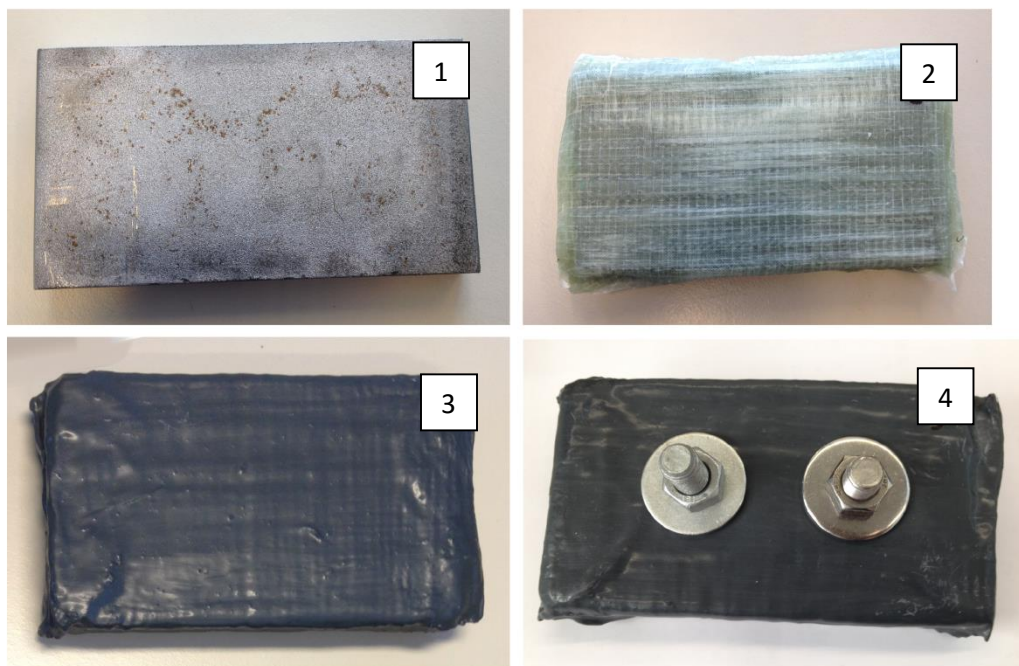


Figure 4.1: the four test specimens before the accelerated corrosion test

- The first specimen is untreated bare steel for reference.
- The second specimen is covered in unsaturated polyester, combined with three layers of glass fibers, 1200 g/m^2 each. The philosophy behind the three layers of glass is that the material is representative for the material being used in practice, while at the same time being thinner than in the actual use case. If three layers are enough to protect the steel against corrosion, the actual minimum of 10 layers should be more



than sufficient. The glass fiber layers were applied through a hand lay-up method. The impregnation of this specimen is not perfect at certain places to see whether this has influence on the end result.

- The third specimen is also covered in three layers of glass reinforced polyester, after which one layer of gelcoat and one layer of topcoat is applied.
- The fourth specimen is treated identical to specimen number three. This time, however, two holes with a diameter of 12 mm were drilled through the specimen and fitted with bolts; one galvanized bolt, one made of stainless steel. The bolts are combined with washers and nuts of the same material and tightened with a socket wrench.

Table 4.1: material specifications for the accelerated corrosion test specimens

Material	Specifications
Steel	S235JR, grit-blasted (stainless steel grit, 30x40 µm at 6 bar)
Glass reinforcement	Jushi 386 Direct Roving E-glass, 1200 g/m ² , unidirectional
Unsaturated polyester	DSM Synolite 1967 (97.9% by weight)
Curing agent	AkzoNobel Trigonox 249 VR (2.1% by weight)
Gelcoat	De IJssel ISO/NPG polyester gelcoat
Topcoat	De IJssel ISO/NPG polyester gelcoat (97%) and paraffin (3%)
Nut + washer + bolt 1	M12, A4-70 stainless steel
Nut + washer + bolt 2	M12, grade 8.8 galvanized

4.3 Test procedure

The neutral salt spray corrosion test is performed according to the ISO 9227 standard. The test specimens are placed inside the Liebis[®] S 1000 A-TR Constamatic[®] salt spray cabinet in an inert, non-metallic fixture under an angle of approximately 20° to the vertical (see Figure 4.2). For 720 hours (30 days) the specimens are continuously sprayed with a salt solution, while the following conditions are maintained:

- Temperature: 35 °C ± 2 °C
- Average collection rate for a horizontal collecting area of 80 cm²: 1.5 ml/h ± 0.5 ml/h
- Concentration of sodium chloride (collected solution): 50 g/l ± 5 g/l
- pH (collected solution): 6.5 to 7.2



4. Corrosion of steel embedded in GFRP

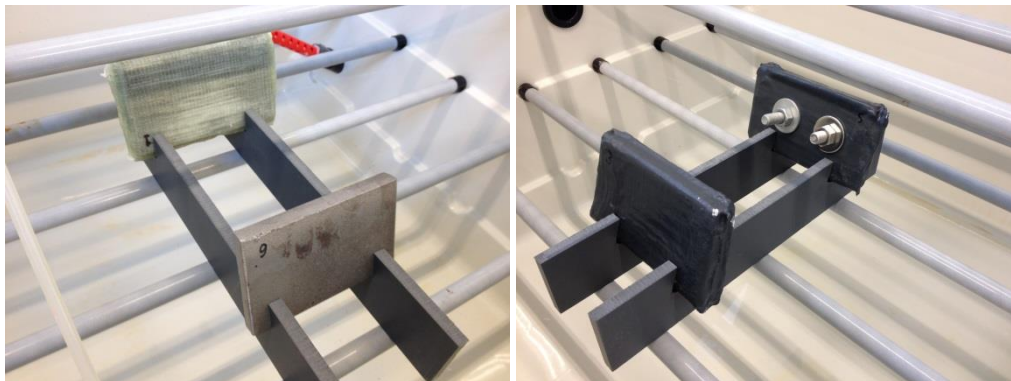


Figure 4.2: the corrosion test specimens in a non-corrosive fixture inside the salt spray cabinet

4.4 Results

After 720 hours, the test is stopped and the test specimens are taken out of the cabinet. Next, the specimens are dried for 30 minutes and carefully rinsed in clean, lukewarm water to remove the residues of the salt solution from the surface. The specimens after rinsing and drying are depicted in Figure 4.3 ².

Table 4.2 shows the weight increase of the test specimens after the test. Iron oxide is heavier than the iron it is formed of, which is clearly shown for reference specimen 1. Specimen 3 is completely unaffected by the test and the weight increase of this specimen is only attributed to moisture uptake. The same holds for a large part for specimens 2 and 4, although a very light discoloration is visible in specimen 2. Closer inspection shows that this specimen is affected by corrosion due to improper impregnation of the specimen and the resulting lack of protective polyester at some places. The washers used in specimen 4 did not shield either of the two bolt holes completely. The salt solution was able to penetrate the specimen and caused corrosion inside the holes.

Table 4.2: the weights of the test specimens before and after the accelerated corrosion test

Specimen #	Weight before test	Weight after test	Weight increase
1	1230.3 g	1242.4 g	0.98%
2	1554.9 g	1556.7 g	0.12%
3	1525.1 g	1526.8 g	0.11%
4	1743.7 g	1746.2 g	0.14%

² When comparing Figure 4.1 with Figure 4.3, it might seem as though the test specimens are highly discolored after the test. In reality, however, the test specimens show no discoloration at all. The observed difference in color is merely the result of unresolvable white balance issues in the camera settings.

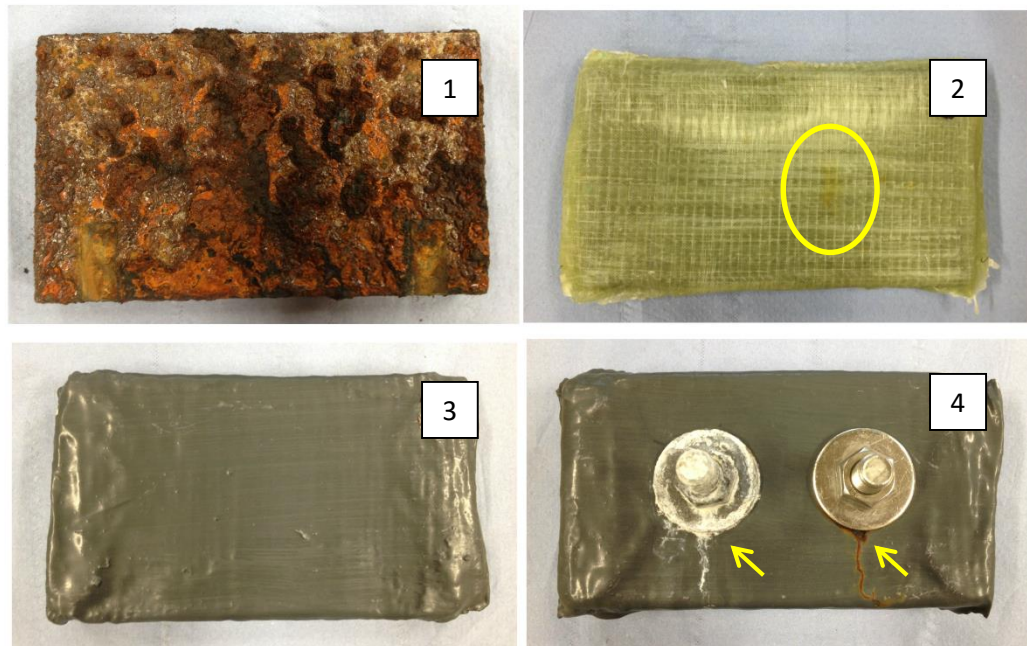


Figure 4.3: the four test specimens after the accelerated corrosion test

4.5 Conclusions

Three layers of glass fiber reinforced polyester are sufficient to shield bare steel and prevent corrosion during an accelerated corrosion test according to the ISO 9227 standard which lasted 720 hours. The protective nature is only valid if the impregnation of the glass reinforcement fibers is complete. Where dry spots are present, water is able to penetrate the structure, reach the steel and cause material degradation through corrosion. A steel structure shielded by glass fiber reinforced polyester, one layer of gelcoat and one layer of topcoat does not show any effects of the corrosive environment. A thicker layer of GFRP, cover by gelcoats and a topcoat is expected to withstand a corrosive environment for a long time, as long as the protective outer surface is not damaged. The performed test is not suitable to make exact statements about the long-term behavior of the applied protective layer. When holes are drilled through the protective layer, adequate shielding is required to prevent moisture penetration and the subsequent corrosion.

4.6 References

- [1] Carlsson, B., et al., *Guideline for selection of accelerated corrosion test for product qualification*. 2006, Nordic Innovation Centre.
- [2] ISO 9227, Corrosion tests in artificial atmospheres — Salt spray tests, ISO, Geneva, 2006



5

Adhesive bond strength between steel and GFRP

In the previous chapter, the corrosive nature of steel embedded in a glass fiber reinforced polyester structure was discussed. One of the other questions that arise when looking into this hybrid material concept concerns the strength of the bond between the individual components. Depending on the implementation, the shear strength of the adhesive bond between the steel and the reinforced polyester can become a dominating factor for failure. In any structural design the maximum allowable stresses must be known to ensure that these are not exceeded. For this reason the adhesive bond strength between reinforced polyester and structural steel is analyzed.

As became clear in the discussion about the design boundary conditions in Chapter 2, the steel elements should be incorporated inside the reinforced polyester structure during the vacuum infusion process. When the unsaturated polyester cures, cross-links between the polyester monomers are formed and at the interface with the steel surface an adhesive bond is created. The strength of this bond is an important input parameter for the design of steel/GFRP hybrid structures. In order to determine the adhesive bond strength as accurately as possible, full-scale destructive tests are often required. In a concept-orientation program, full-scale testing is for numerous reasons not feasible. The logical preceding levels of testing often start at material level. Once the material properties are known, tests on coupon level are performed, followed by tests on component level. Only then, when there are still uncertainties left or specific certifications are required, tests can be carried out on full-scale level.

The relevant properties of the materials used in this study (S235JR structural steel, E-glass reinforcement fibers and Synolite unsaturated polyester) are very well known. The adhesive bond strength between these three materials, especially when the steel is embedded during an infusion process, is still unknown. To compare the behavior of this new material combination with the previously used combination of only glass fibers and polyester, tests at coupon level are required. A suitable comparison test for adhesive bond strengths is the single-lap joint shear test as described by the ASTM D1002 standard (ASTM International [1]).



Only when these tests do not result in insurmountable objections to continue with the proposed materials, it is useful to spend more resources on the further design and selection of sub-concepts, for which tests at component level can be performed. Unfortunately, considering the proposed work and the time frame of this thesis project, tests at component level cannot be performed.

5.1 Specimen production

The test standard prescribes a thickness of 1.62 mm for the metal strips. Sheet metal with this specific thickness appears to be hard to find and was not available at FiberCore Europe's default steel supplier. Therefore strips are cut from S235JR sheet metal with a thickness of 2.0 mm. With the expected low values of the joint's shear strength, the influence of the extra thickness is assumed to be negligible. The length and width of the steel strips are 100 mm and 25 mm respectively. The unsaturated polyester which will be used as adhesive is reinforced with glass fibers to mimic the actual use case as closely as possible.

5.1.1 Pretreatment

Before bonding the test specimens, the steel surfaces are pretreated to improve the bond strength. Many studies have been performed to find the most efficient pretreatment method for bonding steel to organic material (e.g., Kim, et al. [2], Gohil, et al. [3], Teng, et al. [4], Jiang, et al. [5]). Of all available surface treatments, grit-blasting is often mentioned as a relatively cheap, easy to apply and highly effective method. This pretreatment is a very likely candidate to be used once steel is going to be implemented in an actual bridge. For this reason, this method is chosen for the test. Another promising surface treatment was suggested by a representative of Lloyds Register maritime classification society (Petkovic [6]). Although undocumented, this method with the name "wet sanding" seems in potential interesting enough to investigate and its performance shall be compared to that of grit blasting. Both surface treatments are described in more detail in the next sections.

Grit blasting

An overlap of 25 mm for the single-lap joint is prescribed. This area at the end of the steel strips is grit-blasted. To ensure that the complete area of 25 x 25 mm is pretreated, a protective film is taped on one side of the strips at a distance of at least 40 mm from one end. The exposed area of the steel strips is blasted at a pressure of 6 bar with stainless steel grit with a diameter between 30 and 40 μm .

Wet sanding

The wet sanding method comprises the sanding of the bonding surfaces through a wet, uncured layer of the bonding agent, prior to bonding. The formation of an undesirable corrosion layer is prevented through this method, which should improve the adhesive bond strength. The complete procedure is as follows:

- Degrease the steel specimens with acetone.
- Apply wet, uncured polyester at one end.
- Sand the specimens in the wet, uncured polyester by hand with grit 80 sandpaper for about 20 seconds



5. Adhesive bond strength between steel and GFRP

- Let the polyester cure
- Sand the cured polyester lightly by hand with grit 80 sandpaper
- Clean the area with a clean cloth

Figure 5.1 shows two steel strips with two different surface treatments.

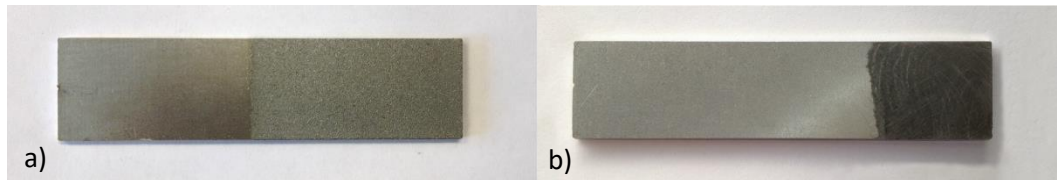


Figure 5.1: two pretreated steel strips (right side pretreated): a) grit-blasted and b) wet-sanded

5.1.2 Bonding of the test specimens

After the surface pretreatments, two steel strips are bonded together, with an overlap of 25 mm. To come as close as possible to the actual use case, FiberCore Europe's default polyester resin system is used as adhesive, combined with one layer of glass fiber reinforcement. The material specifications are given in Table 5.1.

Table 5.1: material specifications for the single-lap joint bond strength test

Material	Specifications
Steel	S235JR structural steel, 100 x 25 x 2.0 mm
Polyester	DSM Synolite 1967 (97.9% by weight)
Curing agent	AkzoNobel Trigonox 249 VR (2.1% by weight)
Glass fibers	Jushi 386 Direct Roving E-glass
Glass fabric	[manufacturer], 1200 g/m ² , unidirectional, stitched
Stitching yarns	Polyester, 167 decitex

The following steps are taken to bond two steel strips together to form a single-lap joint test specimen:

- Resin is applied to the glass fibers (25x25 mm) with a brush until the fabric is completely impregnated.
- The wetted glass fibers are placed on the surface-treated end of a steel strip.
- A second steel strip is placed upside down, with the pretreated end on the wetted glass fibers.
- Spacers are used to ensure an accurate horizontal alignment and to prevent bending.
- A vacuum bag and pump are used to apply a compressive force on the specimens during curing of the resin.
- The excess resin is removed mechanically.



5. Adhesive bond strength between steel and GFRP

The build-up and dimensions of the test specimens are depicted in Figure 5.2. A close-up of the bonded joint is shown in Figure 5.3.

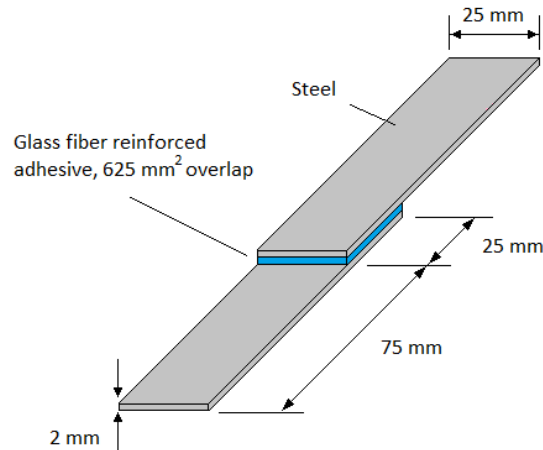


Figure 5.2: dimensions of the single-lap joint test specimens

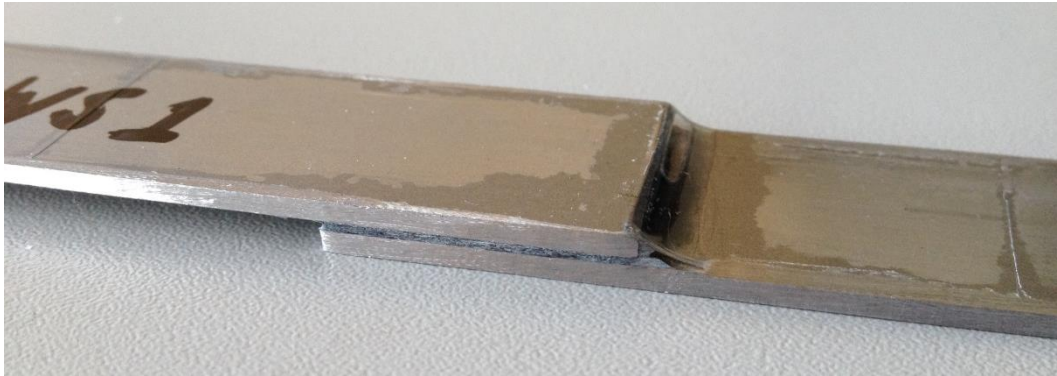


Figure 5.3: a close-up of the bonded overlap

In total 15 test specimens per surface treatment have been produced. All specimens after removing the excess adhesive material are depicted in Figure 5.4 ³. The thickness of the adhesive bond layer for all test specimens is between 0.7 and 0.8 mm.

³ The designation "SB", written on the test specimens, is used for the grit-blasted specimens and originates from the incorrect term "sand blasting". The designation "WS" is used for the wet-sanded specimens.



Figure 5.4: the single-lap joint test specimens: a) grit-blasted and b) wet-sanded

5.2 Test procedure

The single-lap joint shear tests are performed at the DASM-Lab on a Zwick 250 kN tensile bench. The test specimens are clamped in hydraulic grips so that 25 mm of the specimen ends are inside the grip's jaws. The grips should be aligned in such a way that the direction of the applied pull through the center line of the grip assembly coincides with the long axis of the test specimen. The specimen loading rate is set to 1.3 mm/min. The loading force is recorded until failure occurs.

The shear strength of the lap joint is determined as follows:

$$\tau_{max} = \frac{P_f}{w \cdot L_o} \quad (5.1)$$

Where

- τ_{max} = the shear strength in MPa
- P_f = the load at failure in N
- w = the width of the test specimen in mm
- L_o = the length of the bonded overlap in mm



5.3 Results

After the test, the specimens have been inspected to determine the failure mode. Close-ups of typical fracture surfaces are shown in Figure 5.5. In all cases the dominant failure mode is adhesive failure. The interface between the steel and the polyester is the weakest link; the steel and the polyester themselves appear unaffected. It must be noted that the interfacial bond strength between the thermoplastic polyester stitching fibers and the polyester resin is lower than the interfacial bond strength between the pretreated steel and the polyester resin. The amount of resin residue on the bare steel breaking surface only appears at the location of the stitching fiber. For the grit-blasted specimens the amount of residue is in general a bit more than for the wet-sanded specimens. This is a first indication that grit-blasting might be more efficient than wet sanding.

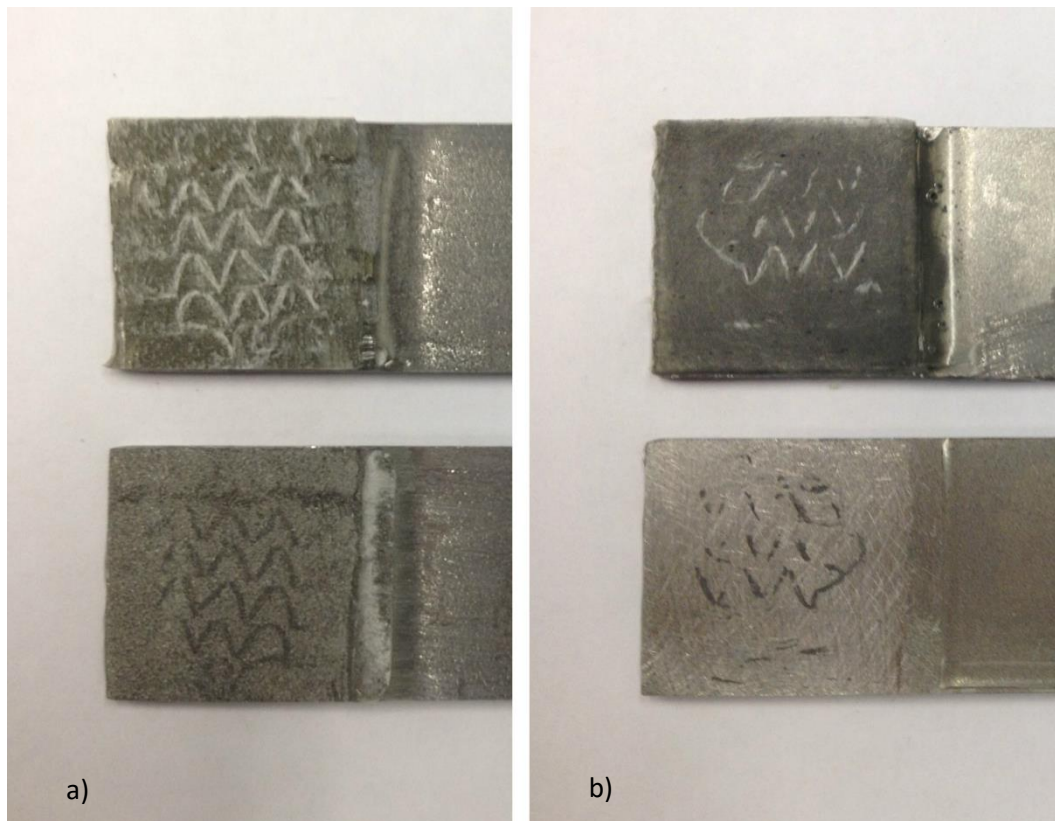


Figure 5.5: fracture surfaces of a) a grit-blasted specimen and b) a wet-sanded specimen

Table 5.2 shows values for the maximum load and the calculated shear strength for all specimens. In some cases the tensile test terminated prematurely without recording data. For these cases no value for the failure load and consequently the shear strength are given in the table.



5. Adhesive bond strength between steel and GFRP

Table 5.2: the failure loads and shear strengths of all test specimens

Grit-blasted			Wet-sanded		
Specimen #	P_f [N]	τ_{max} [MPa]	Specimen #	P_f [N]	τ_{max} [MPa]
SB1	-	-	WS1	2971	4.75
SB2	5261	8.42	WS2	-	-
SB3	4182	6.69	WS3	3722	5.95
SB4	4948	7.92	WS4	3578	5.73
SB5	4256	6.81	WS5	3135	5.02
SB6	4115	6.58	WS6	3530	5.65
SB7	4895	7.83	WS7	-	-
SB8	-	-	WS8	3063	4.90
SB9	4020	6.43	WS9	3082	4.93
SB10	5289	8.46	WS10	2763	4.42
SB11	4206	6.73	WS11	3265	5.22
SB12	4476	7.16	WS12	3566	5.71
SB13	4348	6.96	WS13	2974	4.76
SB14	4503	7.21	WS14	3250	5.20
SB15	4906	7.85	WS15	3617	5.79

The Dutch design guideline CUR96:2003 for civil engineering structures of fiber reinforced plastics (CUR [7]) prescribes a certainty of at least 95% in material data values. Assuming that the variations in shear strength values follow a Gaussian distribution around the average value, 97.7% of all shear strength values will be above the average value minus two times the standard deviation. The resulting values are given in Table 5.3.

Table 5.3: values for the shear strengths, corrected for standard deviation

	Grit-blasted	Wet-sanded
Average shear strength	7.31 MPa	5.23 MPa
Standard deviation	0.70 MPa	0.49 MPa
Coefficient of variation	9.6 %	9.3 %
Average minus 2× standard deviation	5.91 MPa	4.26 MPa

5.4 Conclusions

The shear strength of the adhesive bond between SR235JR structural steel and glass fiber reinforced Synolite 1967 polyester is tested with a single-lap joint tensile test according to the ASTM D 1002 standard. Two surface pretreatments are compared: grit blasting and wet sanding. Inspection of the break surface shows only adhesive failure. Adhesive residue on the steel break surface suggests cohesive failure as well, but closer inspection learns that this failure is also interfacial of nature. It occurs at the interface with the polyester stitching thread.



The assumption that larger resin residues on the grit-blasted specimens indicate a better performance of this pretreatment as compared to the wet-sanded specimens is confirmed by the numerical values for the shear strength. The grit-blasted specimens show, after correction for standard deviation, a 39% higher value for the failure load than the wet-sanded specimens. Wet sanding is a more labor-intensive pretreatment than grit-blasting, making it more expensive. It is a relatively dirty job, involving mechanical work through wet polyester resin. And lastly, the performance of this pretreatment is less than grit blasting. When steel is incorporated inside a composite bridge structure, grit-blasting is the preferred method over wet sanding to improve the adhesive bond strength.

A value of 5.9 MPa is found for the shear strength of the adhesive bond between grit-blasted S235JR steel and Synolite polyester⁴. This value cannot be used as a design allowable, because of the nature of the single-lap joint tests. The relatively large edge effects on the small adhesive overlap surface dominate the failure strength, resulting in lower values than the actual bond strength in a full-scale product. The value found might be used as a conservative lower boundary, but it is highly advised to perform tests on component level to find a more accurate value for the adhesive bond strength between S235JR steel and Synolite unsaturated polyester.

5.5 References

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⁴ Long-term behavior (e.g., degradation of the adhesive bond strength over time) is disregarded in this study.



6

Determination of the most suitable carbon

Carbon fibers are made of the chemical element carbon. In contrast to glass fibers, where E-glass is E-glass, no matter the source, the properties of carbon fibers are highly dependent on their production process. Depending on the production method, values for tensile strength range from 2 GPa to more than 7 GPa. Tensile moduli are possible from just above 200 GPa all the way up to almost 1000 GPa (Morgan [1]). The outer surface of carbon fibers is generally treated with a sizing agent. This agent protects the fiber against processing and handling damage and improves the wetting and adhesive properties with respect to the resin system. Many different sizing agents and methods are available. Individual carbon fibers, also known as filaments, have a diameter starting from approximately 5 μm . The filaments are bundled into strings or tows, where bundle sizes start from approximately 1000 fibers, up to more than 300,000 fibers for high yield tows (Bank [2], Kelly [3]). The tows are subsequently formed into fabrics by specialized weaving companies. Once the sheer limitless processing techniques of these companies are added to the equation, one can imagine that the diversity in carbon fiber fabrics is enormous.

Combining carbon fibers in a large hybrid, load-bearing structure raises the question which carbon fiber or fabric is the most suitable for this application. A number of parameters influence the answer to this question. Not only the mechanical properties of the fabric and resin combination should be investigated, but of course prices for bulk material play a major role as well. Other than these factors, it is very important that guarantees can be given that the required carbon fabrics are actually available within the timeframe of the project. Something that is not as apparent as one might think in the current dynamic carbon market where demand and supply are not always perfectly balanced. In this market, traceability of materials is a prerequisite and with so many different fiber properties around, only the type that the technical design is based on can be used.



6.1 Carbon samples

The search for the most suitable carbon starts with an inventory of the current carbon fiber manufacturers. An overview of the largest manufacturers worldwide is given in Table 6.1, where the Toray Group is, at the time of writing, by far leading production. The number of fiber processing companies for fabric production is many times greater.

Table 6.1: an overview of the largest carbon fiber manufacturers in the world (2015)

Carbon fiber manufacturers		
Cytec	Hyosung	Teijin Limited
DowAksa	Kemrock	Toho Tenax
Formosa Plastics	Mitsubishi Rayon Co., LTD.	Toray Group
Hexcel	Nippon Graphite Fiber Corporation	UHT Unitech
High Gain Industrial Limited	SGL Group	Zoltek

On behalf of FiberCore Europe a request for suitable carbon fibers was sent out to all these companies. Prior to this, a preselection has taken place based on technical data sheets (TDS). The specific application (composite bridges, made from polyester) was explained and the companies were asked to provide a sample of their high-potential candidates, based on their expertise. The main requirements for the product were:

- unidirectional material
- a non-crimp fabric (non-woven)
- polyester compatible sizing.
- high stiffness per euro

The request resulted in a total of 14 different carbon fabrics being delivered. An overview of the samples is given in Table 6.2. In total 4 fabrics were received made of the Zoltek PanEx35 fiber, all processed by different weaving companies. Sample number 12 came directly from Zoltek and is treated with an experimental sizing, specifically developed to improve the adhesive properties to polyester resin. This fabric is given the designation “PanEx35-UP” to distinguish it from other Zoltek PanEx35 fibers, which are treated with the default universal sizing. Not all fabric samples are unidirectional material; 4 samples are woven fabrics (samples 2, 5, 6, and 7). These samples were not ruled out, enabling a comparison of the different fibers in these fabrics with one another. Sample numbers 8 and 13 are unidirectional, but the fabrics are both woven in a way that the tows are undulating, creating fabrics that are not non-crimp. The maximum theoretical tensile strength and stiffness of the carbon fibers are not fully utilized in woven fabrics. This results in less efficient materials with higher costs per unit strength and stiffness as compared to their non-crimp counterparts.



Table 6.2: an overview of all received carbon fabric samples in order of delivery date

Sample #	Fiber manufacturer	Fiber type	FAW [g/m ²]	Weave form
1	Zoltek	PanEx35 ¹⁾	300	UD
2	Toray	Torayca T700 FOE	800	DIAG.4/8
3	Mitsubishi Rayon	Pyrofil TRW40 50L - 50K	607	UD
4	Toray	Torayca T620 50C - 24K	375	UD
5	Mitsubishi Rayon	Grafil 34700WD - 12K	650	2x2 Twill
6	DowAksa	Aksaca A-42 - 12K	650	2x2 Twill
7	Toray	Torayca T700SC - 12K	600	2x2 Twill
8	DowAksa	Aksaca A-49 - 24K	626	UD ³⁾
9	Zoltek	PanEx35 ¹⁾	600	UD
10	Toray	Torayca T700SC 50C - 24K	150	UD
11	Zoltek	PanEx35 ¹⁾	882	UD
12	Zoltek	PanEx35 - UP sizing ²⁾	600	UD
13	Tairafil	TC-35R 48K	608	UD ³⁾
14	DowAksa	Aksaca A-42 - 12K	600	UD

¹⁾ Zoltek PanEx35 fibers with the universal -13 sizing

²⁾ Zoltek PanEx35 fibers with an experimental polyester compatible sizing.

³⁾ Not a non-crimp fabric

6.2 Carbon/polyester compatibility test

A fiber reinforced material consists in general of two main components: the reinforcement fibers and a bonding matrix material. The primary function of the reinforcement fibers is to carry the loads acting on the structure. The matrix material has as main function to hold the reinforcement fibers in place and transfer stresses between the fibers. The structure as a whole can only be load-bearing when the interaction between the fibers and matrix material is good enough. The interfacial bond strength between carbon fibers and polyester is known to be weak, when compared to the more commonly used epoxy resins. However, polyester resin is much cheaper than epoxy and is often a determining factor for the economic success of large, load-bearing structures. To investigate and compare the compatibility between the different carbon fibers and FiberCore's polyester resin system, the short-beam strength test according to the ASTM D2344 standard (ASTM International [4]) is used. This test is used to find the interlaminar shear strength (ILSS). Failure in this test is dominated by the resin and interlaminar properties, providing a good tool to compare the interfacial properties.

From all 14 sample fabrics a small composite plate of approximately 200 x 150 mm is manufactured via vacuum infusion. The ASTM D2344 standard mentions a typical specimen thickness of 6 mm. For future reference, Table 6.3 gives an overview for all carbon samples of the fabric areal weight (FAW), the number of plies in the laminate and the resulting laminate thickness. From each plate 5 test specimens are cut and tested. For the first sample the test specimens are depicted in Figure 6.1. The test specimen production specifications are summarized in Table 6.4.



6. Determination of the most suitable carbon

Table 6.3: an overview of the number of plies per test specimen and the resulting laminate thickness

sample #	FAW [g/m ²]	Number of plies	Thickness [mm]	Sample #	FAW [g/m ²]	Number of plies	Thickness [mm]
1	300	20	6.45	8	626	12	6.37
2	800	9	6.67	9	600	12	6.46
3	607	12	6.44	10	150	40	7.05
4	375	19	6.89	11	882	8	6.07
5	650	11	6.38	12	600	11	6.44
6	650	11	6.02	13	600	11	5.87
7	600	12	6.36	14	600	11	6.69

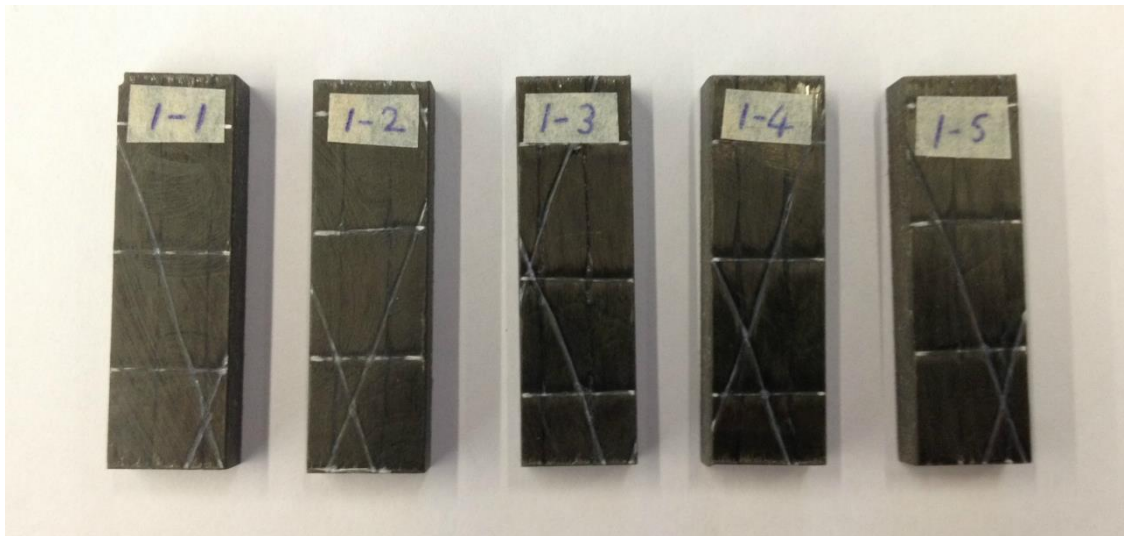


Figure 6.1: the first ILSS test specimens

Table 6.4: Test specimen production specifications

Product/process	Specifications
Polyester	DSM Synolite 1967 (97.9% by weight)
Curing agent	AkzoNobel Trigonox 249 VR (2.1% by weight)
Laminate production method	Vacuum infusion between glass plates
Specimen dimensional shaping	High precision water jet cutting

The short-beam strength tests are performed at the DASM-lab on a Zwick/Roell 20 kN tensile bench in combination with a three-point-bending fixture. The test setup is depicted in Figure 6.2. The speed of testing is set at a constant rate of crosshead movement of 1.0 mm/min. The load versus crosshead displacement is recorded until failure occurs.



The short-beam strength is calculated according to the following formula:

$$F^{sbs} = 0.75 \times \frac{P_{max}}{b \times h} \quad (6.1)$$

Where

- F^{sbs} = short-beam strength [MPa]
- P_m = the maximum load [N]
- b = specimen width [mm]
- h = specimen thickness [mm]

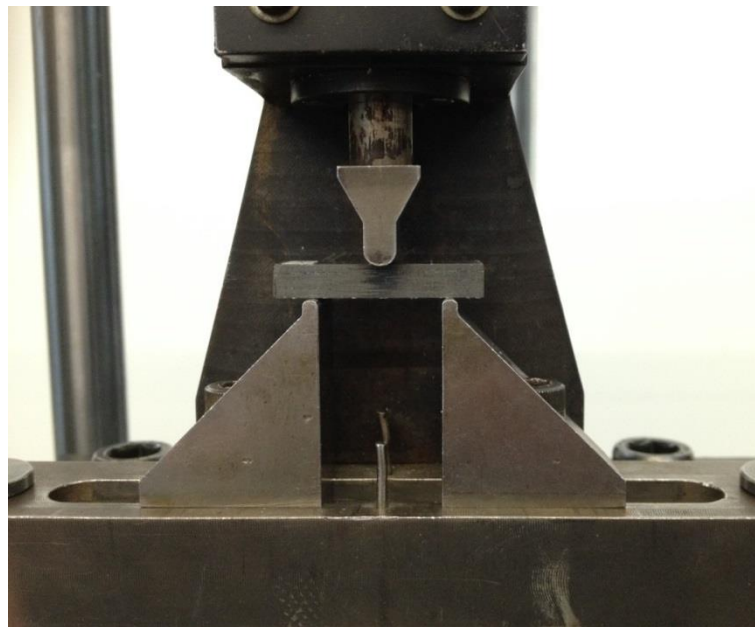


Figure 6.2: a test specimen in the three-point-bending fixture

6.2.1 Compatibility test results

For all 14 samples the short-beam strength is determined based on 5 test specimens. The average short-beam strengths are summarized in Table 6.5. Dutch regulatory standards for civil engineering structures of fiber reinforced plastics (CUR [5]) prescribe a certainty of at least 95% in material data values. Assuming that the variations in short beam strength values follow a Gaussian distribution around the average value, 97.7% of all short-beam strength values will be above the average value minus two times the standard deviation. The values for the standard deviation, coefficient of variation and the resulting corrected short-beam strength for standard deviation are also given in Table 6.5.



6. Determination of the most suitable carbon

Table 6.5: overview of short-beam strengths per sample

Sample #	Carbon fiber	Average F_{sbs} [MPa]	Standard deviation [MPa]	Coeff. of variation [-]	Corrected F_{sbs} [MPa]
1	PanEx35	52.7	1.6	3.0 %	49.5
2	Torayca T700 FOE	29.1	0.7	2.3 %	27.8
3	Pyrofil TRW40 50L - 50K	54.4	2.0	3.7 %	50.4
4	Torayca T620 50C - 24K	48.0	1.8	3.7 %	44.4
5	Grafil 34700WD - 12K	18.9	1.2	6.5 %	16.5
6	Aksaca A-42 - 12K	18.0	0.7	3.9 %	16.6
7	Torayca T700SC - 12K	23.1	0.4	1.8 %	22.3
8	Aksaca A-49 - 24K	23.1	1.2	5.3 %	20.6
9	PanEx35	26.0	1.9	7.2 %	22.3
10	Torayca T700SC 50C - 24K	44.0	0.9	2.0 %	42.2
11	PanEx35	26.6	2.6	9.6 %	21.5
12	PanEx35 - UP sizing	28.8	0.6	2.2 %	27.5
13	Tairafil TC-35R 48K	29.8	0.4	1.5 %	28.9
14	Aksaca A-42 - 12K	27.1	0.8	3.1 %	25.4

The results from Table 6.5 are graphically illustrated in Figure 6.3. The non-UD fabrics (samples 2, 5, 6, and 7) are given a light grey color and the samples not made from non-crimp fabric (samples 8 and 13) are given a lighter shade of blue.

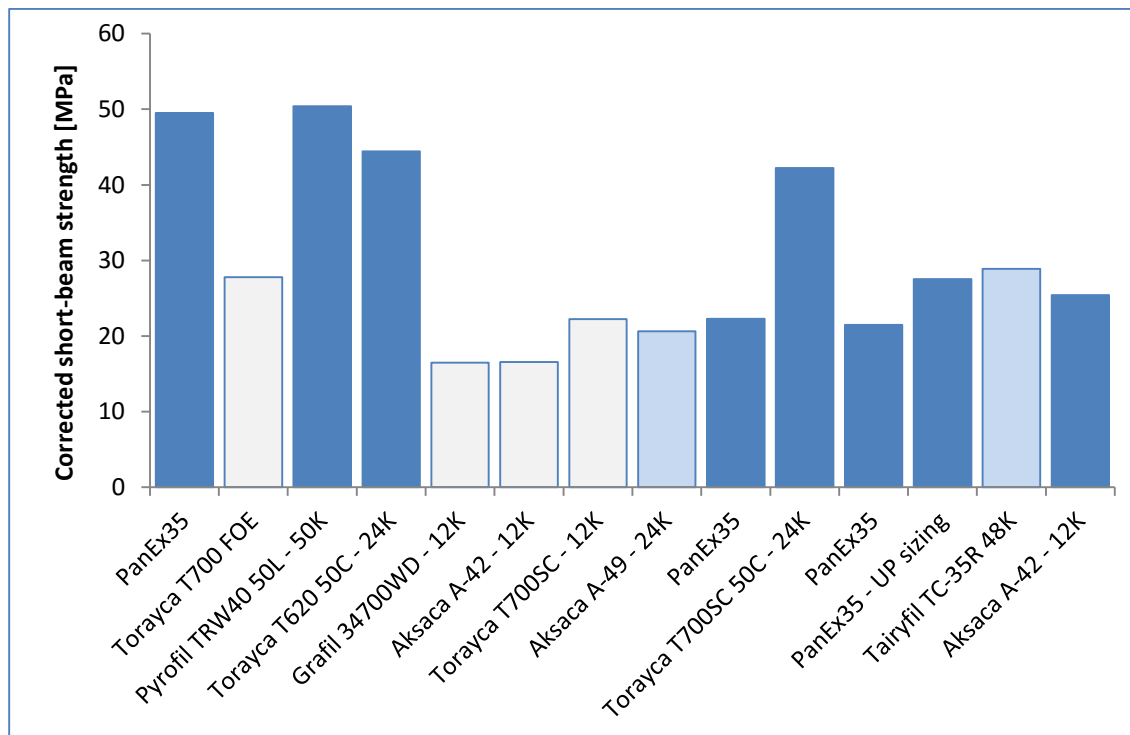


Figure 6.3: corrected values of the short-beam strength per fabric



Zoltek PanEx35 comparison

A comparison of the results for the four PanEx35 samples raises some questions. The results for these specific samples are highlighted in Figure 6.4. The first sample, with a universal sizing, shows a value for the short-beam strength which is more than two times higher than the other two, similarly-sized samples.

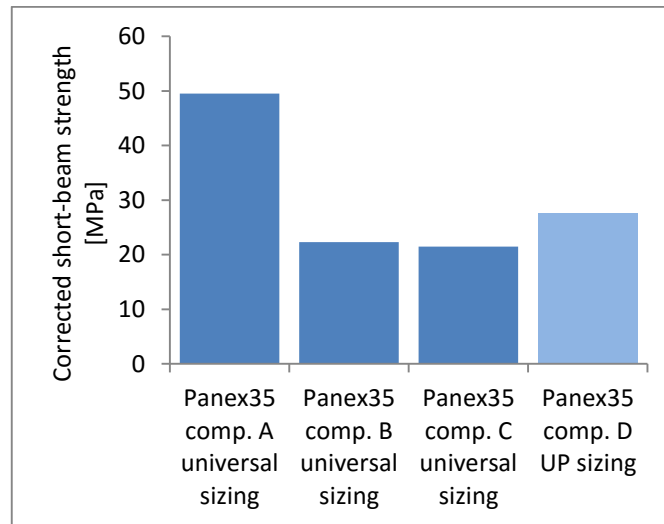


Figure 6.4: the corrected short-beam strength values of the Zoltek PanEx35 samples

The supplier of the first sample, **company A**, is not the manufacturer of the fibers or the fabric but only the distributor. Upon inquiry, it was confirmed that the delivered sample is made from PanEx35 fibers with the universal sizing. However, the supplier mentions that this specific sample has undergone a special treatment to enhance the adhesive properties. This treatment is not sizing-related, but because of the competitive sensitive nature of the process, more information cannot be provided.

In order to gain more insight in the cause of the observed discrepancy, multiple weaving companies were contacted to find the actual manufacturer of the mystery fabric. This inquiry led to **company E**. A representative of this company visited FiberCore Europe and confirmed **company E** as the origin of the fabric. From this visit it also became clear that no special treatment was given to the fibers or fabric by **company E** to enhance the adhesive properties, as claimed by **company A**. The amount of diagonal, thermoplastic scrim material in the sample is not deemed to be enough to cause better bonding or higher ILSS values. Discussing the results with different parties, including Zoltek's research and development department, different fabric manufacturing companies, and FiberCore's CTO and head of engineering did not lead to a clear answer. The following hypothesis was suggested: the polyester threads that are used to stitch the carbon fiber tows together to form a fabric act as crack initiators. Stress concentrations around these threads cause the formation of initial cracks, resulting in lower ILSS values than expected from pure carbon fabrics without stitching yarns. The four PanEx35 fabrics and the differences in stitching materials and patterns are shown in Figure 6.5.

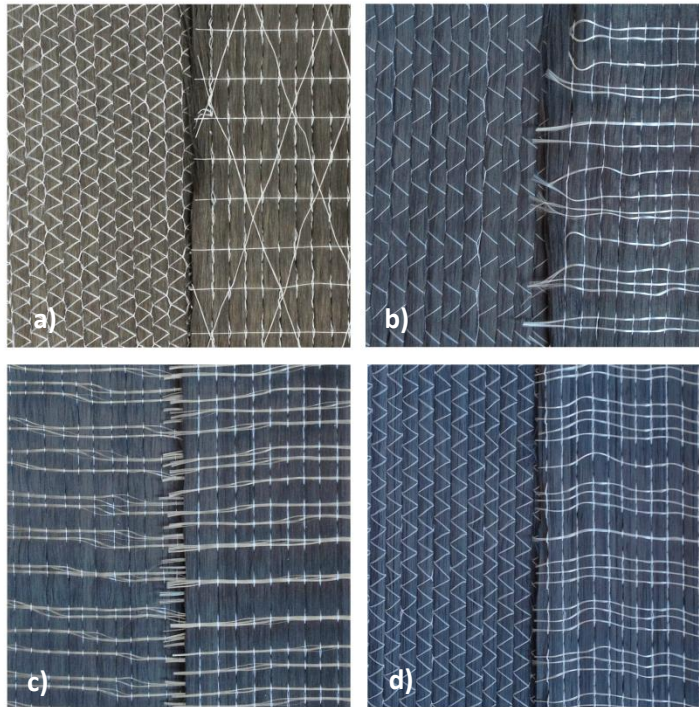


Figure 6.5: the PanEx35 fabrics delivered by a) company A, b) company B, c) company C, and d) company D

From a scientific point of view it is very interesting to find out what caused the deviations in the test result for fabrics made from the same fibers. The stitching thread material and pattern seem to have a large effect on the ILSS value. Zoltek has sent a spool with dry PanEx35 carbon fiber tow, treated with the experimental sizing. From this tow a new composite laminate can be produced without stitching fibers. Tests on specimens from this material can provide more accurate values for the ILSS of the carbon fibers without interference from any other materials.

While a theoretical investigation into carbon fiber laminates without stitching yarns is very interesting in general, the outcome of this research is of less importance for the remainder of this thesis work. For the application of carbon fibers in its bridges, FiberCore Europe focusses on materials which are available right now. Therefore the topic above of is not further addressed in this study.

6.3 Price and availability of carbon fibers and fabrics

The global carbon fiber market is very dynamic and competitive. A seemingly structural imbalance between offer and demand in this specific market continuously causes price variations. In general, fixed prices do not exist; prices are always the result of negotiations. Order quantities and long-term agreements with suppliers can cause different prices for the same fabric. For these reasons, prices for carbon fabrics are not publicly available. From contact with numerous suppliers it is found that prices currently range roughly from 18-22 euro per kg for fabrics made from standard modulus fibers. These prices are based on fabrics suitable for FiberCore Europe's specific application and the estimated order quantity. When



fabrics made from ultra-high modulus fibers are ordered, prices easily go up to 100 euro per kg and higher.

Before discussing prices with carbon fabric suppliers, it is often more common to discuss guaranteed available quantities. This holds in particular for large, long-term projects. One can imagine the problems associated with shortage of material halfway production. Additional costs resulting from these planning errors are generally much higher than spending a few cents or even euros per kilogram extra for a fabric which is widely available. Not only the availability of the carbon fibers has to be taken into account; the time needed to process these fibers to fabrics is crucial as well. It is not uncommon for weaving companies to have their machinery booked for 6 months ahead. Even if planning allows, setting up these machines for a completely different fabric is time-consuming and therefore costly.

FiberCore Europe is currently not producing bridges with carbon fibers. It is hard to estimate the demand for these fibers, once production does start. Based on current demand and knowledge, a few metric tons will probably suffice for the first months. For carbon fiber manufacturers, this amount poses in general no delivery problems. When planning ahead with weaving companies, availability challenges from this link in the chain are also not expected.

6.4 Conclusions

From the polyester compatibility tests it is found that the PanEx35 sample with the polyester sizing performs 24% to 28% better than the conventional PanEx35 material. This is only valid if the odd outlier from **company A** is disregarded. The latter sample performed 80% better than the specially sized fabric. Exact prices per kilogram of the fibers with special sizing are not available yet, but it is estimated that this is not much higher than the price of approximately [xx.xx] euro per kilogram for the conventional PanEx35. The price for the better performing PanEx35 fabric from **company A/E** is approximately [xx.xx] euro per kilogram. This is higher than the best-performing fabric in the test, made from Mitsubishi Rayon's Pyrofil TRW40 50L - 50K fibers. Depending on the supplier and fiber areal weight, fabrics made from this specific fiber range in price between [xx.xx] and [xx.xx] euro per kilogram.

Based in this information and the sufficient availability of both fibers, it is decided to narrow the search for the best carbon fabric down to [following two] fabrics: Zoltek's PanEx35 and Mitsubishi Rayon's Pyrofil TRW40 50L - 50K respectively. Extended mechanical tests will be performed on fabrics from both fibers, to determine their structural performance. This is the topic of the next chapter. Based on the results found there, a more informed choice can be made for one of the two remaining candidates.

6.5 References

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6. Determination of the most suitable carbon

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7

Mechanical tests of two carbon fabrics

From the analysis in the previous chapter, two carbon fabrics were found as potential candidates for the incorporation in a hybrid composite bridge design: fabrics made from Zoltek's PanEx35-UP fibers and from Mitsubishi Rayon's TRW40 50L fiber. Short-beam strength tests were performed and values for the interlaminar shear strength (ILSS) are known. For design calculations and modeling, more material properties are required.

Continuous fiber reinforced materials are anisotropic of nature. This means that material properties are not identical in any direction. Values for tensile and compressive strengths depend on the fiber volume fraction and ply lay-up sequence of the laminate, the fiber orientation per ply and the direction of loading. The same holds for the modulus of elasticity and Poisson's ratio. In order to determine these parameters, tensile and compressive tests have to be performed on unidirectional material in both the longitudinal (0°) and the transverse (90°) direction. Classical laminate theory can then be used to determine the properties of a laminate, built up of multiple, randomly oriented plies.

7.1 Specimen production

The tensile and compressive tests are performed according to the ASTM standards D 3039 (ASTM International [1]) and D 6641 (ASTM International [2]) respectively. Test specimen dimensions as prescribed by these standards are summarized in Table 7.1.

Table 7.1: test specimen dimensions prescribed by the respective ASTM standards

Test Standard	Load direction	Length [mm]	Width [mm]	Thickness [mm]
ASTM D 3039 (tensile)	Longitudinal (0°)	250	15	1.0
	Transverse (90°)	175	25	2.0
ASTM D 6641 (compressive)	Longitudinal (0°)	140	12	Varied, but uniform
	Transverse (90°)	140	12	Varied, but uniform



7. Mechanical tests of two carbon fabrics

FiberCore Europe has performed material tests on GFRP materials in the past. In order to compare the results from these tests with the current test results, the circumstances of all tests are kept as constant as possible. This leads to deviations from the tensile test standard with regard to the specimen dimensions. Per fabric, a single laminate is manufactured with a thickness of approximately 2.5 mm. From these plates the test specimens are cut for the mechanical tests. For all tensile test specimens a length and width of 250 x 25 mm is adopted. The production specifications are shown in Table 7.2.

Table 7.2: production specifications of the two carbon fabric laminates

Material/Process	Specifications
Carbon fabric #1	Zoltek PanEx35, polyester sizing, UD, 600 g/m ² , $v_f = 53\%$
Carbon fabric #2	Mitsubishi Rayon TRW40 50L, UD, 607 g/m ² , $v_f = 57\%$
Polyester resin	DSM Synolite 1967 (97.9% by weight)
Curing agent	AkzoNobel Trigonox 249 VR (2.1% by weight)
Production process	Vacuum infusion
Specimen dimensional shaping	High precision water jet cutting
Strain gages	Kyowa KFG-5-120-C1-11
Strain gage adhesive	Kyowa CC-33A strain gage cement
Tensile test tab material	Plain office paper, 160 g/m ²

A density analysis is performed on the Synolite 1967 resin after curing. In total 10 specimens are tested; 5 from the excess resin after the Zoltek PanEx35-UP laminate production and 5 from the left-over resin after the production of the Mitsubishi Rayon TRW40 50L laminate. With a coefficient of variation (COV) as small as 0.16% a value for the density of the cured Synolite 1967 is found to be 1193 kg/m³. This is 2.4% higher than the value of 1165 kg/m³ mentioned in the Technical Data Sheet for the cured polyester. From the determined densities of the two laminates, the volumetric fiber fraction can be determined. A value of 53% was found for the Zoltek PanEx35-UP composite. This value is similar to what is achieved in the GFRP skin panels of the bridges currently produced by FiberCore Europe. For the Mitsubishi Rayon TRW40 50L composite the fiber-volume fraction turned out to be 57%⁵.

To determine the material stiffnesses, the elongation and contraction of the specimens are recorded during the tests. An extensometer and strain gages are used for this purpose in the tensile tests. Strain gages are used in the compressive test. In total 15 test specimens are produced for each test. Due to shortage of strain gages, only 5 out of every 15 test specimens are monitored this way. Figure 7.1 shows the Zoltek PanEx35-UP specimens prior to testing. The white polyester stitching threads are clearly visible.

⁵ Due to problems with the vacuum valve, the Mitsubishi Rayon fibers were infused at a larger pressure difference than the usual $\Delta p = 0.8$ bar, resulting in a somewhat higher fiber-volume fraction.



7. Mechanical tests of two carbon fabrics



Figure 7.1: the Zoltek PanEx35-UP tensile and compressive test specimens, prior to testing

One of the first things that stands out after the production of the laminates and the test specimens is the observation that the Synolite polyester resin does not adhere properly to the carbon fibers. When the peel ply is removed from the laminate after manufacturing, the top layer of resin is pulled off easily if no special care is taken. This leaves the first layer of carbon fibers dry. Test specimens were bundled with paper tape prior to testing; removing this tape pulls off the resin and the first layer of carbon fibers. When the transverse test specimens are bent by hand with little force, cracking noises are heard and the polyester stitching fibers become clearly visible. All these phenomena are shown in Figure 7.2 and raise initial qualitative concerns when it comes to the combination of carbon fibers and Synolite 1967 polyester. The mechanical tests should provide a more quantitative indication of the materials behavior.

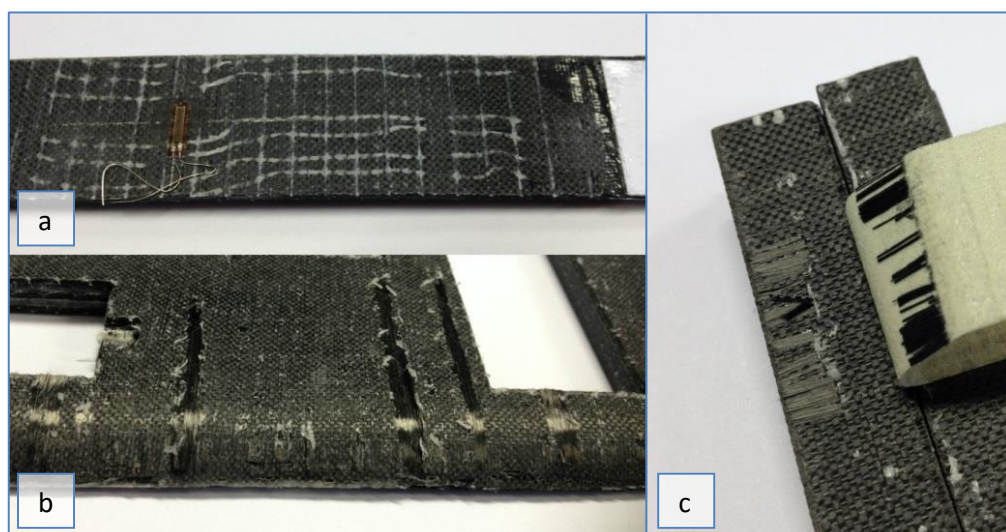


Figure 7.2: debonding of polyester resin (a) from stitching fibers (b) when removing peel ply, (c) when removing paper tape



7.2 Tensile tests

The tensile tests are performed at the DASM-lab on a Zwick 250 kN test bench with hydraulically operated grips. The speed of testing is set to a constant head displacement rate of 2 mm/min. During the tests, the applied load and displacements in longitudinal and transverse direction of the test specimens are recorded. The test with the first specimen revealed that the friction between the hydraulic grips and the specimen was not large enough; slip occurred. Tab material at the ends of the specimens is required to prevent slipping. Advised by the laboratory technical staff, plain office paper of 160 g/m² is used as tab material. The paper is cut into rectangular pieces of 56 x 25 mm and bonded with superglue to the ends of the specimens on both sides. The first five specimens after bonding of the tabs are depicted in Figure 7.3. After bonding of the tabs, slip did not occur anymore.

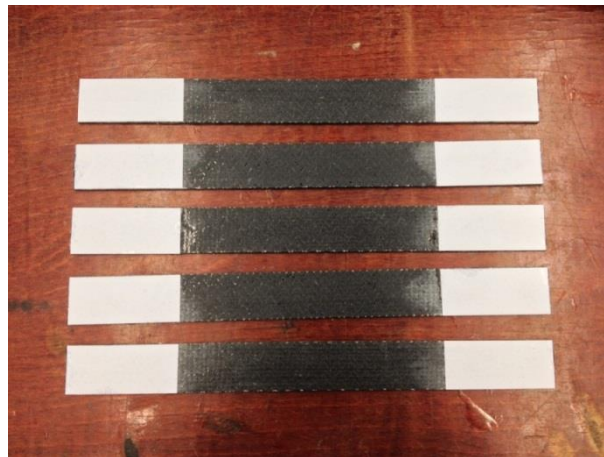


Figure 7.3: five tensile test specimens with bonded tabs

Tensile test results

The tensile force on the test specimens is increased and monitored until failure occurs. Especially the test specimens with the fibers in the direction of the applied force (0°) fail in an explosive manner. Figure 7.4 shows the remains of a Zoltek PanEx35-UP tensile sample after the test.



Figure 7.4: a longitudinal (0°) test specimen after the tensile test



Tensile strength

The theoretical tensile strength of a unidirectional laminate in fiber direction can be found by the rule of mixtures. The rule is given in equation (7.1).

$$\sigma_c(0^\circ) = v_f \sigma_f + (1 - v_f) \sigma_m \quad (7.1)$$

In this equation, σ is the tensile strength. The subscripts c , f and m stand for the composite, the fiber and the matrix properties respectively. v_f is the volumetric fraction of fibers in the composite. The tensile strengths of the individual constituents are found in their respective technical data sheets:

$$\sigma_f (\text{PanEx35-UP}) = 4137 \text{ MPa}$$

$$\sigma_f (\text{TRW40 50L}) = 4120 \text{ MPa}$$

$$\sigma_m (\text{Synolite 1967}) = 70 \text{ MPa}$$

Substituting all known values in equation (7.1) yields for the theoretical composite tensile strength values of 2226 MPa (Zoltek PanEx35-UP) and 2379 MPa (Mitsubishi Rayon TRW40 50L).

The tensile strength in transverse direction is mainly dominated by the tensile strength of the matrix. To approximate this transverse tensile strength, the following equation can be used:

$$\sigma_c(90^\circ) = \sigma_m \left[1 - 2 \left(\frac{v_f}{\pi} \right)^{\frac{1}{2}} \right] \quad (7.2)$$

Substituting the known values for the matrix tensile strength and the fiber-volume fraction of the laminate yields a value of 12.2 MPa for the transverse tensile strength of the Zoltek PanEx35-UP laminate. For the Mitsubishi Rayon TRW40 50L laminate, this value is 10.3 MPa.

The theoretically derived values for the tensile stresses can now be compared with the experimentally obtained values. During the tensile tests, the force at which the first failure occurs is registered for each specimen. Dividing this force by the surface area of the specimen yields the tensile strength. The results for the Zoltek PanEx35-UP and Mitsubishi Rayon TRW40 50L specimens are summarized in Table 7.3 and Table 7.4 respectively.

Table 7.3: tensile strengths of the Zoltek PanEx35-UP composite

Zoltek PanEx35-UP	Longitudinal (0°)	Transverse (90°)
Average tensile strength	1577 MPa	7.9 MPa
Standard deviation	112 MPa	0.7 MPa
Coefficient of variation	7.1 %	8.9%
Corrected tensile strength	1353 MPa	6.5 MPa



Table 7.4: tensile strengths of the Mitsubishi Rayon TRW40 50L composite

Mitsubishi Rayon TRW40 50L	Longitudinal (0°)	Transverse (90°)
Average tensile strength	1841 MPa	12.9 MPa
Standard deviation	124 MPa	1.5 MPa
Coefficient of variation	6.8 %	12.0%
Corrected tensile strength	1592 MPa	9.8 MPa

Tensile modulus

Similar as with the tensile strength, the theoretical stiffness in fiber direction of a unidirectional laminate can also be determined using the rule of mixtures. Equation (7.3) shows this rule.

$$E_c = v_f E_f + (1 - v_f)E_m \quad (7.3)$$

In this equation the symbol E stands for the material's stiffness. The Young's moduli of the individual constituents are found in their respective technical data sheets:

$$E_f (\text{PanEx35-UP}) = 242 \text{ GPa}$$

$$E_f (\text{TRW40 50L}) = 240 \text{ GPa}$$

$$E_m (\text{Synolite 1967}) = 3.8 \text{ GPa}$$

Substituting all known values in equation (7.3) yields for the theoretical composite tensile stiffness values of 131 GPa (Zoltek PanEx35-UP) and 139 GPa (Mitsubishi Rayon TRW40 50L). This is (almost) exactly equal to the experimentally found average values: 131 GPa and 141 GPa, respectively. The tensile Young's moduli for both composites are shown in Table 7.5 and Table 7.6.

Table 7.5: the tensile moduli of the PanEx35-UP composite in longitudinal and transverse direction

Zoltek PanEx35-UP	Longitudinal (0°)	Transverse (90°)
Average tensile modulus	131 GPa	7.9 GPa
Standard deviation	10 GPa	0.7 GPa
Coefficient of variation	7.9%	8.9%
Corrected tensile modulus	110 GPa	6.5 GPa



Table 7.6: the tensile moduli of the TRW40 50L composite in longitudinal and transverse direction

Mitsubishi Rayon TRW40 50L	Longitudinal (0°)	Transverse (90°)
Average tensile modulus	141 GPa	12.9 GPa
Standard deviation	5.6 GPa	1.5 GPa
Coefficient of variation	4.0%	12.0%
Corrected tensile modulus	130 GPa	9.8 GPa

7.3 Compression tests

The compressive tests are performed according to the ASTM D6641 standard (ASTM International [2]) on the same Zwick 250 kN test bench as used for the tensile tests. A combined loading compression (CLC) fixture as depicted in Figure 7.5 is added. A compressive force is applied at a constant rate of 1.3 mm/min until failure occurs. The average thickness of the specimens is 2.4 mm.

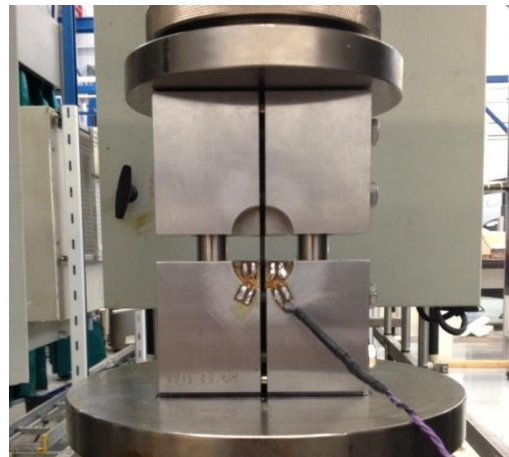


Figure 7.5: the combined loading compression (CLC) test fixture

Compression test results

The displacements of the test specimens and the applied force are monitored during the test until failure occurs. The thickness of the test specimens is not prescribed by the ASTM standard, as long as this is constant over the length and width. An analysis of the test specimens after failure shows a few different failure modes, as depicted in Figure 7.6. The failure plane is made more visible in Figure 7.7. Some specimens fail in compression crushing and show a horizontal failure plane. Other specimens fail in shear, showing a failure plane under an angle of 45°. It is unclear whether Euler buckling occurs, but it is recommended for future compressive tests that thicker specimens are used. A value of 6.6 mm is used in the next chapter for compressive tests of the carbon-glass hybrid material and this shows more consistent failure modes.



7. Mechanical tests of two carbon fabrics



Figure 7.6: different failure modes in the 0° compressive test specimens

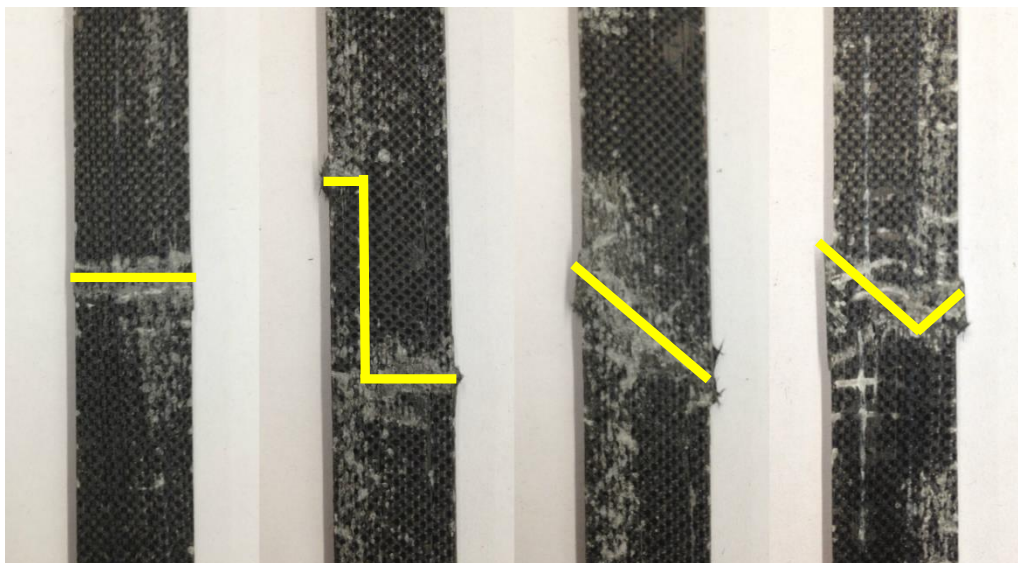


Figure 7.7: a better visualization of the fracture planes

Compressive strength

Dividing the compressive force at failure by the cross sectional area yields the compressive strength. For both laminates the results are given in Table 7.7 and Table 7.8 for the longitudinal and transverse direction.



Table 7.7: compressive strengths of the Zoltek PanEx35-UP composite

Zoltek PanEx35-UP	Longitudinal (0°)	Transverse (90°)
Average compressive strength	344 MPa	52 MPa
Standard deviation	47 MPa	6 MPa
Coefficient of variation	13.8%	11.6%
Corrected compressive strength	249 MPa	40 MPa

Table 7.8: compressive strengths of the Mitsubishi rayon TRW40 50L composite

Mitsubishi Rayon TRW40 50L	Longitudinal (0°)	Transverse (90°)
Average compressive strength	532 MPa	122 MPa
Standard deviation	66 MPa	4 MPa
Coefficient of variation	12.3%	3.4%
Corrected compressive strength	401 MPa	114 MPa

Compressive modulus

Due to a shortage of strain gages, the compressive modulus is only determined for the composite made from Zoltek's PanEx35-UP fibers. The results are shown in Table 7.9.

Table 7.9: the compressive moduli of the PanEx35-UP composite in longitudinal and transverse direction

Zoltek PanEx35-UP	Longitudinal (0°)	Transverse (90°)
Average compressive modulus	120 GPa	9.7 GPa
Standard deviation	9.6 GPa	0.8 GPa
Coefficient of variation	8.0%	7.8%
Corrected compressive modulus	101 GPa	8.2 GPa

7.4 Conclusions

Delamination phenomena are observed when combining carbon fibers with Synolite polyester. These phenomena are not, or to a much lesser extent observed in glass-polyester laminates. From this it is concluded that the interfacial bond strength between carbon fibers and polyester is lower than between glass fibers and polyester. The mechanical tests provide numerical values for the material's properties, which can be used as design allowables.

When comparing the theoretical tensile strengths in fiber direction of both laminates with the actually obtained tensile strengths, large differences are seen (e.g., 41% for the PanEx35-UP fabric). The deviations are the result of an accumulation of many factors. The most important ones are: inaccuracies during the build-up of the laminate, damage initiations as a result of the cutting of the specimens and fiber damage during clamping of the specimens in the tensile bench. The rule of mixtures cannot be used to accurately predict the tensile strength of a unidirectional laminate manufactured by hand. The same conclusion holds for the tensile



strengths in transverse direction. As expected, the rule of mixtures for the tensile stiffness of a unidirectional laminate gives very accurate results.

Now that the material properties of two carbon/polyester composite materials are known, a hybrid composite material can be designed where glass fibers, carbon fibers and polyester are combined. The design, manufacturing and testing of this material will be the topic of the next chapter.

7.5 References

- [1] ASTM D 3039/D 3039M - 00, Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials, ASTM International, West Conshohocken, PA, 2000
- [2] ASTM D 6641/D 6641M - 01, Standard Test Method for Determining the Compressive Properties of Polymer Matrix Composite Laminates Using a Combined Loading Compression (CLC) Test Fixture1, ASTM International, West Conshohocken, PA, 2001



8

Carbon-glass-polyester hybrid composites

In the previous chapter the properties of two carbon-polyester composite materials were determined. This chapter focusses on the design and testing of a hybrid composite material, built-up from glass fibers, carbon fibers and polyester resin. Based on the previous test results and bulk prices of both carbon fabrics, Zoltek's PanEx35 carbon fibers with a polyester sizing are chosen to be used in the hybrid material. The combination of glass fibers, carbon fibers and polyester as matrix material is new and information about the mechanical behavior is currently unknown.

8.1 Hybrid design

Since the hybrid material combination is new, tests at coupon level are required to gain basic knowledge about the mechanical properties. Before testing can take place, the composite material first needs to be designed. The following parameters play an important role in the design and can be used to fine-tune the laminate's behavior:

- Ratio of carbon fibers to glass fibers
- Individual ply thickness
- Individual ply orientation
- Stacking order

One of the first starting points in the design is the assumption that, when combining glass fibers and carbon fibers, the expensive carbon fibers should be placed only in the direction in which strength and stiffness are most required, i.e., in span direction (0°). All other fibers, transverse to the span direction (90°) and in the $\pm 45^\circ$ direction, will be glass fibers.

Initially, three different hybrid laminates are investigated:

- Carbon fibers in 0° and glass fibers in $\pm 45^\circ$ direction ($+45^\circ:-45^\circ = 1:1$)
- Carbon fibers in 0° and glass fibers in 90° and $\pm 45^\circ$ direction ($90^\circ:+45^\circ:-45^\circ = 1:1:1$)
- Carbon fibers in 0° and glass fibers in 90° and $\pm 45^\circ$ direction ($90^\circ:+45^\circ:-45^\circ = 2:1:1$)



8. Carbon-glass-polyester hybrid composites

The percentage carbon is varied from 0% to 100% and the remainder is complemented with glass fibers. Classical laminate theory is used to determine the stiffness of the laminate in span or x direction (0°) and transverse or y direction (90°). For the three laminates, the resulting values for E_x and E_y are plotted as a function of the percentage carbon in Figure 8.⁶

From a discussion with FiberCore's chief technology officer it became clear that the design stiffness of the laminate in transverse direction is currently 16 GPa. This stiffness works very well and should be maintained in the new hybrid bridge. In Figure 8.1 a line is drawn at this threshold. It can be seen that the transverse stiffness of the composites with only glass fibers in the $\pm 45^\circ$ direction drops below 16 GPa when more than 20% carbon fibers are used. The accompanying longitudinal stiffness is only 36 GPa. The laminates with glass fibers in the 90° and $\pm 45^\circ$ direction can contain carbon fibers up to 55%, before the transverse stiffness drops below 16 GPa. From a practical point of view the laminate with 50% carbon fibers in 0° direction, 25% glass fibers in 90° direction and 25% glass fibers in $\pm 45^\circ$ direction is chosen. The transverse stiffness of this laminate is 16.9 GPa and the stiffness in span direction is 61.5 GPa.

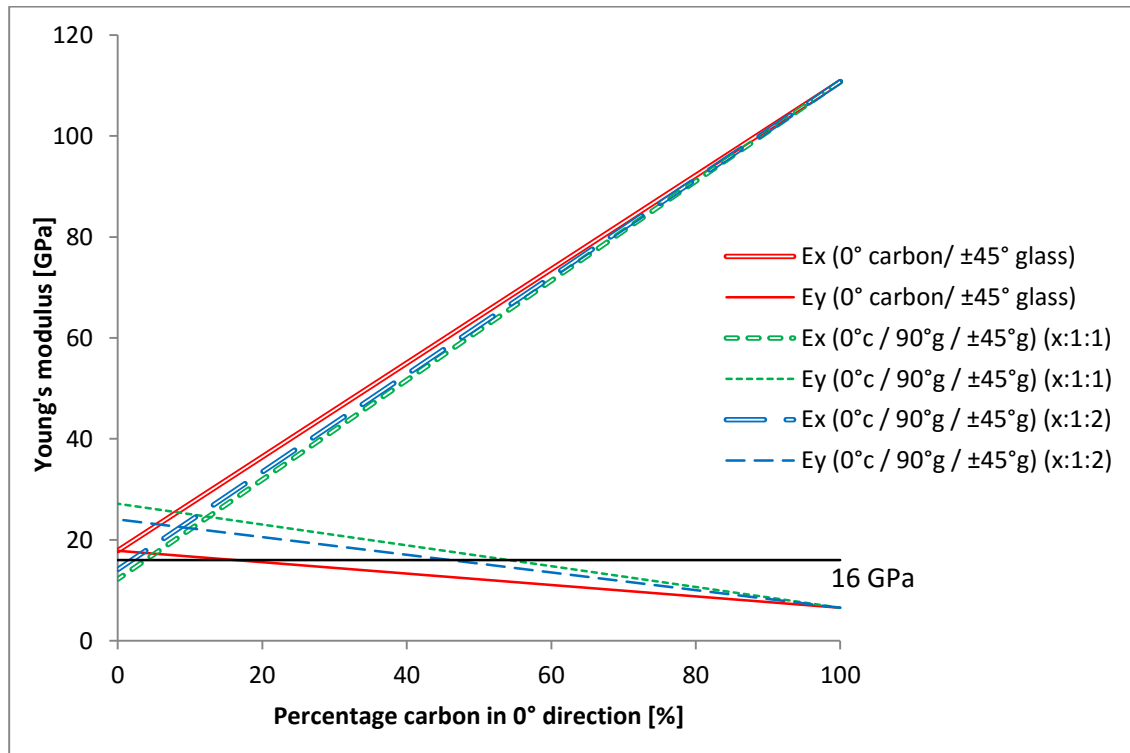


Figure 8.1: the stiffness in 0° and 90° direction of three hybrid laminates as a function of the percentage carbon

⁶ All calculated values are based on a fiber-volume fraction of 53% for both the glass and the carbon part in the laminate. This fiber-to-matrix ratio is achieved during multiple tests.



With the ratio of carbon fibers to glass fibers known, the next step is to determine a suitable stacking order. The following design rules and guidelines are kept in mind when designing the hybrid laminate:

- To prevent coupling effects between bending and extension of the laminate, a balanced and symmetrical stacking sequence is required.
- The stacking order should be compatible with FiberCore Europe's bridge building concept, consisting of core-wraps, Z-layers and intermediate layers as described in Chapter 3.
- For coupon testing and comparison of the results, the thickness of the laminate is restrained and should be close to the thickness as prescribed by the relevant test standards (see Table 7.1).
- Specifically for the short-beam bending tests, the interface plane of interest should be located at the center of the laminate where the shear forces are at their maximum.
- Instinctively it feels right to prevent large jumps in stiffness between adjacent plies. Carbon fibers in 0° direction ($E_x = 110$ GPa) should not be directly adjacent to glass fibers in the 90° direction ($E_x = 16$ GPa) to prevent large interlaminar shear stresses.

In the design of the hybrid laminate it quickly became apparent that it is not possible to meet all previously mentioned conditions simultaneously. Therefore three different laminates are designed as a compromise to provide as much information as possible during testing: a laminate for reference purposes, a laminate to perform short-beam bending tests on and a laminate for compression and tensile tests. The stacking orders of these laminates and their thicknesses after production are given in Table 8.1. Since the stacking sequence notation as used in Table 8.1 does not immediately provide a clear image of the laminate build-up, a more graphical representation is given in Figure 8.2. The thicknesses of the individual plies in Figure 8.2 are derived from the build-up and total thickness of previously manufactured laminates with the same fabrics.

Table 8.1: the designation, stacking order and thickness of the three carbon-glass-polyester hybrid laminates

Laminate #	Designation	Stacking order	Thickness [mm]
1	Ref. (Reference laminate)	$[(0c)_2, 0g, (0c)_2, \overline{0g}]_s$	6.8
2	ILSS (Short-beam bending tests)	$[(0c)_2, 90g, \pm 45g, (0c)_2, 90g, \pm 45g, (0c)_2]_T$	6.6
3	T/C (Tensile and compressive tests)	$[(0c)_2, \pm 45g, 90g, 0c]_s$	6.6



Reference	ILSS	T/C
0° carbon - 0.59 mm	0° carbon - 0.59 mm	0° carbon - 0.59 mm
0° carbon - 0.59 mm	0° carbon - 0.59 mm	0° carbon - 0.59 mm
0° glass - 0.82 mm	90° glass - 0.82 mm	+45° glass - 0.41 mm
0° carbon - 0.59 mm	+45° glass - 0.41 mm	-45° glass - 0.41 mm
0° carbon - 0.59 mm	-45° glass - 0.41 mm	90° glass - 0.82 mm
0° glass - 0.82 mm	0° carbon - 0.59 mm	0° carbon - 0.59 mm
0° carbon - 0.59 mm	0° carbon - 0.59 mm	0° carbon - 0.59 mm
0° carbon - 0.59 mm	90° glass - 0.82 mm	90° glass - 0.82 mm
0° glass - 0.82 mm	+45° glass - 0.41 mm	-45° glass - 0.41 mm
0° carbon - 0.59 mm	-45° glass - 0.41 mm	+45° glass - 0.41 mm
0° carbon - 0.59 mm	0° carbon - 0.59 mm	0° carbon - 0.59 mm
	0° carbon - 0.59 mm	0° carbon - 0.59 mm

Figure 8.2: the stacking order of the three hybrid laminates visualized

The fabric areal weight (FAW) of the carbon plies is 600 g/m². For both the 90° and the ±45° glass fiber plies this is 1221 g/m². The used materials and production specifications of the hybrid laminates are shown in Table 8.2.

Table 8.2: production specifications of the three carbon-glass-polyester hybrid composite laminates

Material/Process	Specifications
Carbon fabric	Zoltek PanEx35, polyester sizing, UD, 600 g/m ²
Glass fabric	[manufacturer], UD and ±45°, 1221 g/m ²
Polyester resin	DSM Synolite 1967 (97.9% by weight)
Curing agent	AkzoNobel Trigonox 249 VR (2.1% by weight)
Production process	Vacuum infusion at $\Delta p = 0.8$ bar

8.2 Test procedure

8.2.1 Short-beam bending tests

High precision water jet cutting is used to create test specimens from the laminates. Ten test specimens from the reference laminate and ten specimens from the ILSS laminate are submitted to short-beam bending tests according to the ASTM D2234 standard (ASTM International [1]). Figure 8.3 shows one of the hybrid composite test specimen in the 3-point-bending fixture of the Zwick 20 kN test bench at the DASM-lab.

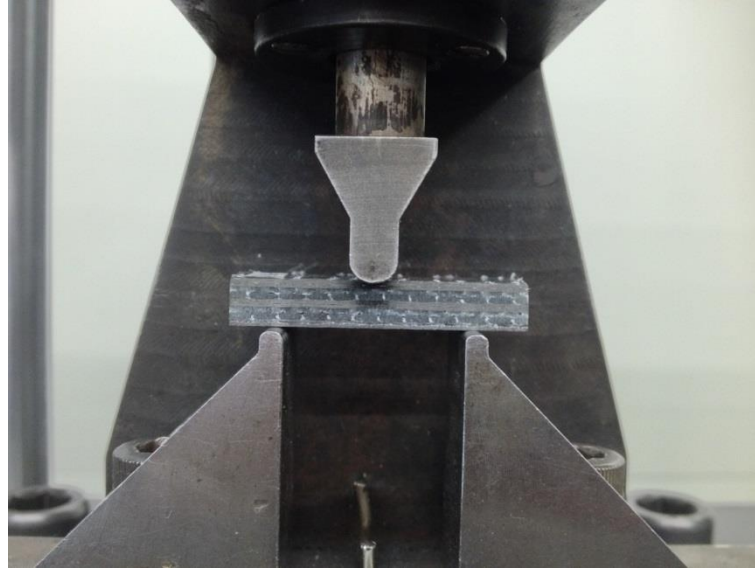


Figure 8.3: a glass-carbon-polyester hybrid composite test specimen in the 3-point-bending fixture

Similar to the short-beam bending tests as performed previously and described in Chapter 6, the speed of testing is set at a constant rate of crosshead movement of 1.0 mm/min. Again, the load and crosshead displacement are recorded until failure occurs and the short-beam strength is calculated according to the following formula:

$$F^{sbs} = 0.75 \times \frac{P_m}{b \times h} \quad (8.1)$$

Where

- F^{sbs} = short-beam strength [MPa]
- P_m = the maximum load [N]
- b = specimen width [mm]
- h = specimen thickness [mm]

Analyzing the test specimens after failure under a microscope clearly revealed that all test specimens failed in interlaminar shear. The location of failure, however, was often not in the midplane as expected from beam theory. In the next sections for each laminate and for each direction of testing, the typical failure locations are shown and described.

Reference laminate in 0° direction

All five test specimens of the reference laminate with fibers in the 0° direction and tested in this direction failed in an outer glass layer. Beam theory as used above predicts the highest shear values at the mid-plane of the test specimens. However, an elastic analysis of orthotropic beams (Whitney [2]) shows that, under concentrated loads, the maximum shear force lies much closer to the location where the load is applied, i.e., the upside of the test specimens. This is much more consistent with the observed results. The location of failure is indicated in Figure 8.4.

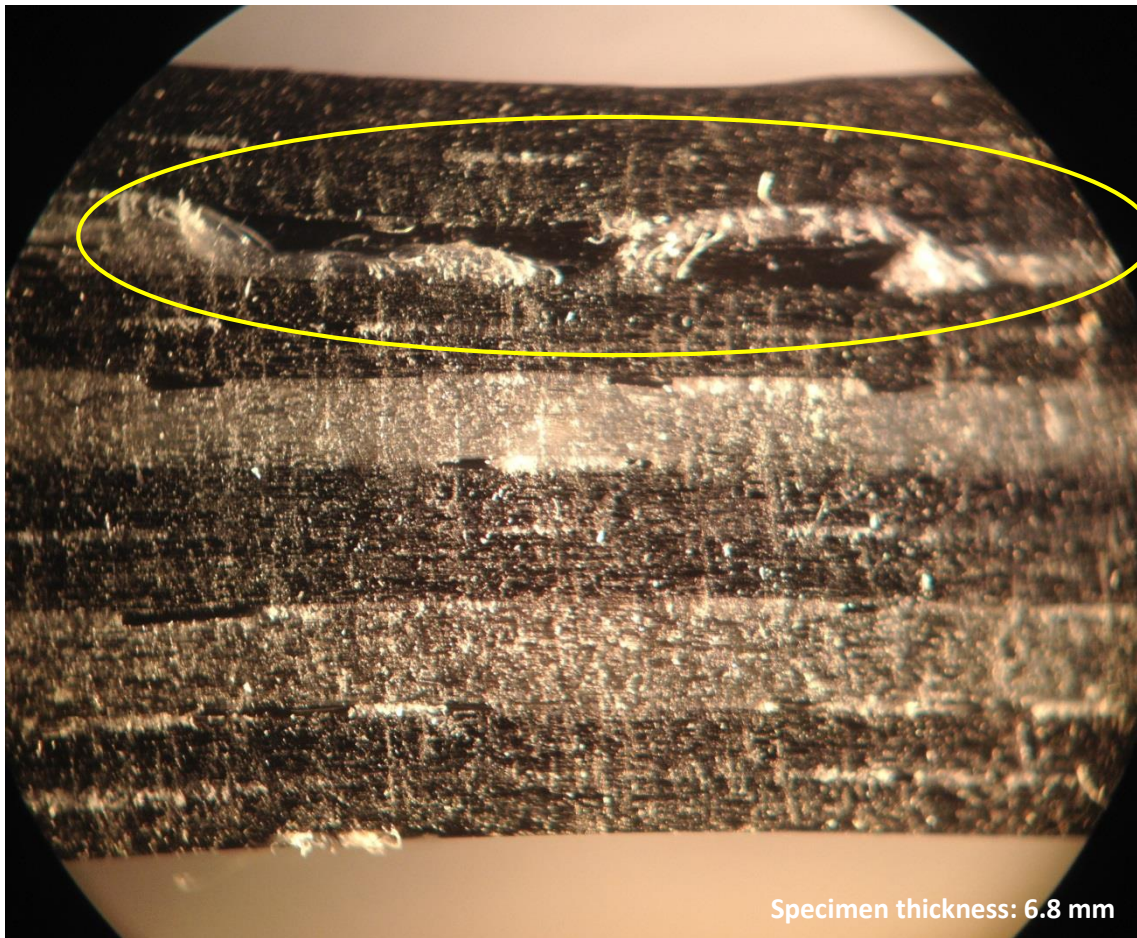


Figure 8.4: the typical location of failure of reference test specimens in the 0° direction

Reference laminate in 90° direction

The specimens of the reference laminate tested in the 90° direction failed at multiple locations. Analyzing the specimens after the tests showed cracks from the mid-planes up to the top surface. It was hard to determine where the first failure took place. Figure 8.5 shows a large fracture line between the glass ply in the central plane and an adjacent carbon ply. A smaller crack can be observed near the upper surface. A careful analysis of all test specimens shows that the cracks appear to initiate at the location of the polyester stitching threads. This is consistent with the observations made in Chapter 6, where the stitching fibers were also suspect to play a crucial role in the initiation of cracks.

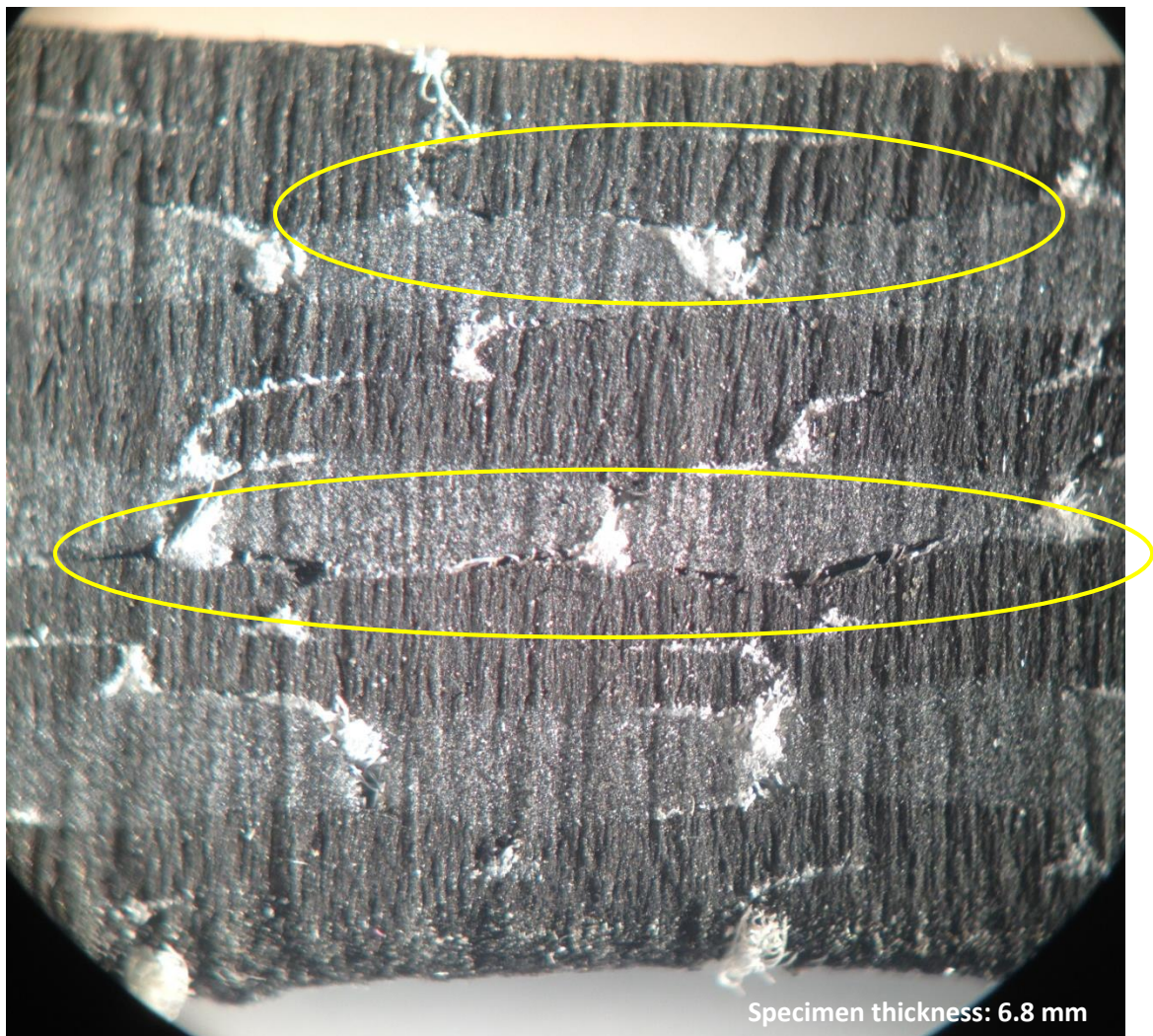


Figure 8.5: the typical location of failure of reference test specimens in the 90° direction

Hybrid ILSS laminate in 0° direction

The hybrid ILSS laminate tested in the longitudinal (0°) direction fails between a 45° glass layer and a 90° glass layer. This can be seen in Figure 8.6. Reason for this behavior could be the asymmetrical build-up of the laminate. Bending during the test will result in twisting of the test specimen. This might strain the two glass layers in a way fracture occurs between them. It is also observed that the polyester stitching fibers in the glass plies leave relatively large voids in the laminate. These defects are larger than in the carbon plies and could very well be the reason for early failure.

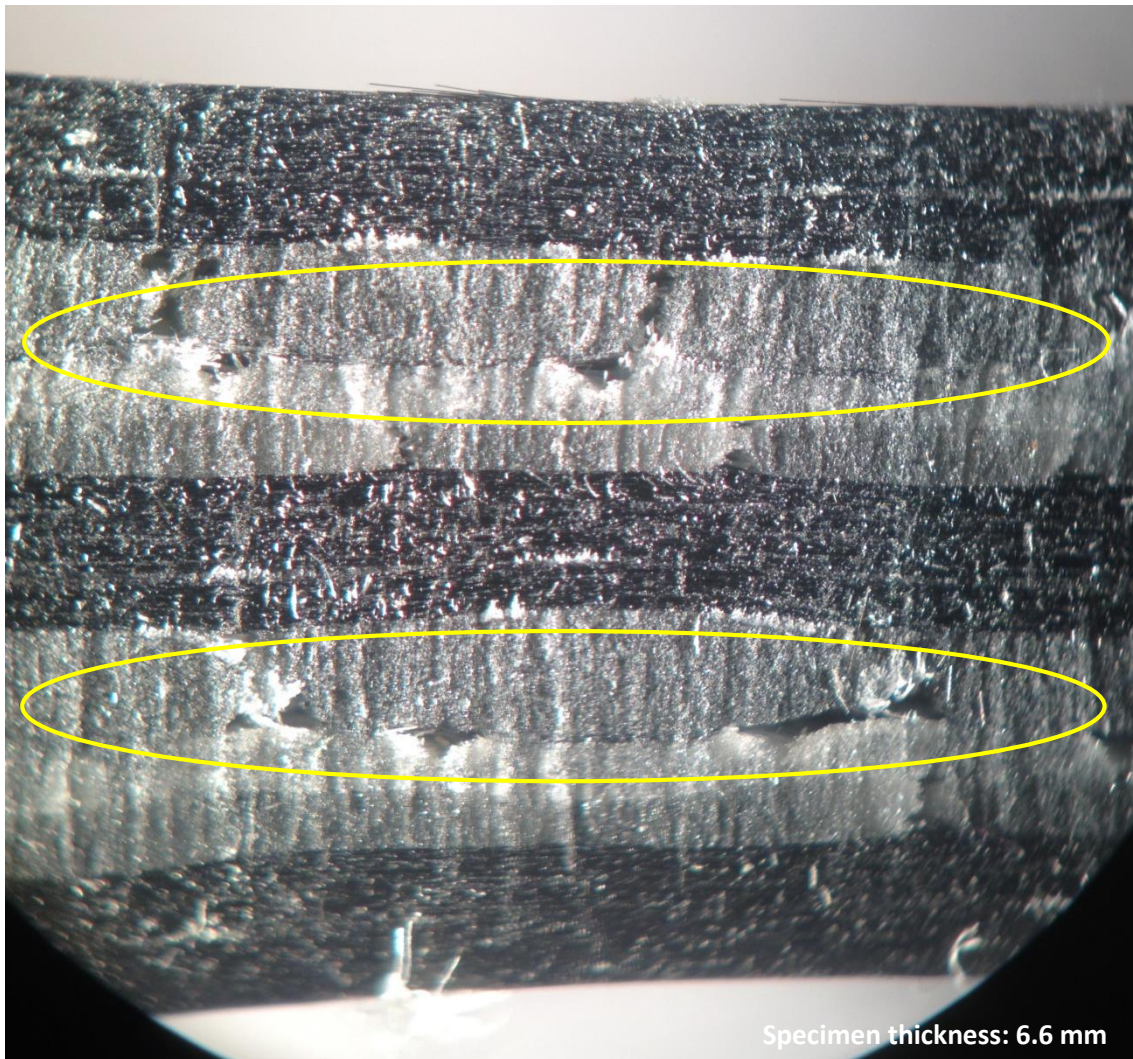


Figure 8.6: the typical locations of failure of hybrid ILSS test specimens in the 0° direction

Hybrid ILSS laminate in 90° direction

Similar as for the 0° direction, also the hybrid ILSS specimens tested in the 90° direction show failure between a 45° and 90° glass plie. Figure 8.7 shows the detrimental way in which both 45° glass plies appear to disbond from the 90° glass layer. Due to the microscopic enlargement, cavities where stitching fibers used to be present are clearly visible. These cavities are also visible in untested specimens and in the remainder of the laminate from which the specimens are cut. High precision water jet cutting could very well be the cause of these imperfections. Figure 8.7 clearly shows the rough surface quality of the test specimens as a result of the dimensional shaping. Another theory is that the stitching threads, consisting of a bundle of small thermoplastic polyester fibers, somehow repel the unsaturated polyester and prevent the latter from completely impregnating the laminate at the location of the stitching. This theory is backed by visual inspection of previously manufactured single glass, single carbon and carbon-glass hybrid laminates where voids are clearly visible along the stitching lines.

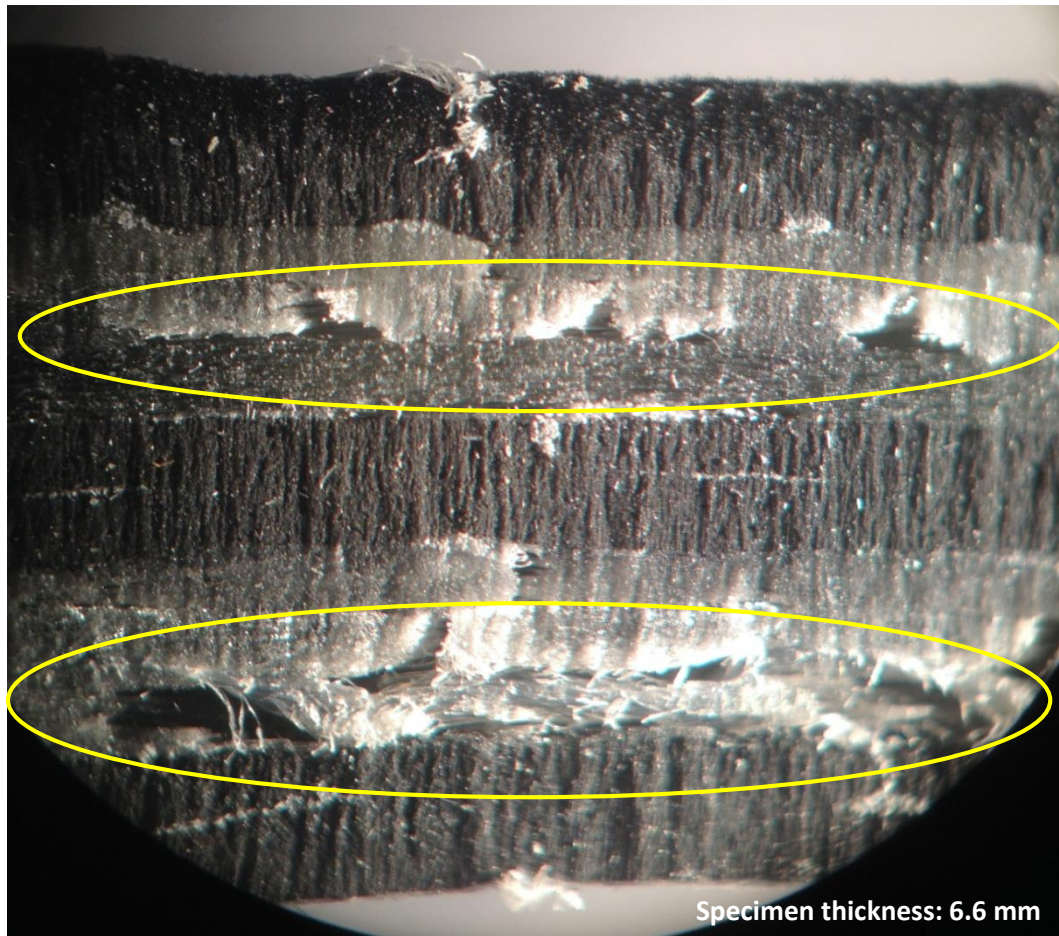


Figure 8.7: the typical locations of failure of hybrid ILSS test specimens in the 90° direction

Results

The numerical values for the interlaminar shear strength as obtained with the short-beam bending tests are given in Table 8.3 and Table 8.4 for the reference laminate and the ILSS laminate respectively.

Table 8.3: the short-beam bending strength of the reference laminate in longitudinal and transverse direction

Reference hybrid laminate	Longitudinal (0°)	Transverse (90°)
Average short-beam strength	25.0 MPa	2.1 MPa
Standard deviation	2.4 MPa	0.4 MPa
Coefficient of variation	9.7%	17.6%
Corrected short-beam strength	20.2 MPa	1.3 MPa



Table 8.4: the short-beam bending strength of the ILSS laminate in longitudinal and transverse direction

ILSS hybrid laminate	Longitudinal (0°)	Transverse (90°)
Average short-beam strength	19.2 MPa	10.5 MPa
Standard deviation	1.5 MPa	0.6 MPa
Coefficient of variation	7.8%	5.5%
Corrected short-beam strength	16.2 MPa	9.4 MPa

8.2.2 Tensile tests

The tensile tests are performed according to the ASTM D3039 standard (ASTM International [3]) on a Zwick 250 kN test bench at the DASM-lab. The test specimens have a length of 250 mm, a width of 25 mm and an average thickness of 6.6 mm. Plain paper tabs (160 g/m²) of 56 x 25 mm are bonded with general purpose superglue on the four ends of the test specimens to prevent slip in the hydraulic grips. The displacement of the test bench's head is set at a constant rate of 2 mm/min. Strain gages (Kyowa KFG-5-120-C1-11) are used to register the elongation of the test specimens during the test. The force and head displacement are registered during the test until failure occurs. Figure 8.8 shows three carbon-glass-polyester tensile test specimens: an untested specimen, a specimen after test with carbon fibers in the longitudinal (0°) direction and a specimen after test with the carbon fibers in the transverse (90°) direction.



Figure 8.8: three hybrid tensile test specimens: (a) before test, (b) 0° after test, and (c) 90° after test

Tensile strength

By dividing the applied force at first failure over the cross sectional area of the test specimen, the tensile strength of the hybrid laminate is determined. For the tensile tests in longitudinal and transverse direction, the strengths are given in Table 8.5.



Table 8.5: the tensile strength of the T/C hybrid laminate in longitudinal and transverse direction

T/C hybrid laminate	Longitudinal (0°)	Transverse (90°)
Average tensile strength	863 MPa	207 MPa
Standard deviation	29 MPa	20 MPa
Coefficient of variation	3.3%	9.5%
Corrected tensile strength	806 MPa	167 MPa

Tensile modulus

Strain gages are used to register the elongation of the test specimens during the test. The results for the tests in the longitudinal direction clearly show a linear relation between the applied force and deformation of the specimens. For the tests in transverse direction, this linear relation is less clear. Zooming in on the very first phase of the test up till a tensile force of 5 kN, however, also shows the linear behavior. By dividing the applied force over the cross sectional area and dividing the result over the registered strain, the Young's modulus of the hybrid laminate in both directions is determined. The results are given in Table 8.6.

Table 8.6: the Young's moduli of the T/C hybrid laminate in longitudinal and transverse direction

T/C hybrid laminate	Longitudinal (0°)	Transverse (90°)
Average tensile modulus	72 GPa	21 GPa
Standard deviation	3 GPa	3 GPa
Coefficient of variation	3.6%	12.6%
Corrected tensile modulus	67 GPa	16 GPa

8.2.3 Compression tests

The compression tests are performed according to the ASTM D6641 standard (ASTM International [4]). The length of the test specimen is 140mm, the width is 12 mm and the average thickness is 6.6 mm. The specimens are placed in a combined loading compression (CLC) fixture inside the same Zwick 250 kN test bench as used for the tensile tests. A compressive force is applied at a constant head displacement rate of 1.3 mm/min until failure occurs. Figure 8.9 shows three carbon-glass-polyester hybrid compression test specimens: a specimen before testing, a specimen after testing with the carbon fibers in the longitudinal direction and a specimen after testing with the carbon fibers in the transverse direction. The tests appear to be running with a more consistent failure mode than the compressive tests of the carbon-polyester laminates from Chapter 7. This is mainly attributed to the increased thickness of the hybrid test specimens (6.6 mm for the hybrid laminate vs. 2.4 mm for the carbon laminate).



8. Carbon-glass-polyester hybrid composites



Figure 8.9: three hybrid compression test specimens: (a) before test, (b) 0° after test, and (c) 90° after test

Compressive strength

The compressive strength is determined by dividing the failure load over the cross sectional area of the test specimen. The results are given in Table 8.7.

Table 8.7: the compressive strength of the T/C hybrid laminate in longitudinal and transverse direction

T/C hybrid laminate	Longitudinal (0°)	Transverse (90°)
Average compressive strength	233 MPa	196 MPa
Standard deviation	30 MPa	7 MPa
Coefficient of variation	12.8%	3.4%
Corrected compressive strength	173 MPa	182 MPa

Compressive modulus

The shortening of the test specimens is registered with the use of strain gages during the test. The Young's modulus of the hybrid material is again derived by dividing the compressive stress (applied force divided by the cross sectional area) by the registered strain over the first linear phase of the tests. The results are given in Table 8.8.

Table 8.8: The Young's moduli of the T/C hybrid laminate in the longitudinal and transverse direction

T/C hybrid laminate	Longitudinal (0°)	Transverse (90°)
Average compressive modulus	69 GPa	18 GPa
Standard deviation	2 GPa	1 GPa
Coefficient of variation	2.5%	4.6 GPa
Corrected compressive modulus	66 GPa	16 GPa



8.3 Comparison of laminates from different materials

In the previous chapter the mechanical properties of two carbon-polyester laminates were determined. The laminates were built-up of carbon fabrics with all fibers in the same direction. In this chapter the mechanical properties of a carbon-glass-polyester hybrid laminate were determined. The individual plies in the hybrid laminates are placed at angles of 0°, +45°, -45°, and 90°. The build-up of the hybrid laminates are given in Table 8.1 and Figure 8.2. From previous tests at FiberCore Europe the properties of a glass-polyester laminate were determined. The latter laminate consists of 75% glass fibers in the 0° direction and 25% glass fibers in the 90° direction. The differences in stacking order of all laminates make it impossible to compare the mechanical properties one-on-one. Nevertheless, for a rough qualitative comparison, the mechanical properties of all three laminates are summarized in Table 8.9.

Table 8.9: the obtained mechanical properties for three different laminates

	ILSS		Tensile strength [MPa]		Compressive strength [MPa]		Tensile modulus [GPa]		Compressive Modulus [GPa]	
	0°	90°								
Glass-Polyester	38	15	666	278	491	243	34	16	36	20
Carbon-Polyester ^{*)}	28	-	1353	7	249	40	110	7	101	8
Carbon-Glass-Polyester	16	9	806	167	173	182	67	16	66	16

^{*)} values taken from the Zoltek PanEx35-UP laminate

8.4 Conclusions

The mechanical tests provide numerical values for the hybrid material's properties which can be used as design allowables. From the tests it becomes clear that the Young's moduli for tension and compression in both test directions are, as expected, very similar. Most of the derived values for the hybrid laminate lie in between the values of a single-glass and single-carbon composite.

Microscopic analysis of the ILSS test specimens shows clear indications that the thermoplastic polyester stitching fibers play a large role in crack initiation.

8.5 References

- [1] ASTM D 2344/D 2344M - 00, Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates, ASTM International, West Conshohocken, PA, 2006
- [2] Whitney, J.M., *Elasticity analysis of orthotropic beams under concentrated loads*. Composites Science and Technology, 1985. 22(3): p. 167-184.
- [3] ASTM D 3039/D 3039M - 00, Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials, ASTM International, West Conshohocken, PA, 2000
- [4] ASTM D 6641/D 6641M - 01, Standard Test Method for Determining the Compressive Properties of Polymer Matrix Composite Laminates Using a Combined Loading Compression (CLC) Test Fixture1, ASTM International, West Conshohocken, PA, 2001



9

Evaluation of thermal stresses

In general, every material shows changes in dimension in reaction to changes in temperature. Most materials expand when warming up and contract when cooling down. Carbon fibers react in an opposite fashion; they contract when temperature increases and expand when the temperature decreases. The degree to which a material changes its dimensional properties as a result of changes in temperature is indicated by its coefficient of thermal expansion (CTE), often indicated by the Greek letter α (unit: K^{-1}). A list of coefficients of linear thermal expansion for the materials used in the design concepts is given in Table 9.1. These values are obtained from the respective suppliers. When materials with different CTE's are interconnected, thermal stresses occur as a result of changes in temperature. In this chapter, these thermal stresses for both design concepts will be quantified and the implications of these stresses will be addressed.

Table 9.1: coefficients of thermal expansion of relevant materials

Material	CTE [$10^{-6} K^{-1}$]
Jushi 386 Direct Roving glass fibers	2.8
Zoltek PanEx35 carbon fibers	-0.75
DSM Synolite 1967 unsaturated polyester	100
S235JR structural steel	12

9.1 Thermal stresses in hybrid composite structures

For composite bridges, there are no regulatory guidelines for thermal loads. In practice, the temperatures for calculations of thermal expansions and stresses are derived from the NEN-EN-1991-1-5 standard with national annex (NEN [1], NEN [2]). This standard prescribes temperature ranges for bridges made from concrete and steel. The reaction of composite bridges to temperature is more similar to concrete bridges than to steel bridges and therefore the temperatures prescribed for the former structures are used. These temperatures are defined as follows:



- Minimum temperature in the shadow: $T_{\min} = -25 \text{ }^{\circ}\text{C}$
- Maximum temperature in the shadow: $T_{\max} = 30 \text{ }^{\circ}\text{C}$
- Design/initial temperature: $T_0 = 10 \text{ }^{\circ}\text{C}$
- Minimum uniform temperature component: $T_{e.\min} = T_{\min} + 8 \text{ }^{\circ}\text{C} = -17 \text{ }^{\circ}\text{C}$
- Maximum uniform temperature component: $T_{e.\max} = T_{\max} + 2 \text{ }^{\circ}\text{C} = 32 \text{ }^{\circ}\text{C}$
- Maximum temperature range contraction: $\Delta T_{N.\text{con}} = T_0 - T_{e.\min} = 27 \text{ }^{\circ}\text{C}$
- Maximum temperature range expansion: $\Delta T_{N.\text{exp}} = T_{e.\max} - T_0 = 22 \text{ }^{\circ}\text{C}$
- Total range uniform temperature component: $\Delta T_N = T_{e.\max} - T_{e.\min} = 49 \text{ }^{\circ}\text{C}$

A bundle of glass fibers with a length of 1 meter increases 2.8 μm in length if the temperature increases 1 $^{\circ}\text{C}$. The increase of polyester material with an initial length of 1 meter will be 100 μm for the same temperature increase. When the two materials are bonded together, the glass fibers prevent the polyester from expanding all the way up to the 100 μm . The polyester, at the same time, pulls on the glass fibers and extends them beyond 2.8 μm . The final length will be somewhere between 2.8 and 100 μm . A force equilibrium approach can be used to calculate the resultant stresses in both materials. The following equation can be used to link the extension of the glass fibers and the compression of the polyester matrix to the change in lengths of the individual components with respect to their “free”, unconstraint lengths:

$$\frac{\sigma_f \cdot L}{E_f} + \frac{\sigma_m \cdot L}{E_m} = (\alpha_m - \alpha_f) L \Delta T \quad (9.1)$$

In this expression, σ represents the stress in the material, L is the original length, E is the stiffness, α is the coefficient of linear thermal expansion and ΔT is the change in temperature. The subscripts f and m stand for the fiber and matrix properties respectively. The length L appears on both sides of the equation and drops out. The resulting thermal stresses are independent of the length of structure. In this case, the fibers are E-glass and the matrix is the Synolite polyester. For equilibrium, Newton’s third law of motion requires that the tensile force in the glass is equal to the compressive force in the polyester. This is expressed in the following equation:

$$\sigma_f \cdot A_f = \sigma_m \cdot A_m \quad (9.2)$$

In this expression A is used to represent the surface area of the fiber and matrix materials. Equations (9.1) and (9.2) provide a system of two equations with two unknowns (σ_f and σ_m), which can easily be solved. Combining and rewriting the equations yields:

$$\sigma_f = \frac{(\alpha_m - \alpha_f) \Delta T}{\frac{1}{E_f} + \frac{A_f}{E_m A_m}} \quad (9.3)$$

$$\sigma_m = \sigma_f \frac{A_f}{A_m} \quad (9.4)$$

For a glass-polyester composite with a fiber-volume fraction (v_f) of 52%, the following values can be used to determine the stresses in both fibers and matrix material:



$$\alpha_f = \alpha_{glass} = 2.8 \cdot 10^{-6} K^{-1}$$

$$E_f = E_{glass} = 78.8 GPa$$

$$\alpha_m = \alpha_{polyester} = 100 \cdot 10^{-6} K^{-1}$$

$$E_m = E_{polyester} = 3.8 GPa$$

$$\Delta T = 27 K$$

$$A_f = 52\%$$

$$A_m = 1 - A_f = 48\%$$

The resulting thermal stresses for $\Delta T = 27 K$ are:

$$\sigma_{glass} = 8.8 MPa$$

$$\sigma_{polyester} = -9.5 MPa$$

Repeating this calculation for a carbon-polyester composite with $V_f = 52\%$, the thermal stresses in fiber and matrix respectively become:

$$\sigma_{carbon} = 9.3 MPa$$

$$\sigma_{polyester} = -10.2 MPa$$

A similar approach can be used when steel is combined with GFRP. First the combined coefficient of linear thermal expansion of the glass-polyester composite has to be determined. This can be done as follows for a laminate with the fibers in longitudinal direction:

$$(\alpha E)_{comp} = v_f(\alpha E)_f + (1 - v_f)(\alpha E)_m \quad (9.5)$$

This equation states that the “thermal stiffness” of the composite is a function of the volume ratio of the “thermal stiffnesses” of the fibers and matrix respectively. The latter “thermal stiffnesses” are defined as:

$$(\alpha E)_f = \alpha_f E_f \quad (9.6)$$

$$(\alpha E)_m = \alpha_m E_m \quad (9.7)$$

The stiffness of a composite material is found by applying the rule of mixtures:

$$E_{comp} = v_f E_f + (1 - v_f) E_m \quad (9.8)$$



Finally, the coefficient of linear thermal expansion can be derived by combining equations (9.5) through (9.8) above. This results in:

$$\alpha_{comp} = \frac{(\alpha E)_{comp}}{E_{comp}} = \frac{v_f(\alpha E)_f + (1-v_f)(\alpha E)_m}{v_f E_f + (1-v_f)E_m} \quad (9.9)$$

All parameters on the right side of equation (9.9) are known. Substituting the specific values for glass and polyester yields for the coefficient of linear thermal expansion of the GFRP in longitudinal direction:

$$\alpha_{GFRP} = 7.4 \cdot 10^{-6} K^{-1}$$

Similar, for a CFRP composite, the CTE in longitudinal direction becomes:

$$\alpha_{CFRP} = 0.7 \cdot 10^{-6} K^{-1}$$

Using equations (9.3) and (9.4) again and a value of 210 GPa for E_{steel} and $\alpha_{steel} = 12 \cdot 10^{-6} K^{-1}$, the stresses in the GFRP and the steel can be determined. Figure 9.1 shows the stresses in both the steel and the GFRP as a function of the amount of steel embedded. The stresses in the carbon fiber composite and glass fiber composite as a function of the percentage of carbon fibers (with respect to the glass fibers) are shown in Figure 9.2.

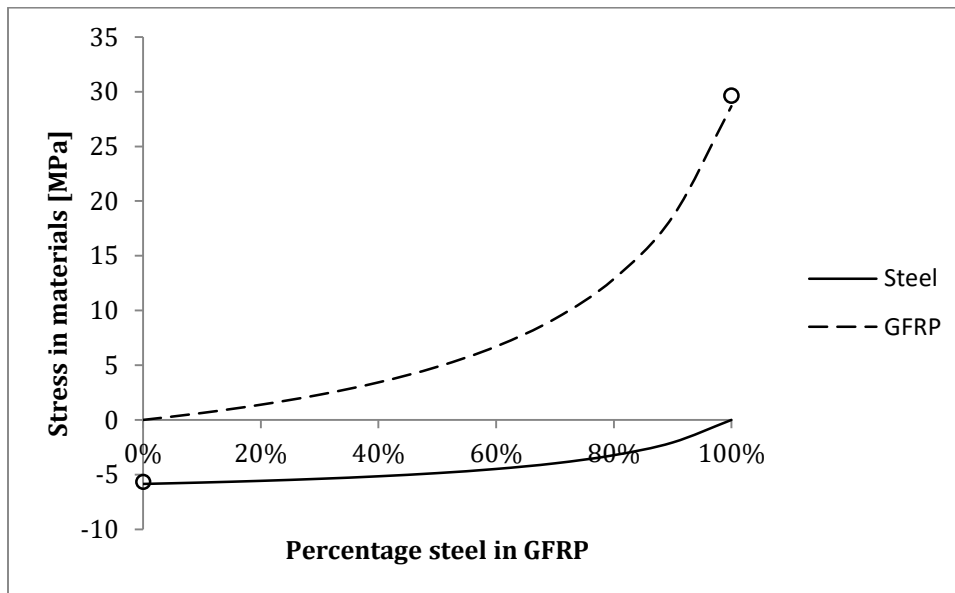


Figure 9.1: stresses in steel and GFRP as a function of the steel content

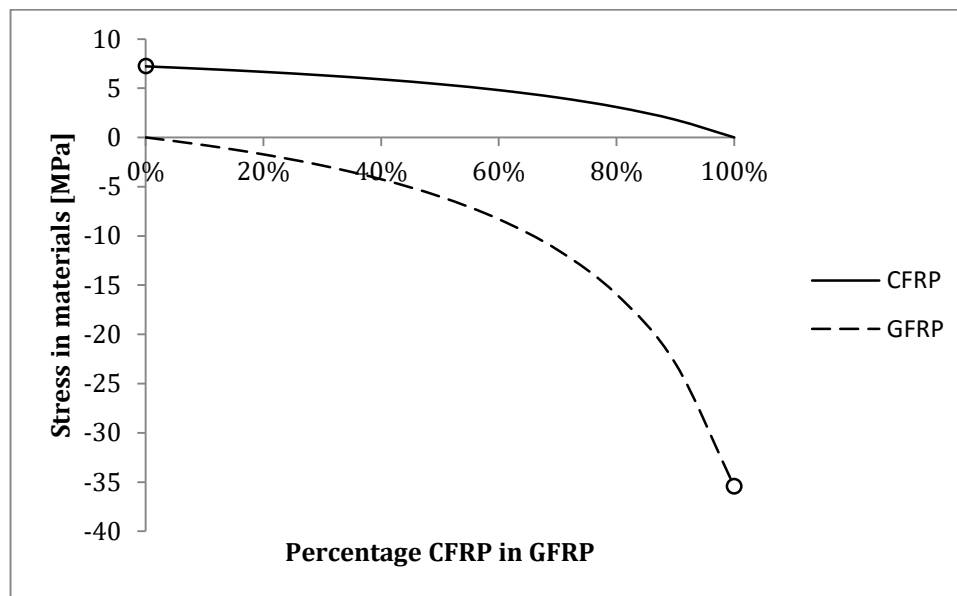


Figure 9.2: stresses in CFRP and GFRP as a function of the carbon content

From tests at FiberCore Europe it was found that the maximum compressive strength of GFRP is 199 MPa. The analyses in Chapters 7 and 8 show that the maximum compressive strengths of the Zoltek PanEx35-UP CFRP and the carbon-glass hybrid material are 249 MPa and 173 MPa respectively. Values for steel are over 200 MPa. From the analysis described above it is clear that the magnitude of the tensile and compressive stresses in all components, as a result of changes in temperature, are much smaller than the maximum allowable stresses. Especially when realizing that steel or carbon percentages in the total hybrid composite structure will remain limited. Dividing the stresses of the fiber composite materials into stresses of the individual constituents does not change the overall outcome. So far, thermal stresses do not pose any threat. However, when two materials are bonded together and unequal internal stresses occur, these stresses are transferred from one material to the other through shear stresses at the interface between the materials. For long and slender structures ($L \gg t$) these shear stresses are zero over the length of the interface except for the ends, where local peak stresses arise. The magnitude of these end stresses can be approximated by a number of numerical methods. Eischen, et al. [3] describe and compare three methods: a theory of elasticity via an eigenvalue expansion approach by Hess, an extended strength of materials theory as proposed by Suhir and a stress analysis through a finite element method. These methods require more time than available in this thesis project and will not be incorporated. To ensure a safe hybrid bridge design, this analysis has to be performed, however.

Extra measures can be taken to lower the risk of inter-material failure at the bridge's end. Mechanical solutions like vertical bars through the deck can be used to divert shear stresses into compressive stresses. Composite materials with plies in the $\pm 45^\circ$ direction show a more



ductile behavior and can be used around stiffer elements to distribute the shear stresses between these components more gradually.

9.2 Conclusions

The compressive and tensile stresses in the individual materials as a result of differences in CTE's and changes in temperature are far below the material allowable stresses. Shear stresses at the interface between the dissimilar materials are zero over the length of the bridge, but show peaks at the ends. The magnitudes of these shear stresses can and have to be approximated through numerical methods (e.g., FEA) in order to safeguard the structural integrity of the final structure. The shear stresses due to thermal loads can pose a serious threat to the relatively weak adhesive bond strength between steel and the glass fiber reinforced polyester. As long as the allowable bond strength is not known from component or full-scale tests, it is highly recommended that the steel/GFRP sub-concepts do not rely on this bond strength for their structural reliability.

9.3 References

- [1] NEN-EN 1991-1-5+C1 - Eurocode 1: Actions on structures - Part 1-5: General actions - Thermal actions, NEN, 2011
- [2] NEN-EN 1991-1-5+C1/NB - National Annex to NEN-EN 1991-1-5+C1: Eurocode 1: Actions on structures - Part 1-5: General actions - Thermal actions, NEN, 2011
- [3] Eischen, J.W., Chung, C., and Kim, J.H., *Realistic Modeling of Edge Effect Stresses in Bimaterial Elements*. *Journal of Electronic Packaging*, 1990. 112(1): p. 16-23.



10

Design model and tool

In the previous chapters much information has been acquired, all related to a specific part of the design of hybrid composite bridges. In this chapter these results are combined and used as input for a design model for this type of bridges. The model can predict the costs of a bridge design based on the sub-concepts as defined in Chapter 3. It can also be used to optimize these individual sub-concepts to minimize the bridge's costs, mass or building height. The final, but not less important aim of the design model is to identify the parameters that have the largest influence on the bridge's performance. For practical applications, the theoretical design model is implemented as a design tool in Microsoft's spreadsheet program Excel 2010, part of the Microsoft Office Professional Plus suite. The Excel tool is an indispensable part of this thesis work.

10.1 Design model input

For a like-for-like comparison with bridges from conventional materials, the total costs of ownership (TCO) have to be compared. The TCO of a bridge can be broken down into the following cost sub-categories:

- Material
- Labor
- Transport
- Abutments/ground work
- Installation
- Maintenance
- End-of-Life

Although FiberCore Europe, in its contact with clients and their advisors, registers a shift to more sustainable procurement processes where the TCO are considered, the focus in many tender procedures is still primarily on the direct acquisition costs. The latter costs are often only the sum of material and labor costs, disregarding any future costs for maintenance or repairs. It appears as though higher acquisition costs for a bridge are harder to justify, even when this bridge will save money later on in the utilization phase. A very real conundrum,



FiberCore Europe is challenged by on an almost daily basis. It is for this reason that the main focus of the design model is on the costs for material and labor. The other cost-determining factors will be addressed in a more qualitative manner at the end of this chapter.

The input for the design model consists of the following parameters:

- The Design loads and general boundary conditions as described in Chapter 2.
- The bridge geometries and their associated variables from the sub-concepts as described in Chapter 3.
- The material data found in Chapters 5, 7 and 8.

It must be noted that the model is only valid for single-span bridges. Intermediate supports are not implemented. A list of all input variables is given in Appendix C. Any restraints on the dimensions of individual parameters are described here as well.

10.2 Design model compliance checks

As mentioned in the introduction of this chapter, the design model can be used to optimize the sub-concepts for costs, mass or height. To do this, every sub-concept starts in the design model with a given set of initial values for all specific structural elements (e.g., top and bottom skin thicknesses, number of beam elements and their dimensions). With the number of elements, their specific location, dimensions and type of material known, the model can run and calculate the aforementioned output parameters. In order for the bridges to be functional and in accordance with laws and regulations, three important design parameters need to be checked for compliance: deflection, eigenfrequency and strength. The following sections explain how these parameters are implemented in the design model.

10.2.1 Deflection

As stated in Chapter 2, there is a limit to the difference in deflection caused by the bridge structure's own weight and the deflection of the bridge including traffic-loads. This difference should be limited to 1/100th of the span of the bridge. The deflection can be determined in a first approximation with the aid of Euler-Bernoulli beam theory. For the maximum deflection at mid-span of a simply-supported uniform beam, the following formula can be derived:

$$\delta_{max} = \frac{5}{384} \frac{qL^4}{EI} \quad (10.1)$$

Where

- δ_{max} = the maximum deflection of the bridge at mid-span
- q = a distributed load [unit force/unit length]
- L = the length of the bridge
- EI = the flexural rigidity of the bridge

Equation (10.1) can be used to calculate the deflection of the bridge under its own weight by using



$$q = \frac{w}{L} \quad (10.2)$$

Where w is the weight of the bridge. The deflection of the bridge under its own weight plus the prescribed live load of 5000 N/m² is determined by using

$$q = \frac{w}{L} + 5000 \cdot b \quad (10.3)$$

Where b is the bridge's width. The difference between the two calculated deflections should be lower than $L/100$, or 47 cm for a bridge of 47 meters length. It can be quickly shown that the outcome is independent of the initial weight of the bridge. From equation (10.1) follows:

$$\delta_{max}\left(\text{bridge weight} + 5 \frac{kN}{m^2}\right) - \delta_{max}(\text{bridge weight}) = \delta_{max}\left(5 \frac{kN}{m^2}\right) \quad (10.4)$$

Rewriting equation (10.1) directly provides a lower limit for the flexural rigidity:

$$(EI)_{min} = \frac{5}{384} \frac{qL^4}{\delta_{max}} \quad (10.5)$$

Where

$$q = 5000 \cdot b \quad (10.6)$$

It must be noted that any reduction factors are not yet incorporated in the derivations described above. These factors and their implementation will be described in section 10.3 in this chapter.

10.2.2 Eigenfrequency

From the design boundary conditions described in Chapter 2 it became clear that a lower limit of 2.3 Hz exists for the eigenfrequency of a pedestrian/bicycle bridge. The eigenfrequency of a uniform beam, simply supported at both ends and subjected to a uniform load per unit length can be derived using the following equation:

$$f_n = \frac{K_n}{2\pi} \sqrt{\frac{EIg}{wL^4}} \quad (10.7)$$

Where,

- f_n = the eigenfrequency of the bridge
- K_n = a harmonic constant with n referring to the mode of vibration
- EI = the flexural rigidity of the bridge
- g = the gravitational acceleration
- w = the weight of the bridge

For a uniform beam with the support and loading conditions described above, a value of 9.87 can be used for the constant K_n to find the lowest eigenfrequency (Young, et al. [1]). This value is based on perfectly hinged support conditions, without any restraining moment. The actual eigenfrequency of an installed bridge is higher. This is due to the abutment supports



and added stiffness of the railings. FiberCore Europe studied the influence of the latter effects by measuring the eigenfrequency of 20 bridges after installation. The values were compared with the theoretically determined values from FiberCore Europe's engineering department and measurements on bridges with (close-to) perfect hinge conditions. From this analysis it followed that with a certainty of over 95%, the theoretically derived eigenfrequency can be increased by 18%. Incorporating this so-called Panos-factor yields for the harmonic constant:

$$K_n = 9.87 \cdot 1.18 = 11.65 \quad (10.8)$$

As became clear from Chapter 2, the weight of the bridge has to be adjusted for the added weight of the pedestrians. For a density of 0.5 pedestrian per square meter and with an assumed weight of 800 N per pedestrian, the adjusted weight w^* for the eigenfrequency calculation becomes:

$$w^* = m \cdot g + 800 \cdot 0.5 \cdot b \cdot L \quad (10.9)$$

Where m is the mass of the bridge. Substituting (10.9) in (10.7) yields:

$$f_n = \frac{K_n}{2\pi} \sqrt{\frac{EIg}{(mg + 0.4 \cdot bL)L^4}} \quad (10.10)$$

It must be noted that the method of directly relating the natural frequency of a bridge to whether or not discomfort is experienced by its users is questioned. Discomfort is more related to accelerations. While there is a relation between eigenfrequency and accelerations, this relation is rather complex and appears to be still unpredictable for FiberCore Europe's bridges. An eigenfrequency analysis provided reasonably well results and is relatively easy to implement. This is why in practice FiberCore Europe's engineering department is still using an eigenfrequency analysis. For the same reason this analysis is part of the design model. The same remark as for the deflection has to be made here; reduction factors are not yet implemented. These are incorporated in the design model and will be explained in section 10.3.

10.2.3 Strength

In contrast to the deflection and eigenfrequency, the strength of the bridge is a truly safety-related parameter. As a result of the bridge's own weight and additional imposed traffic loads, internal stresses arise. These stresses should be compared to the individual material's design-allowables to make sure catastrophic failure does not occur. The design model only checks the overall strength of the bridge. Local effects are not considered. First the normal stresses will be derived and after that the shear stresses

Normal stress

The normal stress distribution over a cross section of a uniform, homogeneous structure can be approximated with the following equation:

$$\sigma = \frac{M}{I} y \quad (10.11)$$



Where

- σ = the normal stress, either tensile or compressive
- M = the bending moment as a result of the distributed load
- I = the second moment of area of the cross-section
- y = the distance in vertical direction from the neutral axis

The bending moment M can be determined with Euler-Bernoulli beam theory and is given for a simply supported uniform beam under uniform load by the following equation:

$$M = \frac{1}{8} q L^2 \quad (10.12)$$

Where q is a distributed load, comprised of the weight of the bridge and the additional 5 kN/m², similar as derived in equation (10.3). As soon as the structure is no longer homogeneous, but composed of different materials with their own stiffnesses, equation (10.11) can still be used, but needs to be adjusted. Consider a beam, built-up of a PU foam core, enclosed by two sheets of steel, which themselves are covered in two outer layers of GFRP material. The beam is depicted in Figure 10.1.

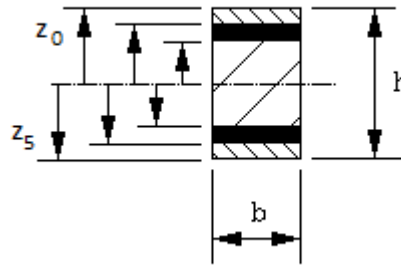


Figure 10.1: a hybrid composite beam, built-up of GFRP, steel and PU foam.

Each material has its own specific stiffness. In order to determine the normal stresses with the aid of equation (10.11), a so-called transformed-area or transformed-section method can be used. In this method, the widths of the individual components are corrected for their stiffnesses. The stiffness of one of the materials is chosen as reference. If, in this example, steel is the reference material, the widths of the GFRP and PU-foam change as follows:

$$b_{GFRP} = b \cdot \frac{E_{GFRP}}{E_{steel}} \quad (10.13)$$

$$b_{PU} = b \cdot \frac{E_{PU}}{E_{steel}} \quad (10.14)$$

The transformed cross-section from Figure 10.1 would now look like the cross-section as depicted in Figure 10.2. The width of the PU foam is reduced to zero because of its negligible



stiffness when compared with steel (3 MPa vs. 210 GPa). The width of the GFRP material is reduced as well, but less drastically.

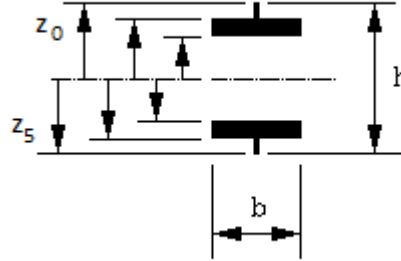


Figure 10.2: the hybrid cross-section transformed to the equivalent all-steel cross-section

From the new cross-section follows a new value for the second moment of area I^* . The normal stresses in the steel parts can now be calculated by substituting I^* directly in equation (10.11). The normal stresses in the other two materials can be calculated as follows:

$$\sigma_{GFRP} = \frac{E_{GFRP}}{E_{steel}} \frac{M}{I^*} y \quad (10.15)$$

$$\sigma_{PU} = \frac{E_{PU}}{E_{steel}} \frac{M}{I^*} y \quad (10.16)$$

The found maximum compressive stress in the top skin and tensile stress in the bottom skin have to be compared to the material's strength design-allowables.

Shear stress

In-plane shear stresses in a hybrid composite structure can be determined with the aid of a simplified shear solution (Bednarczyk, et al. [2]). The procedure will be implemented in the design tool, accompanying this thesis work. Although simplified, the method gives very accurate results when compared with numerical methods. The shear stress at interfaces between different materials can be derived analytically and compared with allowed shear stresses. Similar to the determination of the normal stresses, this method uses a transformed-area technique to cope with differences in stiffnesses.

The results of the method can be verified easily by substituting a homogeneous rectangular beam into the Excel tool. The derived maximum shear stress at the center of the cross section converges to the theoretical value given by:

$$\tau_{max} = \frac{3}{2} \frac{V}{A} \quad (10.16)$$

10.3 Reduction factors

To ensure the effective use of any load-carrying structure and the safety of its users over the design lifetime, reduction factors are used during the structural analysis. These factors



compensate for all kind of uncertainties in the design process. For this thesis project, the relevant reduction factors are explained and defined in the applicable design standards for civil engineering structures and design guidelines. Specific references will be given below. Two usage situations are defined in these standards: the serviceability limit state (SLS), a state in which the structure is loaded in normal usage conditions, and the ultimate limit state (ULS), which describes the most severe conditions a structure can encounter during its design lifetime. For both limit states, three categories of reduction factors are defined and will be shortly explained and summarized in the next sections.

10.3.1 Material factors

Before a material can be used in a structure, the mechanical properties (e.g., strength, stiffness, failure strain, thermal expansion coefficient, etc.) need to be known. These properties are generally determined through material tests. To deal with variations and uncertainties in the outcomes of these tests a material reduction factor γ_{m1} is introduced. Other than this factor, there are also uncertainties in the production process. Uncertainties in material properties as a result of this are covered by the reduction factor γ_{m2} . Material factors for composite materials are all defined in the CUR96 guideline (CUR [3]).

Deflection and eigenfrequency fall in the category serviceability. The combined material reduction factor $\gamma_{m_{SLS}}$ has a value of 1 in this situation. Strength calculations fall under the ultimate limit state. For this situation the following material reduction factors are used:

$$\begin{aligned}\gamma_{m1} &= 1.35 \\ \gamma_{m2} &= 1.2 \\ \gamma_{m_{ULS}} &= \gamma_{m1} \cdot \gamma_{m2} = 1.62\end{aligned}\quad \text{(based on a post-cured, vacuum infused laminate)}$$

10.3.2 Conversion factors

Material properties are not constant over time. High temperatures, moisture and exposure to ozone or UV radiation for instance are known to result in lower material properties over time for some materials. Creep and fatigue are other phenomena that negatively affect the material's behavior. To compensate for any degradation of the properties over time due to these effects, conversion factors are introduced. These factors are related to composite materials and therefore described in the CUR96 guideline (CUR [3]). This document distinguishes between conversion factors for short-lasting loads (e.g., loads due to traffic, wind or snow) and long-lasting or permanent loads.

For the deflection calculation in the serviceability limit state no conversion factor is prescribed. For the eigenfrequency calculation, the loads are assumed to be short-lasting in nature. The relevant conversion factor γ_{CSV} has a value of 1.21. For strength calculations a conversion factor γ_{CSS} with the same value of 1.21 applies.

10.3.3 Load factors

To compensate for uncertainties in loads occurring in practice and for extreme loading conditions that can occur once in the design lifetime of a structure, load factors are introduced. The load factors are prescribed by Eurocode standards (NEN [4], NEN [5]).



For the deflection calculation in the serviceability limit state a load-reduction factor γ_f of 1 is prescribed. No load reduction factor is dictated for the calculation of the eigenfrequency. For the strength calculations, the following load reduction factors are prescribed:

$\gamma_G = 1.10$	for permanent loads
$\gamma_Q = 1.20$	for stresses as a result of temporary uniform loads, like pedestrian or bicycle loads

10.4 Feedback loop

The design model is defined in such a way that every sub-concept can be optimized for either costs, mass or bridge height. As described above, three restraints are used to limit the optimization: the maximum deflection at mid-span has to remain under its upper limit, the eigenfrequency has to have a minimum value and material strengths should never be exceeded. Once an initial geometry is submitted in the model which meets the boundary conditions, the deflection of the structure, the eigenfrequency and stresses are determined. If one of these parameters exceeds its limit, a feedback-loop kicks in and tries to change the geometry and number of elements in such a way that the new bridge does comply with the restraints. It could happen that a solution is found where the deflection is (far) below its limit, the eigenfrequency (far) above it and the stresses are not even close to their allowable values. In this case the bridge complies with all restraints but is over-dimensioned. The optimization routine is told to find lower values for material costs, mass or height while still complying with all restraints. In practice, surplus material is removed until one of the decisive parameters reaches its limit value.

Solver, Microsoft Excel's optimization routine, is used to find the lowest costs, the lowest mass or the lowest bridge height per sub-concept. Since the problem is of a non-linear nature, the "Simplex LP" engine cannot be used. In order to still find a global solution and not stop at the first local optimal solution, the "Generalized Reduced Gradient (GRG) Nonlinear" engine is used (Lasdon, et al. [6]) with an added multistart option. If no errors occur, the engine stops with the notification: "Solver converged in probability to a global solution. The GRG engine has probably found a globally optimal solution". By requiring and setting upper and lower limits for all variables, this probability is further increased. In all cases where a solution is found by this method, the author was unable to find better solutions by hand (i.e., by educated guesses and trial and error methods). It is therefore assumed that the solution found by the solver engine is the optimal solution.

The design model and its feedback-loop as described above is represented in flow-chart format in Figure 10.3 on the next page. This model is implemented in an Excel-tool to provide numerical results. These will be discussed in the next sections.



10. Design model and tool

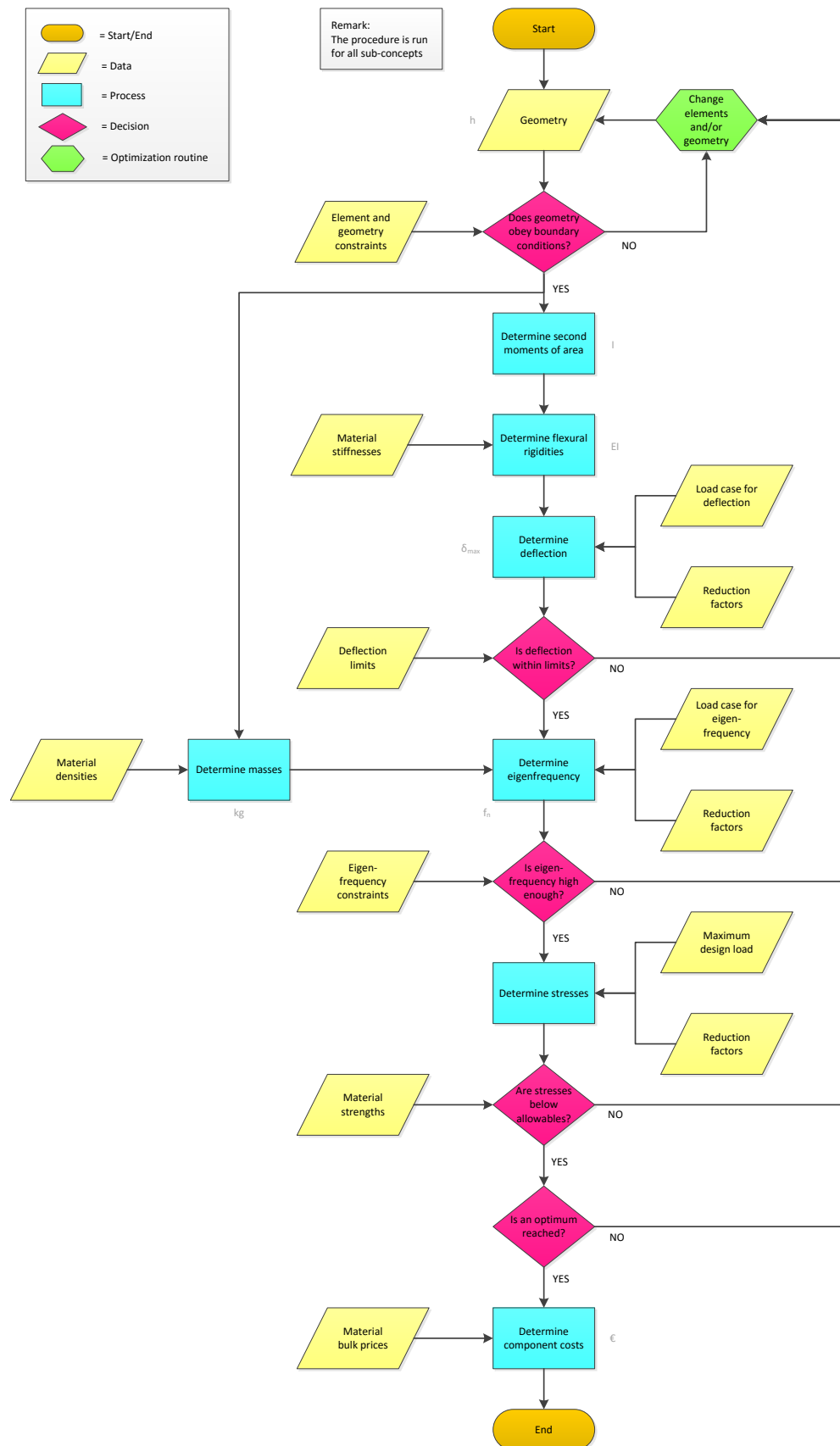


Figure 10.3: a flow-chart representation of the design model



10.5 Labor costs

An estimation of the labor costs for the production of a hybrid composite bridge is based on FiberCore Europe's current cost-predicting model for all-GFRP bridges. The Excel tool has a section dedicated to these expenses. Input for the calculations are the costs for one man-hour of labor, the amount of bulk material needed to be processed, and the dimensions of the bridge and its sub-elements. The costs are sub-divided into the following categories:

- Common tasks as the kick-off meeting
- Preparations in the "Glass house", where fabrics are cut to size and combined with the core material
- Mold adjusting activities
- Mold filling activities
- The vacuum infusion process
- Release from the mold
- Finishing of the bridge prior to delivery

Since carbon fiber fabrics and glass fiber fabrics are processed in a similar manner, the labor cost estimation is not changed when carbon fabrics are used. If the usage of carbon fibers results in less material needed to perform the same function, this will very likely lead to a reduction in labor costs. This reduction is hard to quantify, however, and is only a very small part of all required labor activities. When steel elements are incorporated, an extra cost item is added to the labor model; the placement of the steel elements in the mold.

10.6 Results

Running Excel's optimization routine Solver for every bridge concept to optimize for height, mass or costs shows the following results:

1. For all sub-concepts the natural frequency is by far the most critical design parameter. Once the bridge is optimized and all boundary conditions are obeyed, the unity check⁷ on eigenfrequency is always 1. The unity checks on deflection never exceed 0.20 and those for strength are most of the time even lower.
2. When material with a higher stiffness is added (steel or carbon) the best results are found when this material is located as far away from the neutral axis as possible. This should not come as a surprise. All sub-concepts with steel or carbon in the shear webs perform less (are heavier, higher or more expensive) than the sub-concepts where the steel or carbon is located in or near the outer skins.
3. When upper or lower constraints are removed from the thickness of the outer GFRP skins, these thicknesses are reduced to zero in the sub-concepts with steel. The tool converges towards a complete steel bridge to improve the performance as much as possible in terms

⁷ A unity check is the division of the calculated or measured value of a design parameter over the maximum allowable value of this parameter. The outcome should always be smaller than or equal to 1.



of costs, mass or height. This solution is not valid; for corrosion protection the GFRP outer skin has to be restrained at a minimum thickness as described in Chapter 4.

4. Sub-concept S4 with the horizontal steel sheets shows the best results when optimizing for material costs. In this case, the mass and the height of the bridge are also lower than those of the reference GFRP bridge and all other sub-concepts.
5. Sub-concept S5 with the steel bars performs slightly less than sub-concept S4, but the differences are marginal for all three aspects. Increases in costs, mass or height larger than 2% are not observed.
6. The amount of carbon fibers in the outer skins of sub-concept C1 reduces to zero when this bridge sub-concept is optimized for costs. The bridge then becomes identical to reference sub-concept 0. Carbon fibers can never be incorporated to save on material costs.
7. The only reason to add carbon fibers can be to reduce the mass or height of the bridge. In this, carbon fibers prove themselves very effective. With respect to reference concept 0, weight savings up to 31% can be achieved and height reductions up to 37%. This comes at a (very) large increase in material costs, however; all glass fibers in the skin are replaced by the more expensive carbon fibers. The material costs increase 33% when optimizing for mass and a staggering 98% when optimizing for height. Carbon fibers have to decrease 46% in price (from [xx.xx] to [xx.xx] euro per kg) to reach the same material costs as for the reference concept, when optimized for mass. A price decrease of 69% (to [xx.xx] euro per kg) is needed when the sub-concepts are optimized for height.
8. While the core material does not add at all to the structural performance of the bridge, it can present a very large part of the bridge's total material costs. In Figure 10.4 the contribution of every element to the total flexural rigidity and the material costs are shown for sub-concept S5, optimized for costs. The core material is responsible for over half the total material costs.

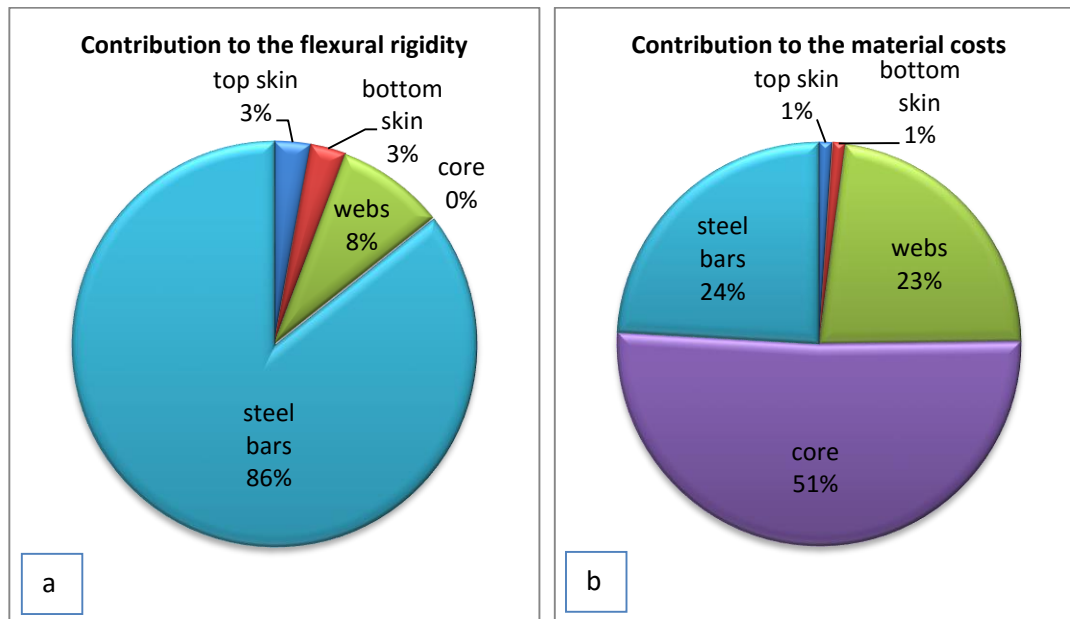


Figure 10.4: the elements' contribution to (a) the flexural rigidity and (b) the material costs

9. Figure 10.5 shows the material costs, mass and heights of all sub-concepts when they are all optimized for costs [because of the competitive nature of this information, all costs are normalized, where the reference bridge is set to 100%]. It can be seen that steel-GFRP sub-concept S4 is able to decrease all three aspects when compared with the reference GFRP bridge. Savings are respectively 14%, 16% and 18%. As mentioned before, sub-concept S5 performs slightly less, but is still able to decrease costs, mass and height with 12%, 16% and 16% respectively. The values for sub-concept C1 are similar to those for sub-concept 0, as explained above in point 6.

	Costs	Mass	Height
Concept 0	100%	100%	100%
Concept S1	97%	95%	88%
Concept S2	97%	95%	88%
Concept S3	102%	102%	100%
Concept S4	86%	84%	82%
Concept S5	88%	84%	84%
Concept C1	100%	100%	100%

Figure 10.5: results from the Excel tool; all sub-concepts optimized for costs



10. The in-plane shear stress analysis shows values far below the allowable interlaminar or interfacial shear stresses. As an example the shear stress distribution for sub-concept S4 is given in Figure 10.6. The sub-concept is optimized for costs in this specific case. The thickness of the outer GFRP skins is 3 mm and the steel sheets have a thickness of 13 mm. As can be seen, the height of the bridge is just less than 2 meter and the maximum shear stress at the center line has a value of 95 kPa. Figure 10.7 shows in more detail the shear stresses at the critical interface between the GFRP outer skin and the bonded steel. The shear stresses are only a fraction of the maximum stress; in this case less than 4 kPa.

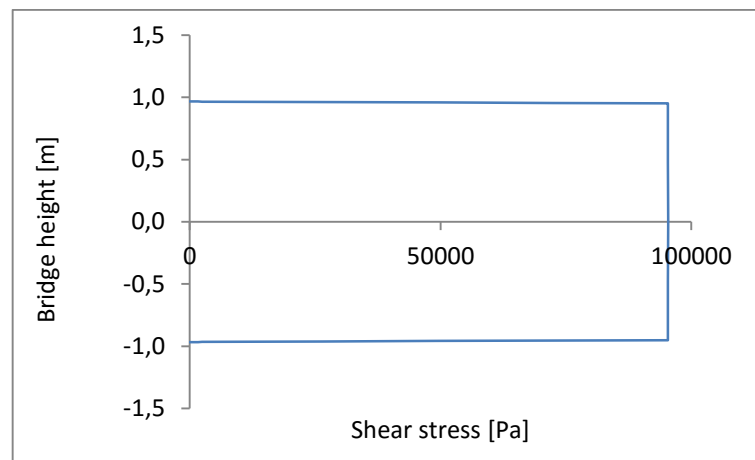


Figure 10.6: the in-plane shear stress distribution over the height of sub-concept S4

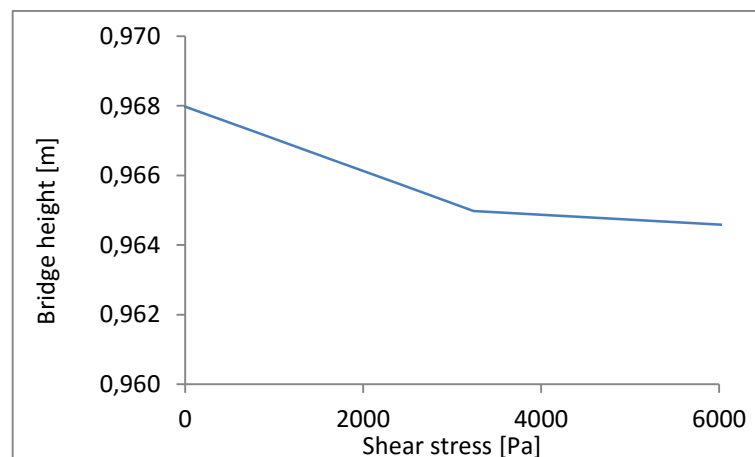


Figure 10.7: the in-plane shear stress at the GFRP-steel interface

11. With respect to the labor costs, the following results were observed: even in a situation where as much as 21 steel elements have to be positioned, the additional labor costs are



less than 2% of the total labor costs. The total estimated labor costs of a 47 meter hybrid composite bridge are around 15% of the material costs.

12. The tool can be used to visualize the influence of individual parameters on costs, mass or height of the bridge. As an example, the influence of the number of steel bars on the material costs is shown for sub-concept S5 in Figure 10.8 [because of the competitive nature of this information, all costs are normalized, where the reference bridge is set to 100%]. When no steel bars are added, the sub-concept is identical to the reference sub-concept and the material costs are equal for both sub-concepts. Adding steel bars drops the material costs considerably. After more than 10 steel bar pairs, the rate at which the material costs decreases slows down. The additional costs savings might no longer compensate for the additional labor costs related to the placement of the steel elements.

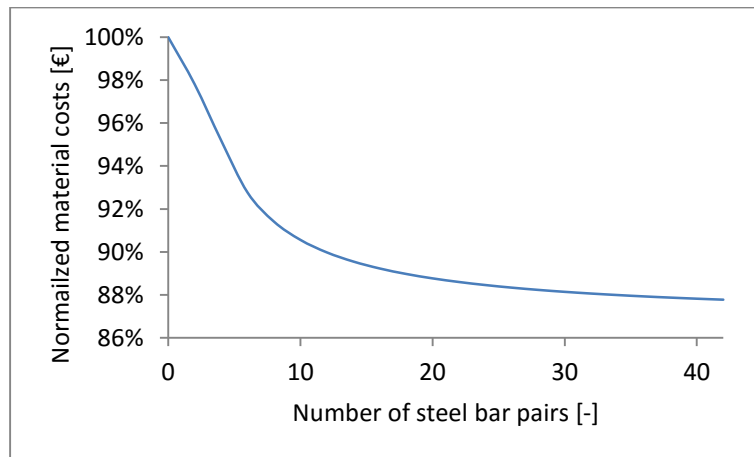


Figure 10.8: influence of number of steel bars in sub-concept S5 on the material costs

A drawing on scale of the reference sub-concept optimized for costs can be found in Appendix D1. Sub-concept S5, optimized for costs, is showed in Appendix D2. Sub-concept C1 yields the lightest and the lowest bridge. These solutions are shown in Appendix D3 and D4 respectively.

10.7 Additional cost contributions

At the beginning of this chapter, it was made clear that for a fair comparison with conventional bridges, the total costs of ownership should be regarded. The material and labor costs are addressed in the previous part and incorporated quantitatively in the design model and tool. The remaining cost items are harder to quantify. In the next sections a comparison between conventional bridges and hybrid composite bridges for other cost aspects and their influence in the big picture are addressed.



10.7.1 Transportation and installation costs

One of the advantages of composite bridges when compared with bridges from steel or concrete is that they can be lighter. This can be beneficial when it comes to the transport and installation of the bridge. A lighter bridge means a lighter truck and smaller or less cranes for horizontal and vertical transport. This advantage mainly plays a role for relatively small bridges. From the analysis with the design tool it follows that the lightest hybrid composite bridge (sub-concept C1 with 100% carbon fibers in the decks) still weighs more than 54 metric tons. A more realistic (cheaper) sub-concept already weighs close to 70 metric tons. When transporting a structure with such weight and a length of 47 meter, one can imagine that this operation requires special attention. The small financial profit that could be gained by renting a smaller crane is likely to disappear in the total transport-related costs, including costs for engineering, planning, permits, insurances and road closures. When looking at the total life cycle costs over a design lifetime of 100 years, the little money saved during transport, if any, becomes even smaller. When comparing a factory made composite bridge with an in-situ manufactured concrete bridge, the hindrance for traffic can be significantly less for the former bridge type. This can play an important role in the tender procedure but is too complex to fall within the scope of this project.

10.7.2 Abutment costs

Similar as in the previous section, the costs for ground work and abutments of a large hybrid composite bridge are not going to make the difference. For small composite bridges with lengths up to 10 meters, it might be possible to place the structure without the need for a concrete abutment. For these small projects, the costs for the abutment represent a large portion of the total costs and lighter bridges can surely benefit from this. However, for large bridges as discussed in this report, specialized ground work will always be necessary. And if this work has to be done, the difference in costs for a somewhat lighter bridge will be a relatively small part of the total groundwork costs. Engineering, planning and ordering of materials and tools are all part of the process when specialized groundwork has to be performed. Formwork for the casting of a concrete abutment has to be made anyhow and in the big picture it does not matter much what the exact volume is. The same holds for any necessary piling works. Getting the equipment and the operator at the location entails a far larger part of the involved costs than driving a few extra piles. The minimal costs savings on the abutment of a large hybrid composite bridge are, compared to the complete life cycle costs, negligibly small.

10.7.3 Maintenance costs

This part of the total life cycle costs is expected to make the big difference when comparing composite bridges, hybrid or not, with conventional bridges. The design lifetime of FiberCore Europe's composite bridges is 100 years and the bridges themselves have very low maintenance requirements. The only maintenance costs are related to replacement items as the wearing surface and, if need be, the railing system. But these costs are similar for conventional bridges. Any applied coatings are based on unsaturated polyester, similar to the bridge's matrix material and form a very durable, integral part of the bridge structure. External corrosion protection of steel and concrete bridges degrades much more over time and need



regular maintenance to uphold their level of performance. In contrast to composite bridges, steel or concrete structures continue to degrade once the outer protective layer is damaged. The rate at which this occurs is even increased.

Many papers have been written and cost models have been derived to estimate the maintenance costs of bridge structures. Last year, Soliman, et al. [7] described an extensive method for a life-cycle cost estimation of steel bridges, including many secondary maintenance costs. The following costs related to maintenance were identified:

- Direct costs
- Costs for materials and tools
- Removing old paint
- Repairing corroded areas
- Applying new paint
- Traffic control expenses
- Indirect or secondary costs:
- Costs for inspection
- Maintenance planning
- Ordering materials
- Social, environmental, and economic costs related to traffic delays

The model predicts the costs for a single maintenance, taking the annual average daily traffic (AADT) into account. Three different scenarios are analyzed where the AADT increases by 0.5%, 1.0% and 1.5%. The outcome of the model is implemented in the Excel tool to show the influence of maintenance costs on the total life-cycle costs. The following assumptions are used:

- The purchase costs of a steel bridge are 30% lower than those for a hybrid composite bridge. This number is rather arbitrary, and in reality the purchase costs for both bridge types are likely to be much closer together. The large difference in initial costs is chosen to give the steel bridge design a good lead with respect to the composite bridge.
- An increase of 0.5% for the AADT is used in the calculations. This is the lowest increase in the model to get a conservative outcome.
- Over a lifetime of 100 years, three maintenance intervals are defined; the first after 40 years, the second 30 years after the first maintenance and the third 25 years after the second maintenance. It is argued that the quality of the paint job during the first maintenance is not as good as initially applied in the manufacturing hall. This explains why the maintenance intervals become shorter.

The material and labor costs for sub-concept S5 are used as input and for comparison. Assuming no maintenance costs for this bridge, the combined costs for purchase and



maintenance are shown in Figure 10.9. [because of the competitive nature of this information, all costs are normalized, where the reference bridge is set to 100%]

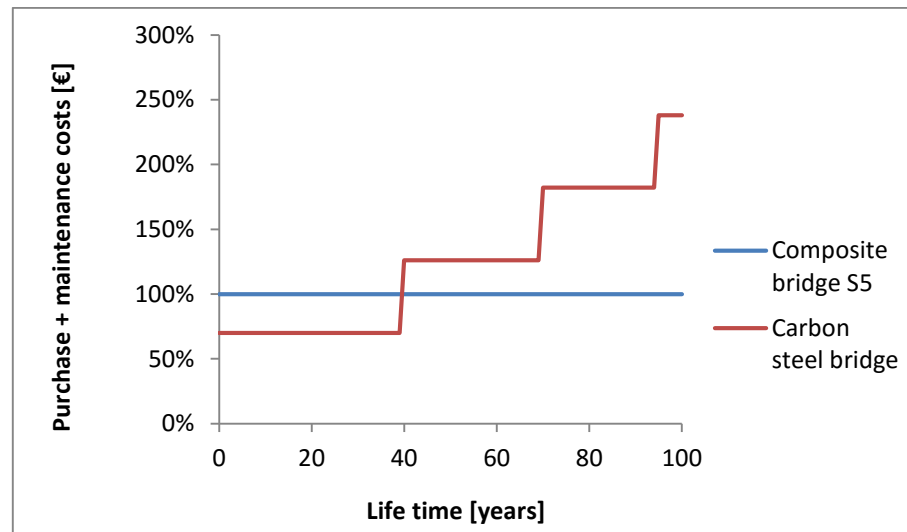


Figure 10.9: purchase plus maintenance costs for a steel bridge and a composite bridge

Although the numbers can never be exact due to the enormous amount of parameters involved in the analysis and their respective uncertainties, the general trend is very real. In this conservative approach, the assumed higher initial purchasing costs for a (hybrid) composite bridge are exceeded by a steel bridge after its first maintenance interval. The differences only become larger over the years. This simplified approach shows the major strength of maintenance-free or low-maintenance composite structures over their steel adversaries.

10.7.4 End-of-life costs

FiberCore Europe designs its bridges for a lifetime of 100 years. Since the first composite bridges are only 20 years old, there is no data available on the disposal of this specific type of structures. Awareness of the benefits of recycling of raw materials continues to increase and is the topic of many research programs. But nobody can predict exactly what is technically possible in 100 years and therefore it is also impossible to predict the residual value of a composite bridge in the 22nd century. It could very well be that FiberCore Europe's bridges can withstand another 100 years of loyal service. End-of-life cost predictions and a comparison with conventional bridges over these long timespans contain too many uncertainties to be quantified properly. This specific part of the LCC analysis remains therefore unaddressed.

10.8 Conclusions

An analysis of all sub-concepts by the design tool showed that the eigenfrequency is always the decisive design parameter for long and slender bridges. The maximum deflection, turned out to be a far less dominant design parameter. The unity checks on strengths are, as expected, also very low. In a normal use case where the eigenfrequency is the design-dominating factor, it is nearly impossible to reach a state where material failure occurs. From



the analysis in Appendix B it follows that CFRP, from a structural point of view, is the most suitable material for a frequency-dominated design. However, taking material bulk prices into account, CFRP is no longer a viable option. Carbon fibers can only be used when strict limits apply for the height or the mass of the bridge.

Sub-concept S4 outperforms all other design concepts. By implementing this design, the material costs, mass and height of the bridge can all be lowered simultaneously, compared with FiberCore Europe's current bridge design. The performance of sub-concept S5 is a little less when compared with sub-concept S4, but the differences are very small. From the discussion in Chapter 3, where the sub-concepts are described, it follows that sub-concept S5 shows considerable advantages over S4 from a manufacturing point of view. Sub-concept S5 therefore is the most interesting sub-concept to use as a basis for the next, more detailed design phase.

Material costs are dominant when compared to labor costs. When comparing the total life-cycle costs of a composite bridge with those of conventional bridges, the main contributing and distinguishing factors are the material costs and the (lack of) costs for maintenance. While the material costs for a steel or concrete bridge might be somewhat lower than for a hybrid composite bridge, the additional costs for the inevitable maintenance quickly nullifies these initial cost savings.

10.9 References

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11

Conclusions and Recommendations

11.1 Conclusions

The goal of this thesis project was to find a way to build composite bridges which are cheaper than bridges from conventional materials, even when the span exceeds approximately 26 meter. With the use of the developed design model and tool it was shown that this is indeed possible.

Using the combination of steel and GFRP as structural material for bridges can lower their costs, mass and design height simultaneously when compared to an all-GFRP bridge. Reductions of respectively 14%, 17% and 18% can be achieved for the steel-GFRP hybrid composite bridge analyzed in this study. Purely looking at the material costs, the maximum reductions are achieved in sub-concept S4 (horizontal steel sheets on top and below the core cells). Taking labor and production costs into account as well, sub-concept S5 (steel bars inside the core cells at top and bottom) shows better results. The adhesive bond strength between steel and GFRP is relatively weak. The structural reliability of a steel-GFRP hybrid bridge should not be dependent on this bond strength, unless further research shows the risks are properly controlled. Steel can still successfully be implemented if, in addition to the initial adhesive bond, mechanical interlocking connections with the adjacent GFRP are used. Practical applications could be the use of coarse rebar steel, an undulating weld bead over the length of the metal or holes in the steel.

Adding carbon fibers is only effective in lowering the mass and the height of the bridge. Cost reductions are not achieved. Only when strict limits on mass and/or height apply, the use of carbon fibers is justified. From the mechanical analysis of the carbon and carbon-glass laminates it became clear that the interfacial bond strength between carbon and polyester is suboptimal. Even when stresses in the design stay below the allowables, the poor interaction remains an important point of concern and should be analyzed thoroughly to justify the design. Possible cost savings on transport, installation, ground work and abutments due to a lighter bridge do not compensate for the added material costs.



By adding steel to a GFRP bridge, the initial costs (material + labor) can be reduced. This can already make the difference in a competition with all-steel or reinforced concrete bridges. Any cost savings on transport, installation, groundwork and abutments will almost always be in favor of a (lighter) composite bridge. The real difference is made when also taking the costs for maintenance into account. A (hybrid) composite bridge will almost certainly be the cheapest solution by far over a design life time of 100 years.

11.2 Recommendations

The adhesive bond strength between steel and GFRP in an actual bridge structure is not clearly established during this project. A physical connection between the steel and the GFRP through mechanical interlocking appears a very promising method to remove the dependency on the bond strength. This method, however, has not been studied. Regardless of the method used to connect the steel and the GFRP, destructive tests on component level are required to determine the actual strength of the connection. These tests are in general expensive and time consuming. It might be beneficial to simulate different types of connections beforehand with the aid of finite element analysis (FEA). The validity of the most promising models can eventually be demonstrated through full-scale tests.

The design model revealed that for large bridges the contribution of the costs for the core material to the total material costs is a substantial part. Finding ways to remove or reduce the core material can prove very beneficial. Looking into alternative production methods to remove the PU foam core material from the designs has not been part of the scope of this thesis work.

The study showed that for all concepts the eigenfrequency was the critical design criterion. The eigenfrequency, however, is an indirect criterion for experiencing discomfort by users of the bridge. Accelerations and their duration are better indicators, but difficult to predict accurately. Adding an acceleration analysis to the design tool can improve the performance of the bridge even more.

Rather than applying steel in the form of sheet metal, bars or rods in a hybrid composite bridge design, a steel mesh can provide additional efficiency. The mesh combines the benefits of the high stiffness of steel and the drapability and permeability of a fabric. Implementing this material poses very little alterations to FiberCore's current manufacturing process. Technical concerns are therefore expected to be minimal. A steel mesh can be distributed more efficient over the surface area of the bridge, reducing stress concentrations as compared with solid steel elements.

Results from a single test hinted in the direction of large potential improvements in the interlaminar shear strength when a proper way of binding the carbon fiber tows into fabrics is used. The effects of the type of material of the stitching threads and stitching patterns on the ILSS values are not well documented yet. This subject can be interesting on an academic level at first. If large improvements in ILSS are found, economic benefits can be thought of as well for situations where the interfacial bond strength is critical in the design.



Appendix A

Literature review

Innovative material solutions for economical composite bridges with large spans and constrained slenderness

A.P. Wilken, BSc

Department of Aerospace Engineering, Delft University of Technology, Delft, The Netherlands.

KEYWORDS: *Composite bridge; Hybrid material; Polyester; Steel; Glass fiber; Carbon fiber*

ABSTRACT: The use of fiber reinforced polymer materials for load-bearing structures in many applications increases rapidly. The high strength and stiffness per unit mass, combined with excellent durability properties gives these composite materials great advantages over conventional structural materials as timber, reinforced concrete and steel. It is for this reason that the Dutch company FiberCore Europe currently builds its bridges from glass fiber reinforced polymeric material. This material approaches its economic and practical limits when the length of the bridge span increases beyond approximately 25 m. Clients acknowledge the competitive strength of composite materials and ask for its implementation in longer bridges. Two hybrid composite material concepts are suggested to overcome the economic and practical limits of the currently used glass fiber reinforced polyester: (1) a combination of glass fibers and carbon fibers in a polyester matrix, and (2) a combination of glass fibers and steel in polyester. Both concepts pose additional challenges in their implementation in bridge structures. This paper summarizes most of these challenges and gives guidelines to successfully address them. Although some challenges seem to require very careful attention, it is concluded that none of the discussed challenges poses insurmountable objections to achieve a functional design when properly addressed. Calculations, simulations and mechanical tests should provide additional information in a later phase to answer remaining questions. This should lead to the successful design and production of competitive long-span composite bridges.

INTRODUCTION

FiberCore Europe is a Dutch company that specializes in the design and manufacturing of composite⁸ load-bearing structures for

architecture and infrastructure through its proprietary technology InfraCore® Inside. The current focus lies mainly on glass fiber reinforced polymer (GFRP) bridges. In 2003 wrote that it is unlikely that fiber reinforced

term is often used to refer to a combination of steel and concrete. Any mention of the term “composite” in this paper refers to the fiber reinforced polymer material.

⁸ In the aerospace industry the term “composite” refers in general to a fiber reinforced polymer (FRP) material. In the civil engineering world this



polymer (FRP) bridges will ever become financially viable compared with conventional bridges built from timber, steel and reinforced concrete. The number of GFRP bridges realized and the rising demand for new FRP bridges have proven the authors wrong. Many studies since then (e.g., , , and) conclude that fiber reinforced polymers can be a competitive alternative in the civil engineering market. While in general the production costs for a composite bridge are higher than for a conventional bridge, the total life-cycle costs can be significantly lower. Specifically for static infrastructural applications, durability characteristics of composite materials compared with conventional materials are superior. Maintenance costs for FRP bridges are significantly lower in comparison with timber, steel and reinforced concrete bridges due to the fact that the former material is far less sensitive to corrosion, rot and aging. Other than durability aspects, one of the obvious competitive strengths of composite bridges lies in the fact that lighter structures can be manufactured. This reduces costs for transport and the structure's foundation. In case of a movable bridge, weight savings also lead to energy savings and the need for lighter and therefore cheaper engines.

Market research shows a demand for longer bridge spans and more slender structures. The slenderness not only affects aesthetics, but the currently used combination of glass as a reinforcement fiber and polyester as the bonding matrix material also reaches its limits with regard to the maximum achievable stiffness at increasing spans with a fixed slenderness. In order for composite materials to become a worthy alternative in the market for longer bridges, new material combinations have to be examined. This paper focuses on two promising material combination concepts: combining GFRP with steel and combining GFRP with carbon fibers. It tries to summarize the currently available knowledge with regard to the technical challenges involved in implementing these concepts. Although most of the relevant challenges will be described, not every technical challenge requires the same in-depth search for available theoretical knowledge and solutions. As will become clear by reading this paper, for many technical challenges there are workable and proven solutions. A primary challenge is the interfacial bond strength between polyester and other materials.

1. CONCEPT DESCRIPTIONS

As soon as the mechanical properties of glass fiber reinforced polymers no longer suffice when it comes to either strength or stiffness, alternatives have to be considered. This can simply be a one-on-one replacement of the used material with a stronger and/or stiffer material, but this method is often too limited to approach a problem like this. Other important aspects like costs or durability properties can be overlooked initially, negating the key selling points of FRP. Especially when it comes to composite materials, it is better to look into the form and function of the product and see if a new material concept can be found that shows better overall performance.

FiberCore Europe operates in the composites market and has its own production facilities. New material concepts have to fit within this given framework in order to be workable solutions. With this in mind, two promising material concepts are suggested where each concept will be described in the next two sections.

1.1 Glass fibers combined with carbon fibers

In a production environment focused on composite materials carbon fibers will often show up as a logical first alternative to be investigated when glass fibers reach their structural limits. While it is true that carbon fibers show superior strength and stiffness properties compared with glass fibers, the price of the former material is much higher. Approaching manufacturers directly learns that the prices for the currently used E-glass fabrics range between x-x euro/kg, while prices for the cheapest suitable carbon fiber fabrics start around xx euro/kg. In contrast to the aerospace industry, where weight savings and the accompanying fuel cost reduction eventually justify much higher material costs, in civil engineering applications these extra material costs are not as easily earned back over the lifespan of a structure. For these applications the lowest price per unit stiffness (euro/GPa) is often decisive. It might turn out beneficial to look at a hybrid composite material where the relatively cheap glass fibers are combined with more expensive but stronger and stiffer carbon fibers in order to improve the overall material properties while at the same time constraining the costs. The



combination of glass fibers and carbon fibers in the same matrix material is not new. Summerscales, et al. [5] mention the first report of using this hybrid material in the body of the Ford GT40 racing car as early as in 1963. Ever since then, this hybrid composite material has found applications in many different industries, including automotive, maritime, wind energy, sporting goods, industrial and medical. One thing almost all of these applications have in common is the use of relatively expensive epoxy as matrix material. In some cases vinyl ester is used. Combination of glass, carbon and cheaper polyester are rare, presumably due to the relatively low interfacial bond strength between carbon fibers and polyester.

1.2 Glass fibers combined with steel

Other than combining glass fibers with carbon fibers to increase the material properties, combinations with conventional construction materials should not be overlooked. Steel has a proven track record as a reliable, well-understood material, perfectly suitable for many constructions. Bridges are often stiffness dominated structures and the Young's Modulus of construction steel (~210 GPa) is more or less equal to that of carbon fibers suitable for infrastructure applications (210-240 GPa). The price for steel sections is currently approximately x euro/kg, classifying steel as "cheap stiffness" compared with carbon fibers. In this study the combination of GFRP and structural steel is also examined. While the combination of steel girders with a composite bridge deck on top (slab-on-girder model) is not new and described extensively by for example Jiang, et al. [6], Ahmed, et al. [7], Keller, et al. [8], and Schollmayer, et al. [9], this study focusses on the incorporation of steel inside the composite structure. Ji, et al. [10] describe a composite deck where steel box girders are actually built inside the composite deck structure. This was done in an effort to improve the buckling and stiffness behavior of the bridge and enabling the production of more cost-effective bridges compared with bridges made from GFRP alone. The authors were able to decrease the thickness of the bridge by 19% in comparison with an all GFRP bridge with similar length. They also claim a reduction in price for a hybrid deck of 46% compared with a full GFRP deck. The steel girders used in this study, however, run in the transverse direction rather than the

longitudinal direction and this deck is then also placed on top of external steel girders.

2. CHALLENGES

The two concepts described in the previous section pose their own specific technical challenges, both in design and in manufacturing. This review tries to summarize most of these challenges and provide per topic relevant information from literature to fully understand the phenomenon and to be able to deal with it during upcoming design phases. Some topics are well-understood and require less elaborate attention. These will be addressed shortly with a minimum amount of references. Other subjects require more attention and are covered more in depth. Sections 3.1 and 3.2 describe challenges that are relevant for both concepts, while sections 3.3 and 3.4 describe specific challenges per concept.

2.1 Market competitors

Customers are not paying for a product; they are paying for a performance. In the specific case of FiberCore Europe, this can be e.g., a connection of two river banks for a duration of 50 years. When looking purely at structural characteristics and for the time being ignoring aesthetics and emotional aspects, in the end the customer wants to pay as little as possible for this performance. No matter what material is being used, the price of the final performance determines whether it can compete with other designs. For a fair comparison, this price should be defined as the total life cycle costs. In practice however, all too often only the initial purchase costs are considered in a tender procedure. While this might lower the price on the first invoice, which could benefit some parties for political reasons, this behavior is often short-sighted. In the long term the overall costs could easily turn out to be higher. This common practice poses a serious challenge in demonstrating the competitiveness of fiber reinforced structures for civil applications. Although the costs aspect is very real and in most cases crucial, it is not part of the current project phase. During the concept development and design phase, cost estimations are imperative to check the feasibility of the proposed designs. Considering the strong selling points of low maintenance requirements for FRPs, it is important that this property is incorporated in the concepts.



2.2 Manufacturability

Bridges are currently manufactured at FiberCore Europe according to a proprietary infusion system with the name InfraCore® technology. In order to manufacture bridges according to this principle, FiberCore Europe invested in very specific production facilities and processes. These include: the production hall with its fixed geometry, a flexible molding system, an intricate prefabrication process leading to short molding times, and the type of resin and its processing practicalities. All these factors combined determine for a large part what new design concepts can be manufactured. Eventually, every promising concept has to more-or-less fit within this framework, avoiding potentially significant investments and making it practically possible to be implemented on short notice. Promising novel or revolutionary solutions are of course constantly considered, but there is always a trade-off between the gain from this new idea and the time and money needed to be invested to actually implement the idea. These challenges are for later and are not further dealt with in this part of the study.

2.3 Glass fiber and carbon fiber

In this section the most relevant technical challenges that occur when combining glass reinforcement fibers with carbon fibers will be summarized. If available, relevant information from literature is given. Information that is still lacking after this theoretical study will need to be obtained through experiments as part of the follow-up study.

2.3.1 Price of carbon

It can be argued whether costs are a technical design parameter or not, but fact is that costs are always a main driving factor and are highly intertwined in any decision-making process. They can therefore never be overlooked and have to be explicitly mentioned in any design process. As already mentioned in section 2.1, carbon is more expensive per unit weight than glass, but has much better structural properties. If glass alone is no longer an option to make a long bridge with a given slenderness, a hybrid construction where glass and carbon are combined might turn out to be a good alternative for currently available solutions. Once a bridge is designed that is able to perform its function in a structural sense, cost calculations should demonstrate the economic

competitiveness. In a commercial context, all alternative solutions should always be both technically and economically viable to be considered as an option.

2.3.2 Interfacial bond strength carbon and polyester

The strength of a composite material lies in the fact that the combined material properties exceed the sum of the properties of the individual constituents. The primary function of the reinforcement fibers is to carry the loads acting on the structure. The matrix material has as main function to hold the reinforcement fibers in place and transfer stresses between the fibers. The degree of interaction between fibers and matrix determines the success of the composite material. Currently, in almost all load-bearing carbon fiber reinforced structures, relatively expensive epoxy is used as matrix material. The main reason for this is the good interfacial bond strength between carbon fibers and epoxy. This bond strength is considerably lower for the combination of carbon fibers with cheaper polyester. Bridges are often stiffness dominated structures; the design is driven by maximum deflections and not by internal stresses. Yet, these internal stresses can still pose a serious challenge to the overall performance of a bridge if the maximum allowable stresses inside the structure are relatively low. When carbon fibers are combined with polyester it is possible that the relatively weak interfacial bond strength requires much more material in order to keep the stresses below their allowable values. This will increase the material costs significantly, undermining the economic viability of the entire structure. In order to improve the fiber/matrix synergy, manufacturers of carbon fibers apply a sizing agent to enhance the interfacial bond strength between the two main components. The value for the interlaminar shear strength (ILSS) is a good indication for the compatibility between fiber and resin. Sizing agents and surface treatments are the topic of many research programs.

Jiang, et al. [11] attribute the low interfacial bond strength to the inert surface properties of the chemically stable carbon fibers. By coating the surface of the untreated carbon fibers with a combination of E51 epoxy and methacryl-polyhedral oligomeric silsesquioxane (methacryl-POSS), the authors were able to



increase values of the ILSS by 21.9% from 47.1 MPa to 57.4 MPa (v_f : 70%). In Jiang, et al. [12] the same authors describe a slightly modified chemical process where amino-POSS is grafted onto carbon fibers. This increases the ILSS values by 22.9% compared with the as-received carbon fibers. It is observed with the use of scanning electron microscopy (SEM), X-ray photoelectron spectroscopy (XPS) and atomic force microscopy (AFM) that the wettability and roughness of the carbon fibers grafted with the two POSS are higher than the untreated carbon fibers.

Another promising technique to improve the interfacial bond strength between carbon fibers and polymer matrix material is modifying the carbon fibers with carbon nanotubes (CNTs). Wu, et al. [13] describe a method where functionalized carbon nanotubes are dispersed in the carbon fiber sizing onto the surface of a Torayca T300B carbon fiber. MR13006 unsaturated polyester and water-soluble epoxy are used as sizing agents and four different types of carbon nanotubes are used (raw CNTs, hydroxyl CNTs, carboxyl CNTs, and vinyl CNTs). Composite test specimen with a fiber content of approximately 65% by weight are produced from the pretreated carbon fibers and unsaturated polyester. In all situations an improvement in the tensile strength, the interlaminar shear strength and the impact toughness was observed. The highest increase in ILSS was found when the carbon fibers were treated with a coating of vinyl CNTs. Values went up 57% from 39.6 MPa for the untreated fibers to 62.4 MPa for the coated fibers. The sizing process, however, is rather elaborate. Before the modified sizing is applied, the original, as-received sizing is removed from the carbon fibers by bathing in acetone for 72 hours. Next, an anodic oxidation process followed by washing in deionized water and drying yields the oxygen-containing group-functionalized carbon fibers. The carbon nanotubes have to undergo a chemical process as well in order to create chemical bonds with the unsaturated polyester sizing agent. Then the sizing has to be prepared by mixing five different components and the last step in the preparation phase is applying the sizing to the fibers by pulling them through a dip bath and a drying oven.

Fathi, et al. [14] propose a corona discharge surface treatment to improve the weak

interfacial bond strength between carbon fibers and polyester. This method is said to be fast, cheap and environmentally cleaner than mechanical or the previously mentioned wet chemical processes. A nonthermal plasma is used at atmospheric pressure to clean and roughen the fibers. This plasma does not require the use of special gas and the associated equipment, containing the costs. Although the interlaminar shear strength was not tested, the authors were able to increase the flexural modulus of the carbon fibers/polyester composite by 10% from 92.5 GPa to 101.8 GPa.

Test performed at FiberCore Europe in May 2014 yielded ILSS values of 41.2 MPa for a combination of the Torayca 700S fiber and the Distitron 110SV2 polyester from Polynt. The fiber volume fraction V_f is estimated to be 40%. For similar test specimen with the Zoltek PanEx35 fiber a value of 26.9 MPa was found. These tests were performed with suboptimal specimens due to production errors, which led to large variations in the results. The report recommends repeating these tests under more precise circumstances.

It is clear that different research groups focus on the improvement of the compatibility between carbon fibers and polyesters. These groups seem to be a minority. The current general consensus in the composite world seems to be that carbon fibers and polyester should not be combined. A visit to the JEC2015 (Journals & Exhibitions on Composites) in Paris and discussing the subject with many market players has led to two widely supported conclusions: "When you can afford carbon fibers, you can afford epoxy." and, a bit less subtle: "Combining carbon fibers and polyester? You are an idiot!". These people somehow do not see the huge market potential when the excellent mechanical properties of carbon fibers can successfully be combined with the relatively cheap polyester. This is especially the case for structures where the material costs represent a significant part of the total costs. Different methods to achieve an improved interaction between carbon fibers and polyester are investigated, all showing promising results. Manufacturers of carbon fibers, however, do not provide detailed information about their sizing agents from a competitor's point of view. Very little information is available with regard to polyester-specific sizings. The main focus lies



on epoxy sizings and to a lesser extent on sizings for vinyl ester. Worldwide, there are just over ten major manufacturers of carbon fiber tows. Some of these manufacturers produce fabrics themselves, but most of them supply their tows including the sizing to third party companies for fabric production. The latter parties often have a limited amount of suppliers and in general have no information at all with respect to the specific sizings. When the author requested carbon fibers with a polyester compatible sizing, the answer was almost always that this is not available, or that the vinyl ester sizing which are available “should work fine” in combination with polyester. This, combined with the enormous amount of different commercially available polyester resin systems, makes it hard, if not impossible, to receive actual values for carbon/polyester composite mechanical properties. In-house testing of carbon fibers from different suppliers with the relevant polyester system remains necessary. Stress calculations are needed to assess the local internal shear stresses which determine the required material properties. In the undesirable case that these properties cannot be obtained with polyester, a more expensive vinyl ester might have to be considered. This resin has better interfacial bonding properties with carbon fiber and is still much cheaper than epoxy. The processing of vinyl ester is similar to polyester, so no significant changes in the production process are required.

2.3.3 Thermal stresses

Carbon has a negative coefficient of thermal expansion (CTE). This means that the volume of carbon will decrease with an increase in temperature. A typical value for the linear CTE of carbon fibers (Torayca T300 and T700S) is $-0.4 \cdot 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ (Toray Industries [15]). This number indicates that a carbon fiber with a length of 1 meter will decrease $0.4 \text{ }\mu\text{m}$ for every degree Celsius temperature increase. FiberCore Europe currently uses glass fibers with a linear CTE of $2.8 \cdot 10^{-6} \text{ }^{\circ}\text{C}^{-1}$. Calculations on thermal expansion and thermal stresses in composite bridges are done in accordance with the Dutch standard NEN-EN 1991 (NEN [16]) and the associated National Annex. Values for operating temperature and minimum and maximum temperatures for calculations are given. Expansion of the complete bridge can be determined according to this method. These changes in dimensions determine the structural demands for the bridge's abutment

which must be able to cope with them. The temperature ranges given in the standard can also be used as input for calculations on the local internal stresses. Internal stresses due to temperature variations are relatively low and orders of magnitude smaller than maximum allowable stresses. Combining carbon fibers and epoxy has led to many successful products over time. The same goes for the combination of glass fibers with both epoxy and polyester. These facts, combined with the low internal stresses as a result of temperature changes, form the basis for the assumption that carbon fibers and polyester can be combined without thermal stresses alone posing insurmountable problems. The same holds for structures where glass fibers and carbon fibers are combined in alternating layers. Calculations of the local stresses in the laminate are relatively straightforward and have to be performed once initial concepts are developed to confirm the assumption.

2.3.4 Galvanic corrosion

When two dissimilar metal or semi-metal components are in electrical contact, the least noble metal (metal with the lowest electrode potential) will start to corrode in the presence of an electrolyte. The larger the potential difference between the two metals, the higher the rate of corrosion will be. The nobility of metals is given by the galvanic series. Graphite (carbon) is the noblest semi-metal heading the list. Any metal in electrical contact with carbon fibers will start to corrode once an electrolyte is present. The electrolyte can be any salty, acidic or alkaline solution. Condensation of water vapor from air can be enough to start the process. Seawater or rain combined with road salt are very active electrolytes, causing high corrosion rates. The vast majority of a composite bridge consists of reinforcement fibers, polymer matrix material and foam core material. However, metal nuts, bolts, center pins and other parts are often used for connections. Galvanic corrosion can have severe consequences in these parts if unaddressed. Dawood [17] notices that a lot of research has been conducted on the galvanic corrosion behavior of steel bonded to carbon fiber reinforced polymer. He concludes that if proper attention is being paid during the design phase, galvanic corrosion poses a minimal risk and can often be avoided all together. Means to prevent galvanic corrosion are generally based upon removing one or more of the necessary elements for this



phenomenon to occur. These elements are: two dissimilar metals, an electrical connection between them and an electrolyte. Simple solutions can be the use of different materials which are non-conductive or have very small potential differences, electrical shielding between dissimilar metals or preventing electrolytes to come in contact with the metals. Specifically for bridge constructions in which both carbon fibers and steel are applied, this means separating the carbon and steel parts; don't use carbon at locations where steel parts are used. If this is undesirable from a structural point of view, the use of non-conducting sleeves over bolts, plastic washers under nuts and non-conductive coatings over center-pins are proven solutions. Cathodic protection is also used often as a means to prevent galvanic corrosion, but mainly for integral steel structures as pipelines, ship hulls, offshore platforms and electrical power line towers. This method is not suitable for applications with carbon fiber reinforced polymers. Glass fiber reinforced polymer acts perfectly as an electrical insulator and is often used in composites as an outer layer to shield carbon fibers. Overall, galvanic corrosion has to be addressed in the design. If this is done properly, it should not pose a threat to the long-term behavior of the structure. A combination of the two design concepts as described in Chapter 2 in one structure therefore should also be possible.

2.3.5 Wet-out of carbon fibers

In a vacuum infusion process liquid resin is transported through dry reinforcement fibers by a gradient in air pressure over the product. Wet-out is the process of replacing all air between the reinforcement fibers by the resin. The better the impregnation, the less air remains trapped as voids in the final part. Yoshida, et al. [18] studied the influence of void content on the interlaminar shear strength of carbon/polyester and carbon/epoxy composites in order to find an allowable limit for this specific defect. During the production of the test specimens a foaming agent (azo-bis-isobutyronitrile) is used to control the void content and assure an even distribution of the voids. The distribution is first checked under a microscope and then the exact void content is determined by incinerating the matrix material. Before burning of the specimens, short-beam bending tests were performed according to ASTM D2344 to determine ILSS values. A value of 0.9% was found for the

critical void content for the combination of carbon and polyester. Specimens with a void content below this number showed no significant difference for the ILSS value with respect to void-free specimens. Increasing void content showed a rapid decrease in tensile and shear strengths. For an optimal performance of the structure it is therefore important to keep the void content as low as possible. Gamstedt, et al. [19] mention that unsaturated polyester exhibits a relatively low viscosity in comparison with epoxide resins. This property has advantages when using resin transfer techniques like vacuum infusion, especially in large structures. The small diameter of carbon fibers with respect to glass fibers leaves smaller openings between the individual filaments. These smaller openings increase the resin flow resistance and make the complete wetting of carbon fibers harder to achieve. Neatly ordered fibers are closer packed than randomly oriented fibers and increase the flow resistance in a similar manner, increasing the risk of voids.

Glass fiber reinforced polymers are optically transparent; dry spots and not too small voids in the material can be seen with the naked eye. This is not the case for carbon fiber reinforced polymers. If defects in the form of resin deficiencies are suspected, a whole range of non-destructive testing (NDT) techniques are available to analyze the structure. Some of these techniques are: IR thermography, C-scan (ultrasonic) inspection, eddy current scanning, X-Ray Radiography or mechanical impedance analysis. When the specific masses of the individual constituents are known, void content in FRP specimens can be determined according to ASTM D2734-09 (ASTM International [20]). By measuring the weight and the volume of a test specimen, the void content can be determined after burning away the polymeric matrix material and weighing the remainder. Low void content in test specimens is absolutely no guaranty that voids will not occur in the final product. However, these tests can be helpful in providing information with respect to the infusion characteristics of fiber and resin combinations. Large carbon fiber/epoxy products are currently already made using vacuum infusion. If a proper injection approach is used, the void content can be kept sufficiently low. It should therefore not be a problem to infuse large structural parts with carbon fibers and the better flowing polyester. If wetting turns out to



be a problem, a more dense resin supply infrastructure can be applied. This system consists of supply lines, splitting into smaller distribution channels inside the structure.

2.3.6 Creep and overstressing due to stress relaxation

Creep is a phenomenon where a material deforms permanently over time under the influence of a relatively small load. A mass suspended from a cable will eventually cause a permanent elongation of this cable, even when the stresses in the cable remain well below the yield stress of the cable's material. Especially polymers with their viscoelastic behavior are susceptible to creep. Although elevated temperatures are shown to increase creep behavior significantly, creep also occurs at ambient temperatures. The consequences of creep for a bridge structure are that at the end of its lifetime the sagging as a result of its own weight is larger than it was when the bridge was newly installed. Designers have to take this effect into account. By incorporating steel into a glass fiber reinforced structure, the creep behavior is expected to improve. For the combination of glass fibers and carbon fibers in polyester, this is not necessarily true. An often heard statement is that carbon fibers are less susceptible to creep than glass fibers. Zureick [21] is more accurate in this matter by stating that carbon fiber reinforced polymer composites are less susceptible to creep than polymer composites reinforced by glass fibers. And even this statement is not completely evident. The premise is based upon the most common combination of carbon fibers with epoxy or vinyl ester resins. It could very well be that the weaker interfacial bond strength between carbon fibers and polyester allow for slowly sliding of the matrix material along the fibers. Under influence of a constant stress state, the individual carbon laminae might shift with respect to one another, causing macroscopic deformations in the long-term. Creep tests are required to prove or debunk this hypothesis.

Many mathematical methods to predict long-term creep behavior are developed over time. Most of these methods are based on fracture mechanics failure criteria or energy-based criteria. Guedes [22] made a comparison of these methods and also included the linear accumulation of damage model. He found that all reviewed methods produce very similar

results. The theoretical results were compared to the results from experimental studies and found to give fairly accurate results. It is concluded that long-term creep behavior can be predicted reasonably well by the currently available theoretical models. Input parameters for the theoretical models are found by material experiments. In order to apply these models to structures build with novel materials, it might be necessary to perform tests at forehand to determine these parameters.

Assuming that carbon fiber composites are in fact less susceptible to creep than glass fibers, another effect of creep in hybrid materials is load shifting as a result of stress relaxation. When combining glass fibers and carbon fibers in one material, both fibers will initially carry a part of the applied load, proportional to their stiffness. If the glass fibers elongate over time under the influence of this load and the carbon fibers remain at their initial length, the loads will gradually be transferred from the glass fibers to the carbon fibers. It might turn out that the glass fibers eventually carry no significant loads anymore and only the carbon fibers perform a load-carrying function. Failure may occur if these loads exceed the maximum load-carrying capacity of the carbon fibers. Most polymers are linear viscoelastic materials for which the time-temperature superposition principle holds. This principle allows mechanical tests to be performed at elevated temperatures in a relatively short time to simulate long-term behavior at ambient temperatures. Lan, et al. [23] have performed creep tests on hybrid unidirectional carbon/glass fiber composite rods using this method. They were able to combine short-term creep data to predict values for creep levels that will occur at the end of the design-lifetime of the rods (30 years). The maximum strains as a result of creep in the rods exposed to a temperature of 120 °C were predicted to be 5% with respect to their initial length. Specifically for the combination of glass fibers and carbon fibers, a phenomenon called "the hybrid effect" occurs. It is observed that the failure strain of carbon increases when glass fibers are added. Enhancements up to 50% have been measured. This increases the creep resistance of glass/carbon hybrid composites considerably.

2.3.7 Health and safety aspects



Working with carbon fibers requires extra attention with regard to safety measures compared with working with glass fibers. Although the material safety data sheets (MSDS) of the carbon fiber suppliers do not classify carbon fibers as hazardous, this does not automatically mean there are no health risks when working with this material. Inthavong, et al. [24] investigated the inhalation and deposition characteristics of both glass and carbon fibers in the respiratory system. They found that almost all fibers either get caught in the nasal cavity at the beginning of the airways, or travel all the way and penetrate deeply into the lungs. Almost no deposition was found in the laryngeal or tracheal region. Carbon fibers were found to be more likely to travel deeper into the respiratory system than glass fibers. This phenomenon is attributed to the fact that carbon fibers are lighter and thinner than glass fibers. Martin, et al. [25] studied the toxicity of carbon fibers to lung cells. They used both in vitro (outside the body) and in vivo (inside living animals) experiments. Results from tests with inert aluminum oxide (Al_2O_3) and the toxic α -quartz (SiO_2) were used for comparison. Carbon fibers seemed much less toxic than quartz and the observed tissue reactions were more similar to those of the Al_2O_3 samples. However, in two out of the six samples some sort of biological effect on the lung tissue was observed. The results from the tests in this one particular study seem to reflect the overall conclusion of many similar studies over the years: negative health effects by inhalation of carbon fibers cannot be ruled out and therefore precautions need to be taken while working with this material. This advice is adopted and common practice in plants where carbon is processed. In any situation where risks are identified it is good practice to follow the so-called hierarchy of hazard control. Schulte, et al. [26] describe these controls in order of preferred application: elimination of the source of the risk, substitution, isolation, engineering controls (environment monitoring), administrative controls (information, training, procedures) and, as a last resort, personal protective equipment. In a production environment where dry fibers are manually processed and handled it is inevitable that employees are exposed to these materials and that personal protective equipment is necessary. This is the current situation at FiberCore Europe where glass fibers are used. When carbon fibers will also be

processed, the above discussion does not lead to the need for additional measures.

Another important aspect of carbon fibers that has to be considered and in fact does pose extra requirements for the production facilities is the electrical conductivity of the material. Any form of cutting or machining dry carbon fibers produces dust/airborne particles. These tiny fibers are attracted by the magnetic field surrounding any electrical apparatus and may cause permanent damage by short-circuiting the internal electrical system. Great care has to be taken to prevent airborne carbon fibers to travel freely through the manufacturing hall and possibly adjacent offices. One way to contain the spreading of airborne carbon fibers is to carry out cutting and other processing of dry fibers in a dedicated, closed area, preferably with a small underpressure with respect to the adjacent rooms. Protective gloves and overcoats or overalls have to be used by anyone occupying this room and these coats are not allowed outside this room.

2.4 Glass fiber and structural steel

This section of the paper focuses on a new concept: the combination of glass fiber reinforced polyester with structural steel. Technical challenges will be mentioned and relevant information and solutions from literature will be presented, if available.

2.4.1 Interfacial bond strength steel and polyester

In Section 3.3.2 it was mentioned that the interfacial bond strength between polyester and carbon fibers is a big challenge to overcome. The second concept is based upon combining glass fibers and polyester with steel and a similar challenge arises. Polyester can be bonded to steel, but the strength of this bond determines for a large part the success of the complete structure. Dawood [17] notices that almost always organic polymers, mainly epoxies, are used in the bonding of FRP material to steel surfaces. Since steel is an inorganic material, the adhesive is not able to form primary chemical bonds with the steel surface. The strength of these adhesive bonds is primarily dominated by secondary Van der Waals forces, adsorption or mechanical anchoring. There are multiple parameters that influence the adhesive bond strength: the type of steel used (mild steel or stainless steel), the surface treatment of the steel and the FRP



parts prior to bonding, the used adhesive and bonding conditions as temperature, pressure, relative humidity and cure times. The required bond strength follows from the design of the bridge; the build-up of the different materials, the length, width and thickness and the acting loads. These parameters combined determine the internal stresses which should always be below the material limits and the bond strength between the individual constituents. First order calculation using classical beam theory up to advanced finite element analysis (FEA) can be used to determine these stresses.

Surface treatments

Kim, et al. [27] describe the effect of different surface preparations on the bond strength of fiber reinforced polymers to mild steel and stainless steel. A single-lap shear test is used, where the metal part is stiffened in order to prevent bending. Four surface treatments are analyzed: no treatment other than wiping with a solvent, sanding with grit 220, grinding, and a treatment using a needle scalar. The authors claim that for the mild steel specimens the three mechanical surface treatments all show a more-or-less similar increase in bond strength of 23-25% compared with the solvent-wiped specimen. This conclusion is based upon the force needed to load the specimens up to failure. However, calculating the actual failure stress from the supplied raw data shows that the specimens which are grinded and needle-treated actually perform on average 34% better than the solvent-wiped specimen. This is a much larger improvement which the authors somehow seem to have missed. The sanded specimens perform on average only 26% better. Looking at the data for the stainless steel specimen, the best surface treatment seems to be sanding, although the differences between the individual surface treatments are very small.

Jiang, et al. [28] tested the mechanical behavior of adhesively bonded joints between FRP and steel. In this study three surface treatments are investigated: degreasing and cleaning with acetone, sanding by hand (grid not specified) and sand blasting. From tests in pure tension and pure shear, the authors conclude that both sanding and sand blasting improve the adhesive bond strength significantly when compared with the specimen that is only cleaned with acetone. The improvement for both mechanical surface treatments is found to be similar.

A method mentioned by a Dutch representative of Lloyds Register maritime classification society is “wet sanding” (Petkovic [29]). This term does not refer to sanding with water, but to sanding with liquid, uncured resin. The method involves the following steps for the best adhesive strength of epoxy sheets to steel ship decks:

- Sand the steel deck
- Clean the deck
- Apply wet/liquid epoxy
- Sand the deck again while the epoxy is still liquid
- Let the epoxy cure as a primer
- Sand again lightly and bond the FRP sheet to the surface

Although no scientific references could be found to support the effectiveness of this method, there are multiple reports, mainly on internet forums, of this technique being used by people in the maritime industry. It is definitely an interesting option to investigate the adhesive properties of polyester to steel using this method. The general hypothesis is that the surface area is increased by the sanding and at the same time the formation of an oxide layer is prevented by the liquid resin. In general, any abrasive surface treatment is not used to improve the interfacial bond strength by mechanical anchoring, but rather by enlarging the surface for adhesive bonding.

Van Rooijen, et al. [30] describe two chemical surface treatments of stainless steel prior to bonding: etching by a sulphuric acidsodium dichromate solution treatment and etching by acid pickling followed by a desmutting treatment. These two surface treatments were chosen as promising from a wide variety of available chemical treatments, based on previous scientific research. Grit blasting with aluminum oxide particles was used as a mechanical surface treatment for comparison. With grit blasting the failure mode turned out to be cohesive, while the chemically treated specimen showed mainly interfacial failure at a much lower stress. This makes grit blasting more efficient as a surface treatment in comparison with the chemical treatments.

The studies mentioned above mainly focus on the mechanical performance of the individual surface treatments and don't address the costs of these treatments. A comparative cost-benefit analysis is therefore hard to make. In most cases the mechanical surface treatments



are done by manual labor, rather than by automated processes. Sandblasting is a relatively simple process which requires the least amount of energy from the worker. This method is cheap and effective and shall often be the preferred option.

Bonding system

Since the concept of combining glass fiber reinforced polyester with steel is based on incorporating the steel inside the composite in a one-shot manufacturing process, the adhesive material is the used unsaturated polyester system. One of the big advantages of a relatively flexible adhesive bond over mechanical fasteners is its potential to lower local stress concentrations between materials with different Young's moduli or coefficients of thermal expansion. Strong adhesive bonds between dissimilar materials as metals and polymers are hard to achieve due to the difference in physiochemical properties of each material group according to Sarlin, et al. [31]. That is why this team looked into the application of a thin EPDM rubber layer as adhesive between glass fiber reinforced epoxy and stainless steel. The rubber can be modified in such a way that it exhibits good adherence properties with metals and polymers simultaneously. Different surface finishes and pretreatments were investigated, but in almost all cases the cohesive strength of the rubber determined the bond strength. The as-received stainless steel specimens performed as well as the surface-treated specimens, which led to the conclusion that a surface treatment is not required when using this method on stainless steel. This makes it cleaner than methods where chemical surface treatments are used and less time consuming than methods that require a mechanical surface treatment. The interfacial bonds between the rubber and the two adherents are stronger than the rubber itself. The strength of the rubber therefore dictates the bond strength, making it a very predictable connection, in contrast to most adhesive bonds where large variations in bond strengths are observed. Since the rubber is used as a bonding agent, the layer is relatively thin. Absolute values for the strains in the flexible rubber are therefore small and loads should still be transferred effectively from the polyester to the steel and vice versa. The steel inside the structure should still be able to perform its function. Although the authors describe the method as promising, a lot of

challenges still need to be overcome in order to make this method applicable in practice. The maximum tensile stress of EPDM based rubbers is still relatively low in comparison with common matrix materials as polyester. The rubber is vulcanized at elevated temperatures (130 - 160 °C) on pre-existing, solid components. In the currently used vacuum infusion process these solid components are initially not present. The author also notes that a lot is unknown about the durability aspects of the prescribed method. From a practical point of view this method is not mature enough yet to investigate further.

2.4.2 Durability

The challenge FiberCore Europe is facing is to come up with a competing composite bridge design for large spans. It might seem that this goal is met once a composite bridge is successfully designed, manufactured and installed. And although this is true for a large part, making sure that the bridge is able to perform its function over a long time span is equally important. Durability aspects therefore have to be considered as well. Factors like ultraviolet radiation, high ozone concentrations, freeze/thaw cycles, salt water and elevated temperatures and humidity all negatively affect the properties of composites over time and their individual influences are all studied extensively over the years. All these elements are relevant for currently existing bridge designs and solutions to deal with them are already well-known and implemented. Reduction factors to cope with time-based degradation in fiber reinforced structures are for example well covered by the Dutch standard CUR 96 (Stichting CUR [32]). Only the factors that pose additional challenges to the two new material concepts will be addressed from this point.

Corrosion

Corrosion of steel parts can occur if the steel comes in contact with moisture and oxygen. In concepts where steel is enclosed by the FRP, the polymer matrix acts as a barrier against environmental attacks. In general, polyesters exhibit good corrosion properties and is therefore used as coating material for metals. Budinski [33] specifies typical thicknesses for polyester coatings from 25-50 μm for decorative purposes up to 1 mm for corrosion protection of fully submerged products. In the



latter case moist is still absorbed by the polymer material, but the rate at which oxygen and ions are transported is so low that oxidation rates are negligible. In the specific case where steel is incorporated inside the FRP structure, the glass reinforced polyester skin acts as a coating where thicknesses can easily reach 20 mm. As long as this coating is not completely breached, it should provide more than adequate corrosion protection. Special care needs to be taken when holes are drilled through the composite. These holes should preferably not be made in the vicinity of the internal steel parts. If this cannot be prevented, additional local sealant measures are needed. Occasional inspections are advised in order to detect local damage that might expose the internal steel parts.

In order to make hard statements about the long-term corrosion behavior of steel incorporated inside a glass/polyester bridge, corrosion tests have to be performed. Carlsson, et al. [34] summarize many standardized accelerated corrosion tests. The data acquired from these tests are only useful when they are compared to reference data. The latter are obtained by real-time outdoor exposure of a similar product. Recommended duration for the outdoor tests are at least one year, but preferably two. In the accelerated tests the same amount of deteriorating as during the reference test is reproduced in a shorter time. These results can then be interpolated to predict future behavior. Fun fact: many accelerated corrosion tests are performed in laboratory salt-spray cabinets. These cabinets are in almost all cases made from polyester due to its corrosion resistant characteristics.

If - against all expectations - the glass/polyester layer is found to be still insufficient, a more resilient material than polyester can be used as a coating prior to bonding. Another option, to be no longer dependent on the corrosion protection methods described above, is to incorporate stainless steel, rather than mild steel. This material, however, is more expensive and harder to bond to polyester.

Durability of the adhesive bond

Bonding of fiber reinforced polymer parts in infrastructure is a practice that is done for many years. Numerous papers are written on the application of FRP plates as external reinforcements for steel and concrete

structures in repair, renovation and upgrading projects. One of the biggest challenges after creating a strong enough adhesive bond between FRP and steel is to make sure this bond will perform its function over a prolonged time. Dawood [17] identifies two parameters that play a major role in the degradation of the relatively weak adhesive bond between FRP and steel: exposure to elevated temperatures and absorption of moisture. A rise in temperature decreases the ultimate strength and elastic modulus and at the same time increases the plastic strain. Moisture absorption has the same effects and, next to that, leads to swelling of the polymer. If strains are restrained, this swelling introduces additional stresses. Moisture diffusion rates through a polymer are accelerated at high temperatures.

Many studies show the detrimental effect water has on adhesive bonds. Nguyen et al. [28] describe the effects of exposure to seawater and high relative humidity levels on the adhesive bond strength between CFRP and steel. Tensile tests of double-strap joints were performed to assess the adhesive bond quality before and after exposure. Prior to bonding, the steel parts were sandblasted and cleaned with acetone. One batch of 50 test specimens was exposed to a 5% NaCl solution at 20 °C and 50 °C during 2, 4, 6, 9 and 12 months. Another batch of 10 specimens was exposed to a relative humidity of 90% at a temperature of 50 °C up to 1000 hours. The last batch of 10 specimens was exposed to 250 and 500 thermal cycles between 20 °C and 50 °C at a relative humidity of 90% lasting 500 and 1000 hours respectively. Five unexposed test specimens were used for reference. It was observed that after 12 months the joint strength decreased 17% for the specimens submerged in seawater of 20 °C and 26% in the seawater of 50 °C. The joint stiffnesses reduced 39% and 45% respectively. After 1000 hours a reduction of less than 10% is observed for both the strength and the stiffness in the specimens exposed to the high relative humidity environment. While submersion in seawater has large detrimental effects on both strength and stiffness of the adhesive bond, exposure to high relative humidity environments shows much smaller reductions.

Nguyen, et al. [35] also describe three ways water can reach the adherent/adhesive interface: by diffusion through the adhesive, by



transport along the oxide/adhesive interface or absorption through the porous adherent. Only the last mechanism is relevant once steel is completely embedded in a thick layer of polyester. Chin, et al. [36] studied the sorption and transport of different water-based liquids through three different polymeric materials. All performed tests showed a diffusion pattern that follows Fick's laws of diffusion: once a specimen is exposed to water it starts to take up this water, the initial rate of moisture uptake decreases gradually until saturation is reached and the moisture content remains constant. The same result is observed by Hand, et al. [37] who examined the moisture absorption in six different polymeric adhesive systems. Test specimen were produced and either immersed in water at ambient temperature or in air exposed to a temperature of 50 °C at a relative humidity >90%. The thickness of all test specimens was 2.54 mm and an equilibrium state (no more water absorption) was reached within a manner of days for both the emerged as the humidity-exposed samples. The amount of water absorbed by the specimens in the warm, humid environment appeared to be only half the amount absorbed by the submerged specimens. Full saturation was never reached. The smallest observed decrease in ultimate tensile strength was no less than 34%. The maximum decrease was 67%. It is safe to assume that a polyester part, even with a thickness of over 20 mm, will reach equilibrium with its environment in a matter of months. Moisture reaches the polyester/steel interface and, depending on the actual amount, might start to degrade the initial bond strength.

Tsai, et al. [38] specifically investigated the effects of moisture uptake on mechanical properties in a hybrid carbon/glass fiber composite material. Epoxy was used as bonding matrix. Both the shear properties as the glass transition temperature decreased with increased water absorption. As long as the water uptake remained under the saturation level, no cracking in the matrix material was observed. Once the specimen were dried after long-term exposure, the initial thermal and mechanical properties returned as long as saturation was not reached.

Fatigue

Fatigue is a phenomenon where local structural damage occurs under the influence

of cyclic loads with amplitude (far) below the material's yield strength. Fatigue behavior is not just a material property, but also depends on the shape of the product, the applied load spectra, load distributions through the part and environmental conditions. It is therefore hard to predict the fatigue behavior of a complete structure made of a novel material beforehand, let alone find relevant literature for this specific application. To still make useful fatigue life predictions, tests are performed on material level, part level and on full-scale completed structures. It is important to match the test conditions as closely as possible to the actual use case. These tests themselves are relatively straightforward and from these tests predictions of the long-term fatigue behavior can be made. A first approximation of fatigue behavior for one specific material can be made without performing the actual tests. Once the internal stresses are known from calculations, these results can be compared to existing fatigue data. As soon as different materials are combined it might turn out to be a lot harder to find representative data from previous tests for comparison and tests are required.

2.4.3 Internal stresses

Inherent to the production process, transport, installation and usage of a bridge is the presence of internal stresses. These stresses can be residual stresses after manufacturing and are also caused by handling and use loads. Structural analyses have to be performed to assess the internal stresses and to make sure the structure is able to cope with these stresses over its lifetime. These analyses vary from first order approximations by e.g., linear beam theory to advanced finite element analysis. While this matter is not new and applied in all previously and currently produced bridges, the incorporation of steel inside a structure might pose new challenges to deal with. Specifically, internal stresses as a result of expansion or contraction of the individual components arise.

The bridges at FiberCore Europe are manufactured by vacuum infusion. All dry components are laid out on a mold, covered with an airtight bag after which vacuum is used as a driving force to transfer a liquid resin through the setup. The resin is a two-component polyester system that cures to a solid, binding all parts into one product. Curing of the polyester is an exothermic



chemical process where temperatures up to 120 °C can be reached. At this temperature the final shape of the product is adopted and adhesive bonds between individual parts are formed. Depending on the coefficient of thermal expansion, the individual parts all contract a dissimilar amount during the cooling process. This contraction is partly prohibited by the bonds between the parts, introducing residual stresses. Other than the thermal contraction, the polyester also shrinks as a result of the chemical cross-linking reaction. Values of approximately 0.15% are observed for the linear contraction of a glass fiber/polyester bridge. Every linear meter will shorten 1.5 mm. This is a combination of the thermal and the chemical contraction. The linear coefficients of thermal expansion of polyester and glass fiber are $100 \cdot 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ and $2.8 \cdot 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ respectively. This is 15 to over 500 times smaller than the total contraction and can be neglected in the overall analysis. Calculations on design concepts should be made to assess the internal stresses as a result of the total contraction and to verify that these stresses don't exceed the material or adhesive bond limits.

3. CONCLUSIONS

Two material concepts are proposed in this paper and each concept poses its own challenges in implementation. The conclusions per challenge are summarized in this chapter.

3.1 Concept-independent challenges

Competitiveness

In order to safeguard the competitiveness of the proposed novel bridge designs, cost predictions throughout the design process are imperative. The results have to be compared with the costs for designs with conventional materials.

Manufacturability

Major adjustments to FiberCore's production facilities are not possible or desirable in short term. The most promising bridge designs should be manufactured within this available framework and should be developed with this in mind.

3.2 Glass fiber and carbon fiber

Price of carbon

Carbon fibers exhibit far better strength and stiffness properties than glass fibers, but are also much more expensive. Carbon fibers can only be applied where the added stiffness compensates for the higher price. Cost calculations must show whether carbon fibers can be applied while keeping the design competitive to conventional solutions.

Interfacial bond strength carbon and polyester

Carbon fibers with specific polyester-compatible sizing agents are currently not available. The intricate chemical processes to develop such a sizing are far beyond the scope of this thesis. To determine the compatibility between currently commercially available carbon fibers and the polyester used by FiberCore, ILSS tests have to be performed. The resulting structural performance must be weighed against the price and availability to determine which carbon fiber is most suitable for near-future bridge designs.

Thermal stresses

Glass and polyester will expand with increasing temperature, while carbon will contract. As a result of a restriction in volumetric changes internal stresses occur. The magnitudes of these stresses are much smaller than the individual allowable material properties. Under normal use conditions, thermal stresses alone should not pose threats to the structural integrity. This is demonstrated in many existing hybrid carbon-glass composite applications. Nonetheless, stress calculations have to be carried out to confirm this.

Galvanic corrosion

Galvanic corrosion is a well-understood failure mechanism. If properly addressed, it should not pose a problem in a hybrid bridge design where carbon fibers are used. By removing one or more of the required elements needed for this form of corrosion it can easily be prevented. Metal parts should be avoided in the vicinity of carbon fibers. If this is unavoidable, non-conductive shielding of metal parts is necessary.

Wet-out of carbon fibers



Large carbon/epoxy parts are already successfully manufactured with vacuum infusion. Polyester is less viscous than epoxy and if the resin injection process is planned and carried out carefully, complete wetting of large structures should not pose big problems. Tests on small material samples yield wettability characteristics. The calculated amount of needed resin should be compared to the actual used amount of resin. Non-destructive testing of finished products is required to make sure the void content remains within allowable limits. More resin supply lines or distribution channels in the structure can be used if the wettability is insufficient.

Creep

Composite bridges made from viscoelastic polymer materials are susceptible to irreversible deflections over time as a result of continuous loading. Creep behavior can be predicted fairly well by theoretical models, once the required material parameters are known. Tests are necessary to determine these parameters. For these tests the time-temperature-superposition principle holds. This makes it possible to make statements on long-term behavior, based on short-term test results. Specifically for the combination of carbon fibers and polyester resin, representative creep data is very hard to find and creep tests have to be performed.

Health and safety aspects

Dust from carbon fibers is generally smaller and lighter than from glass fibers and penetrates deeper into the respiratory system. Adverse health effects have not been demonstrated convincingly, but can also not be excluded. Precautions when handling dry carbon fibers have to be taken. These health-related precautions, however, are similar to the ones already required for handling glass fibers. Dry carbon fibers are also known to cause short-circuiting. For this reason, cutting, transporting and draping of dry carbon fibers should be performed in a dedicated, enclosed area without electrical appliances. Protective gloves and overcoats or overalls should be worn and not be allowed to leave this area.

3.3 Glass fiber and structural steel

Interfacial bond strength steel and polyester

Organic unsaturated polyester is hard to bond to inorganic steel. To ensure the integrity of the bond, its strength needs to be known and mechanical tests are necessary to gain this knowledge. Mechanical surface treatments appear to improve the bond strength more than chemical treatments. Grit blasting and wet sanding look the most promising and have to be investigated. A layer of corrosion lowers the interfacial bond strength and should be avoided. From a structural analysis the stresses at the materials' interfaces can be predicted and these should always be lower than the interfacial bond strength.

Corrosion

Steel parts corrode when they come in contact with water and oxygen. Polyester is already used as coating material to prevent corrosion. Thicknesses up to 1 mm are used and proven to be sufficient. Embedding steel in a polyester layer with thickness of at least 20 mm should be more than adequate to prevent corrosion. Corrosion tests are needed to prove the structure's long-term corrosion behavior. To make hard statements about this behavior, product specific reference data is required to be compared with accelerated corrosion data. The reference data are acquired through real-time outdoor exposure experiments which can easily take up to two years. This duration is well beyond the time frame of this thesis project and alternate ways to test corrosion should be thought of if statements about corrosion behavior are to be made.

Durability of the adhesive bond

Absorption of water and exposure to high temperatures are the main elements that threaten the long-term strength of an adhesive bond. In completely submerged objects, moisture can diffuse even through thick layers of polyester in a matter of months. Oxygen transport, however, is too small to cause corrosion problems. As long as the polyester parts are not completely submerged in water, the saturation point is not reached and the negative effects appear to be less detrimental and reversible. Loss of strength and stiffness has to be accounted for in the design according to applicable standards. The prescribed reduction factor for adhesive bonds will lead to a conservative approach, since the bond interface is never in direct contact to the outdoor environment and is well protected by a thick layer of polyester.



Fatigue

Fatigue life of structures from novel materials can be predicted with the aid of accelerated fatigue tests that represent the actual use case closely. Tests performed on glass/polyester material cannot be used to make predictions about the long-term fatigue behavior of hybrid materials as glass/carbon. For a first approximation, the calculated stresses can be compared to known material data, if present.

Internal stresses

Stresses in the structure are introduced during manufacturing, handling and in the use phase. Structural analyses can be performed to assess these stresses. During manufacturing, contraction of the glass/polyester composite occurs as a result of cooling down from the curing temperature and due to chemical shrinkage. The former phenomenon causes much smaller contractions than the latter and can be neglected in the overall analysis. The large contraction of the glass/polyester with respect to the contraction of the steel can pose a serious threat to the bonded interface. Whether the bond will fail and what the effect of this failure is can be determined with tests and, once the bond strengths are known, with simulations.

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Appendix B

Comparison of steel, GFRP and CFRP

FiberCore Europe currently manufactures its composite bridges from GFRP. Two materials are suggested as potential candidates to replace parts of the GFRP: structural steel and CFRP. The type of steel regarded in this study is S235JR. This type of steel is relatively cheap, can easily be machined, shaped, welded and galvanized and is therefore very common in construction. FiberCore Europe's default metal supplier has lots of experience with this type of steel and put it forward as the most suitable candidate.

A comparison of the three materials can be made based on their structural efficiency. The most relevant material properties for this comparison are given in Table B.. The values for the composite materials are based on a fiber-volume fraction of 53%.

Table B.1: relevant material properties of steel, GFRP and CFRP

	Steel	GFRP	CFRP
Tensile Young's modulus [GPa]	210	34 ¹⁾	85 ²⁾
Density [kg/m ³]	7850	1912	1520
Material Bulk price [€/kg]	XX.XX	XX.XX	XX.XX

¹⁾ based on current GFRP skin design (0/90 – 75%/25%)

²⁾ determined with CLT, based on CFRP design (0/90 – 75%/25%)

The materials are compared on their efficiency in resisting bending and for their influence on the eigenfrequency of a simply supported uniform beam, subjected to a uniformly distributed load.

B.1 Deflection

The maximum deflection at mid-span as a result of the traffic load can be determined according to:

$$\delta_{max} = \frac{5}{384} \frac{qL^4}{EI} \quad (B.1)$$

Where

δ_{max} = the maximum deflection of the bridge at mid-span



q = the prescribed distributed load [unit force/unit length]
 L = the length of the bridge
 EI = the flexural rigidity of the bridge

It can be seen that the deflection of the bridge as a result of the prescribed load is not a function of the mass of the bridge. For a given bridge geometry, values for q , L and I are fixed. From this it follows that

$$\delta_{max} \propto \frac{1}{E} \quad (B.2)$$

Since a smaller deflection is better than a larger deflection, the value of $1/E$ has to be as small as possible. It can be seen directly that a larger value for the Young's modulus E is preferred.

B.2 Eigenfrequency

The eigenfrequency of the simply supported beam under uniform load is given by:

$$f_n = \frac{K_n}{2\pi} \sqrt{\frac{EIg}{wL^4}} \quad (B.3)$$

Where,

f_n = the eigenfrequency of the bridge
 K_n = a harmonic constant with n referring to the mode of vibration
 EI = the flexural rigidity of the bridge
 g = the gravitational acceleration
 w = the weight of the bridge

Dividing the weight w over the gravitational acceleration g , yields the mass of the bridge. Substituting this in equation (B.3) and moving the length L out of the square root sign yields:

$$f_n = \frac{K_n}{2\pi L^2} \sqrt{\frac{EI}{m}} \quad (B.4)$$

For a given bridge geometry, values for K_n , I and L are fixed. The mass of a homogeneous beam directly depends on the material's density ρ . From this it follows that:

$$f_n \propto \sqrt{\frac{E}{\rho}} \quad (B.5)$$

Since the eigenfrequency preferably has a value as high as possible, the right hand side of equation (B.5) has to be as high as possible. Values for this expression are given for all three materials in Table B.2.



Table B.2: eigenfrequency efficiency factors

	E [GPa]	ρ [kg/m ³]	$\sqrt{E/\rho}$	Performance w.r.t. GFRP
Steel	210	7850	0.16	1.23
GFRP	34	1912	0.13	1.00
CFRP	85	1520	0.24	1.50

From this table it appears as though CFRP is the most efficient material to design for eigenfrequency. This statement, however, is purely based on weight. The lightest structure for a specific eigenfrequency can be made from CFRP. When taking material costs into account, the picture might change completely. Rather than using the values for the stiffness in equation (B.5), values for the stiffness per material bulk price (MBP) are used. The results are shown in the following table.

Table B.3: eigenfrequency efficiency factors corrected for MBP

	E [GPa]	ρ [kg/m ³]	$\sqrt{E/\rho}$	MBP [€/kg]	$\frac{\sqrt{E/\rho}}{MBP}$	Performance w.r.t. GFRP
Steel	210	7850	0.16	xx.xx	$xx \cdot 10^{-3}$	1.05
GFRP	34	1912	0.13	xx.xx	$xx \cdot 10^{-3}$	1.00
CFRP	85	1520	0.24	xx.xx	$xx \cdot 10^{-3}$	0.28

When taking the material costs into account, CFRP is no longer the obvious choice. Steel and GFRP show almost the same result and outperform CFRP more than three times. Bridges with the highest eigenfrequency can best be built from CFRP, purely from a structural point of view. Costs, however, play a very large role in bridge design, making steel and GFRP more likely candidates.



C

Appendix

Design model inputs and constraints

In this Appendix all input parameters for the design model are summarized.

C.1 Geometrical dimensions

Table C. lists the elements that are present in all bridge sub-concepts. For every dimension, the numerical values or range of values is given and if constraints are set on these parameters, they will be mentioned and explained.

Table C.1: elements present in all bridge sub-concepts and their numerical values

Parameter	Value	Comments
Bridge length	47 m	Fixed by problem definition/client request
Bridge width	4.5 m	Fixed by problem definition/client request
Bridge height	0.1 - 5 m	Upper and lower boundary for optimization routine. Both values are never reached.
Thickness top skin	3 - 50 mm	Minimum value for corrosion protection and to retain an all-(hybrid) composite structure. The maximum value acts as upper bound for the optimization routine
Thickness bottom skin	3 - 50 mm	Minimum value for corrosion protection and to retain an all-(hybrid) composite structure. The maximum value acts as upper bound for the optimization routine
Thickness shear webs	6.7 mm	Value from current GFRP design
Height of shear webs	derived	Height of the bridge minus thicknesses of the top and bottom skin
Number of core elements	21 - 50	Minimum value to prevent shear web pitch from getting larger than 21 cm. This maximum pitch avoids shear web buckling under wheel prints. Maximum value to maintain a practical minimum width.



Table C.2 lists the remaining elements per specific sub-concept. Again, the numerical values or range of values and constraints are given.

Table C.2: elements per sub-concept and their numerical values

Parameter	Value	Comments
Reference concept		
Height of core elements	derived	Height of the bridge minus thicknesses of the top and bottom skin
Width of core elements	derived	Follows from bridge width, web width and number of core elements
Sub-concept S1		
Height of core elements	derived	Height of the bridge minus thicknesses of the top and bottom skin
Width of core elements	derived	Follows from bridge width, web width and number of core elements
Number of I-beams	2 - 50	But not more than the number of core profiles.
Height of I-beams	derived	Similar to height core elements; height of the bridge minus thicknesses top and bottom skins
Width of I-beams	derived	Similar as width of core elements
Thickness of horizontal flanges	0.5 - 30 cm	Practical upper and lower bound for the optimization routine
Thickness of vertical web	0.5 - 30 cm	Lower bounds are needed to prevent a preferred thickness of 0 mm by the optimization routine
Sub-concept S2		
Height of core elements	derived	Height of the bridge minus thicknesses of the top and bottom skin
Width of core elements	derived	Follows from bridge width, web width and number of core elements
Number of box girders	2 - 50	But not more than the number of core profiles.
Height of box girders	derived	Similar to height core elements; height of the bridge minus thicknesses top and bottom skins
Width of box girders	derived	Similar to width of core elements
Thickness of horizontal flanges	0.5 - 30 cm	Practical upper and lower bound for the optimization routine
Thickness of vertical web	0.25 - 30 cm	Lower bounds are needed to prevent a preferred thickness of 0 mm by the optimization routine
Sub-concept S3		
Height of core elements	derived	Height of the bridge minus thicknesses of the top and bottom skin
Width of core elements	derived	Follows from bridge width, web width, thickness of the steel sheets and number of core elements



C. Design model inputs and constraints

Number of steel sheets	2 - 100	But not more than two times the number of core profiles.
Height of steel sheets	derived	Similar to height core elements; height of the bridge minus thicknesses top and bottom skins
Thickness of steel sheets	1 - 300 mm	Lower bounds are needed to prevent a preferred thickness of 0 mm by the optimization routine
Sub-concept S4		
Height of core elements	derived	Height of the bridge minus thicknesses of the top and bottom skin, minus thickness of two steel sheets
Width of core elements	derived	Follows from bridge width, web width and number of core elements
Number of steel sheet pairs	21 - 50	But not more than the number of core profiles
Width of steel sheets	derived	Similar to width of core elements
Thickness of steel sheets	1 - 300 mm	Practical lower and upper boundary for the optimization routine
Sub-concept S5		
Height of core elements	derived	Height of the bridge minus thicknesses of the top and bottom skin
Width of core elements	derived	Follows from bridge width, web width and number of core elements
Number of steel bar pairs	21 - 50	But not more than the number of core profiles
Width of steel bars	2 - 10 cm	A minimum value is set for the optimization routine. The maximum is the width of the core minus 5 cm on each side to fit inside the core
Height of steel bars	5 - 1000 mm	Minimum value for the optimization routine. The maximum is half the height of the core elements.
Sub-concept C1		
Height of core elements	derived	Height of the bridge minus thicknesses of the top and bottom skin
Width of core elements	derived	Follows from bridge width, web width and number of core elements
Percentage carbon in skins	0 - 100%	From all-GFRP skins to all-CFRP skins



C.2 Material data

In Table C.3 lists the material data as used in the design tool for the determination of the deflection, eigenfrequency and thermal stresses.

Table C.3: material properties as used in the design tool

Material	Specifications	Young's Modulus [GPa]	Material Bulk Price [€/kg]	Density [kg/m ³]	CTE [10 ⁻⁶ m/mK]
Steel	S235JR	210	[xx.xx]	7850	12
Glass fibers	Jushi 386 Direct Roving	79	[xx.xx]	2550	2.8
Carbon fibers	Zoltek PanEx35-UP	242	[xx.xx]	1810	-0.75
GFRP	0°/90°-75%/25% - V _f =53%	32	[xx.xx]	1912	6.9
CFRP	0°/90°-75%/25% - V _f =53%	62	[xx.xx]	1520	0.69
Foam core	Closed cell PU	0.006	[xx.xx]	35	56
Polyester	DSM Synolite 1967	3.8	[xx.xx]	1193	100

C.3 Load cases

Only two load cases are defined to determine the stresses, deflections and eigenfrequencies of the bridge sub-concepts. For the deflection of the bridge, the static load is prescribed at 5000 N/m². A maximum deflection of one hundredth of the length of the bridge is allowed. For a bridge of 47 meter length, the maximum deflection becomes 47 cm.

For the eigenfrequency of a bicycle/pedestrian bridge, the weight of the bridge and an additional load of 400 N/m² have to be taken into account. The minimum resulting eigenfrequency is set at 2.3 Hz.

C.4 Not implemented

The following parameters are not implemented in the design tool, because these aspects are independent of the bridge sub-concept.

- Costs for wearing surface
- Costs for bridge railings
- Costs for lights and electricity

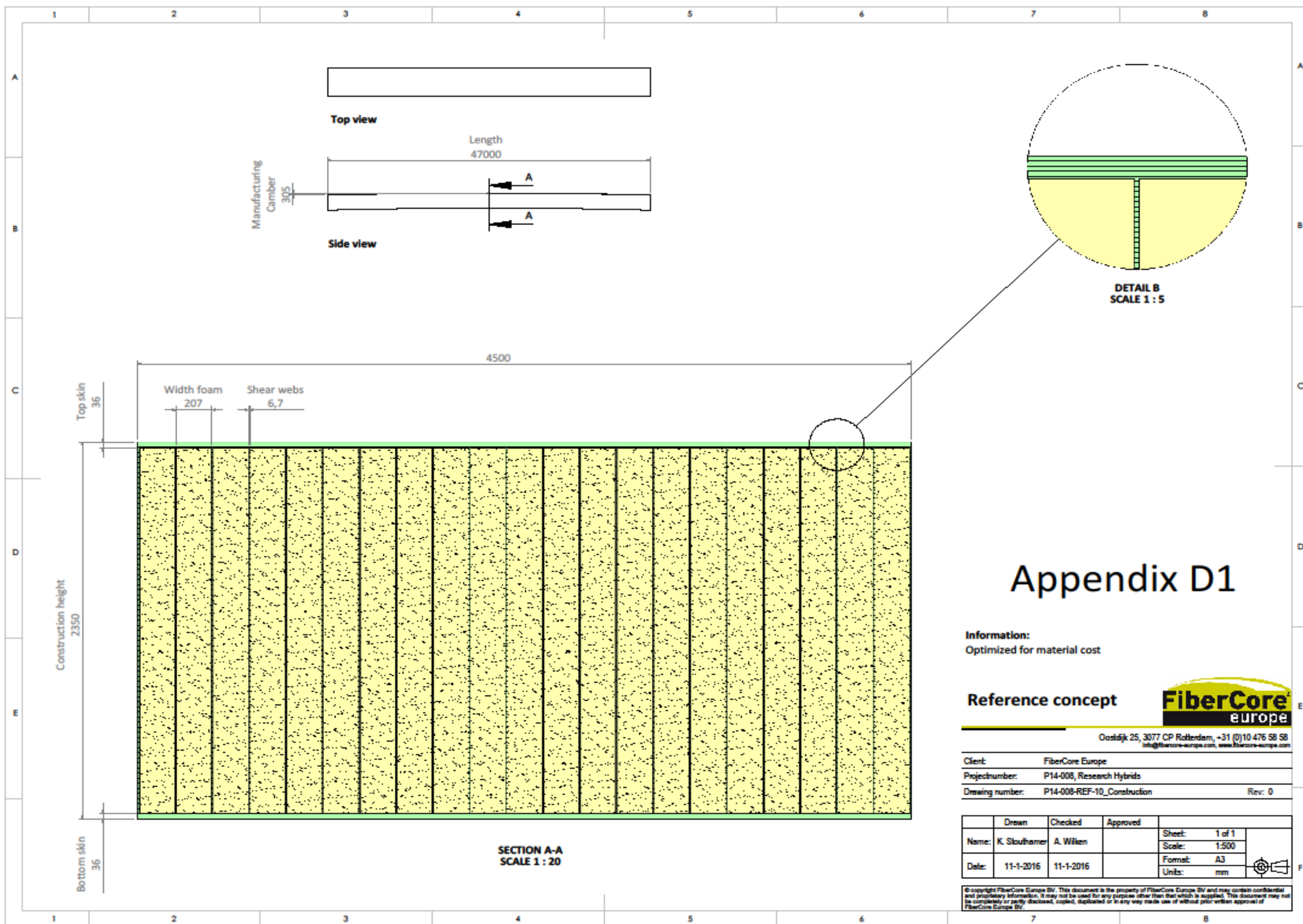
Other than these, the following aspect are also not incorporated

- Other methods to increase the eigenfrequency
- Clamped, rather than simply supported (Panos-factor)
- Additional dampening measures
- Effect of the mass of railings on the eigenfrequency



Appendix D

Design sub-concepts drawn to scale



Appendix D1

Information:
Optimized for material cost

Reference concept

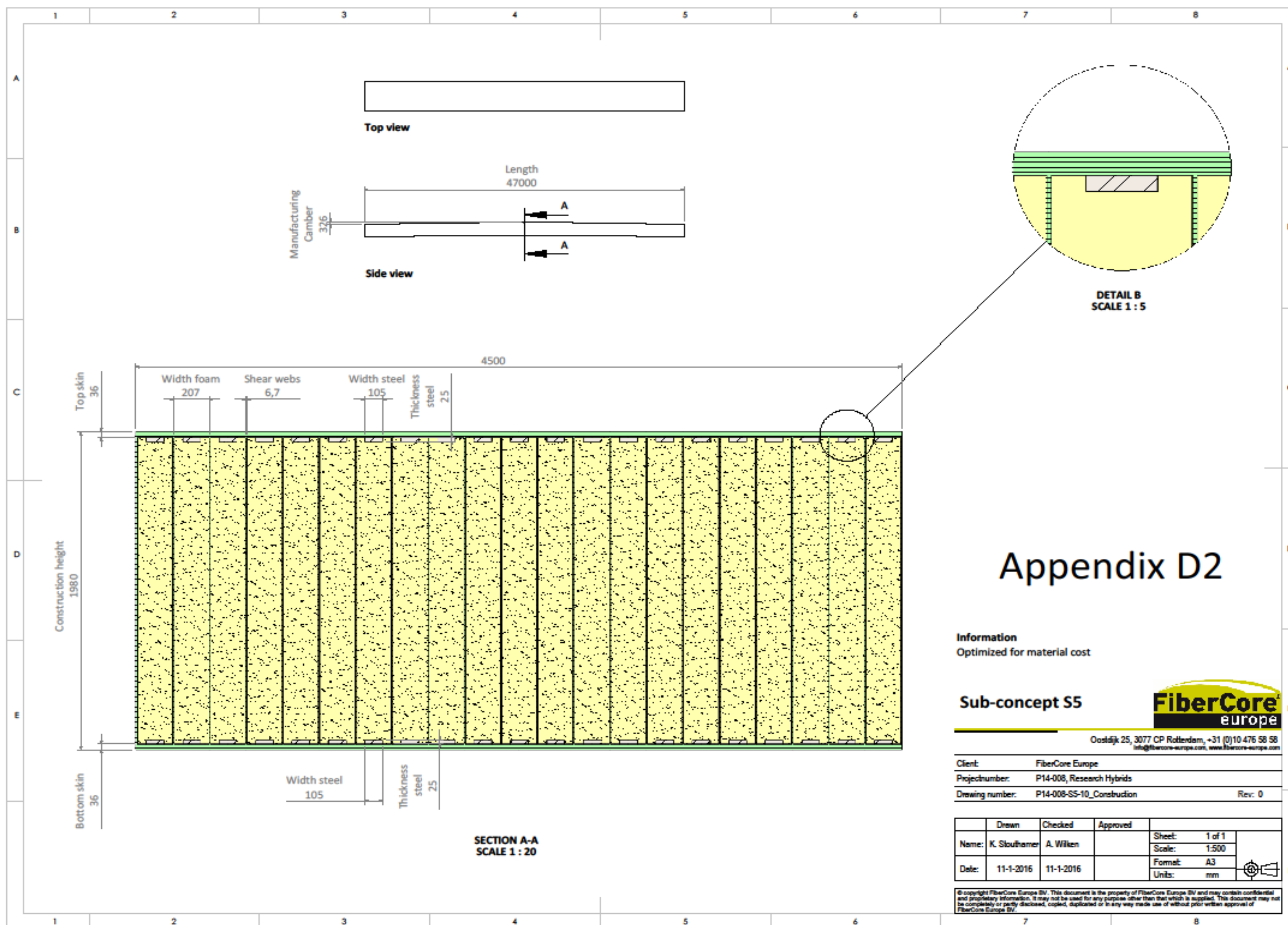


Oostdijk 25, 3077 CP Rotterdam, +31 (0)10 476 58 58
info@fibercore-europe.com, www.fibercore-europe.com

Client: FiberCore Europe
Projectnumber: P14-008, Research Hybrids
Drawing number: P14-008-REF-10_Construction Rev: 0

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Appendix D2

Information
Optimized for material cost

Sub-concept S5



Oostdijk 25, 3077 CP Rotterdam, +31 (0)10 476 58 58
info@fibercore-europe.com, www.fibercore-europe.com

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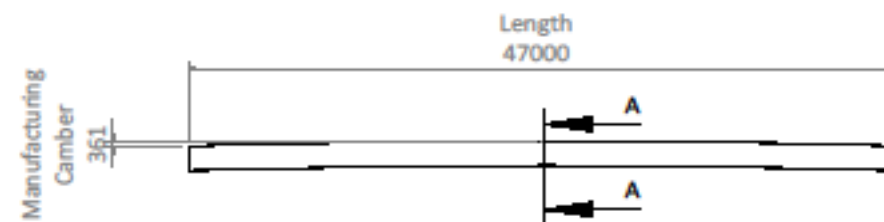
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1 2 3 4 5 6 7 8

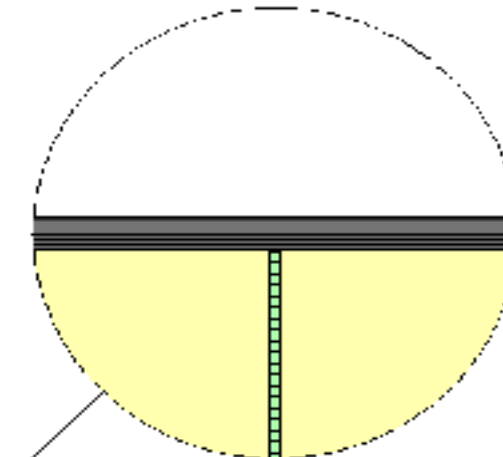
A



Top view

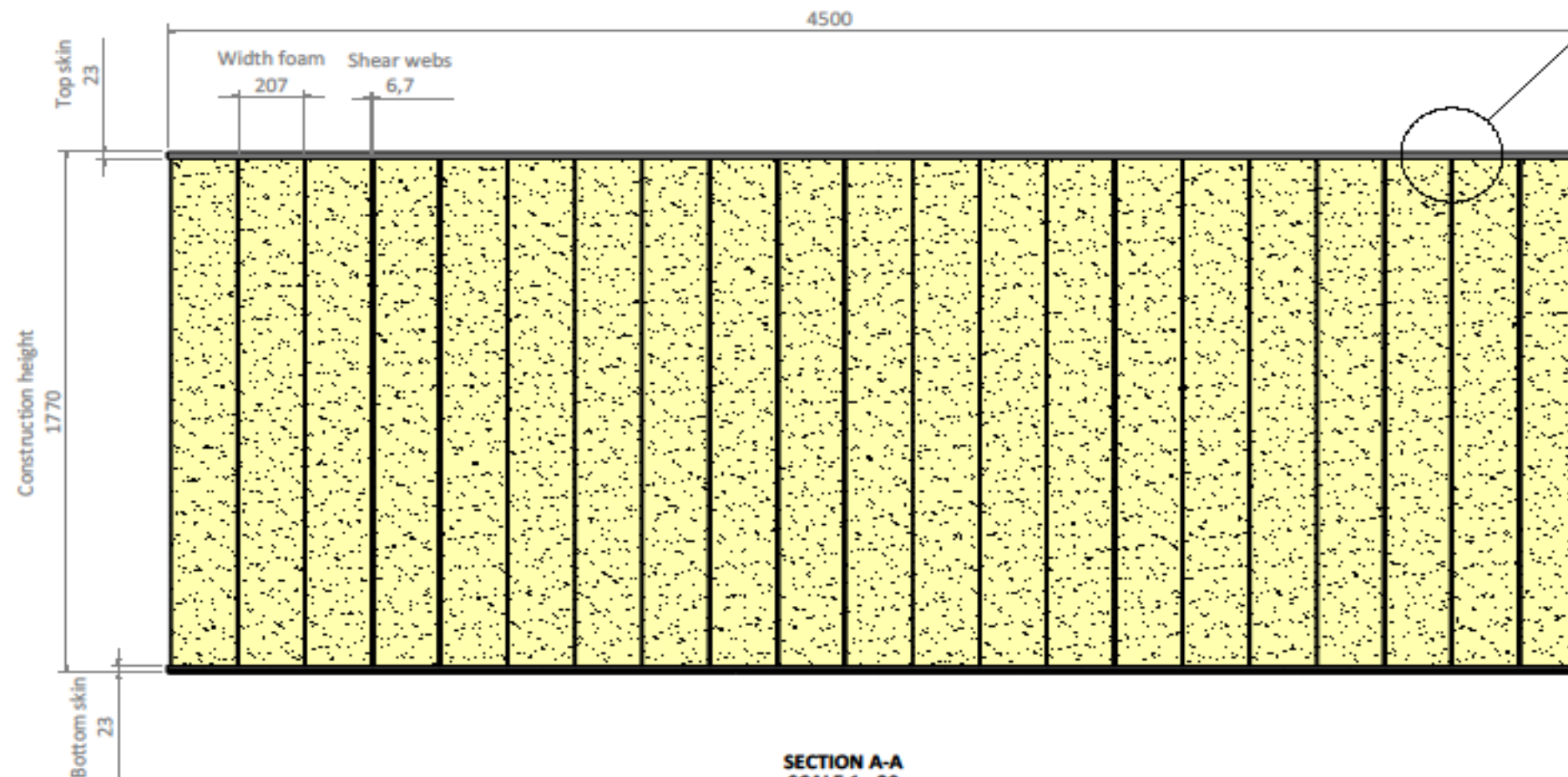


Side view



DETAIL B
SCALE 1 : 5

C



SECTION A-A
SCALE 1 : 20

D

E

Appendix D3

Information
Optimized for mass

Sub-concept C1



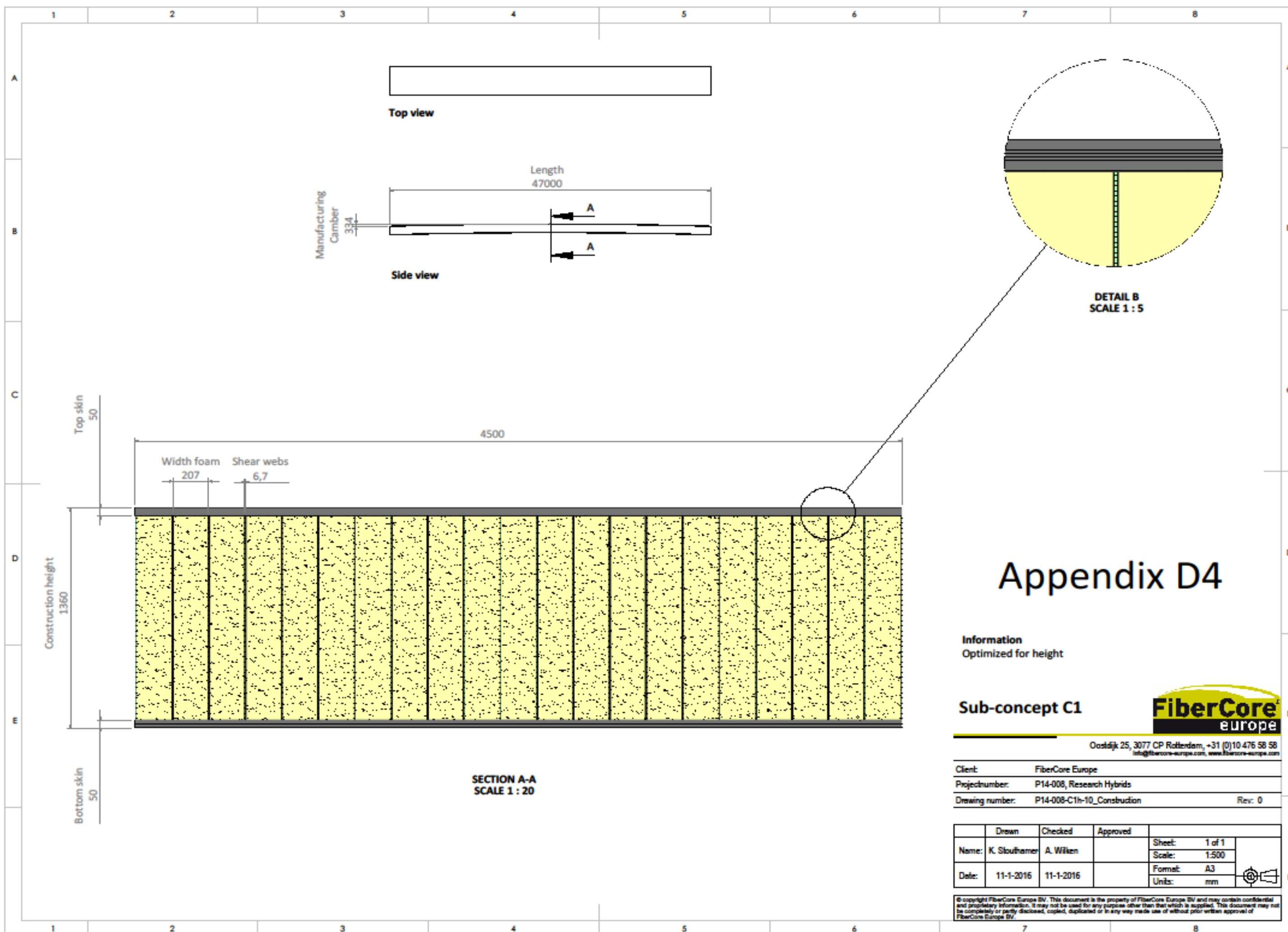
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info@fibercore-europe.com, www.fibercore-europe.com

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Appendix D4

Information
Optimized for height

Sub-concept C1

FiberCore
europe

Oostdijk 25, 3077 CP Rotterdam, +31 (0)10 476 58 58
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