Application and environmental evaluation of fibre reinforced polymers in movable bridge design

Master thesis by
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Preface

This master thesis presents the final graduation assignment from the Integrated Product Design programme of the Industrial Design Engineering faculty at the Delft University of Technology. It revolves around the application and environmental performance of Fibre Reinforced Polymers, a synthetic polymer based material, in the design of movable bridges.

The graduation assignment took place at Movares Adviseurs & Ingenieurs in Utrecht. Among others active in the construction of (movable) bridges, the company is interested in the aspects that are involved in the application of Fibre Reinforced Plastics (FRP) as a structural material. They want to be able to thoroughly and objectively fulfil their role of advisory and engineering in the industry concerning the application of this material. For Movares, aspects such as material properties, production, durability, maintenance, lifespan, and environmental sustainability play a role in assessing the choice for FRP. The final outcome is a redesign proposal for FRP application in movable bridges and an environmental impact assessment for multiple steel and FRP variants.

I would like to thank the following people who attributed to the final outcome of this master thesis. First of al my committee chair Ruud Balkenende and mentor Marko Pavlović from the University for their time, expertise, feedback and guidance during this assignment. Also Anton van ‘t Klooster, my company mentor for his involvement and expertise during my time at Movares and colleagues Arjen Steenbrink, Mark van den Brug, John van Dijk, Ronald Geijsen, Guido Zwart, Jacques Montijn, Julian Sol, Gary Greiner and my co-graduate student Stijn Mouroulis.

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Abstract

This thesis consists of a research study concerning the application and environmental performance of Fibre Reinforced Polymers (FRP) for application in movable bridge design. The research is accompanied by a proposed redesign exploiting the advantageous properties of FRP and a life cycle assessment (LCA) of multiple FRP variants' environmental impact compared to an existing steel variant. The subject of this case study is the Amaliabridge over the Gouwe canal in Gouda.

The thesis was performed during an internship at Movares Adviseurs & Ingenieurs, a Dutch engineering and consultancy firm, among others specialised in movable bridges. The goal of the project was to ascertain how the environmental impact of an FRP movable bridge redesign would compare to the original steel design of the Amaliabridge. The scope of this thesis did not cover the mechanical analysis of the redesign and therefore does not provide a fully accurate representation, rather an indicative and explorative result that asks for further investigation.

The resulting design is a rolling bascule type movable bridge, eliminating the need for a bascule basement as is required in a trunnion type bascule bridge. This leads to significantly less design, engineering and construction efforts. Additionally, the design aims at reusability, prolonging the lifespan of the bridge as much as possible.
The environmental impact assessments yielded partially questionable results. A Cradle to Gate analysis was performed, in which the FRP variants performed better compared to steel variants. A Cradle to Cracle analysis was also performed, where FRP variants performed significantly less, as their End of Life scenario's accounted for a significantly higher impact compared to the steel variants. These differences are probably caused by an allocation error and are therefore not regarded as proof of FRP performing better or worse compared to steel.

Glossary

Below is a list of frequently used abbreviations and acronyms in this report.

C2Cr:	Cradle to Cradle *(lifecycle assessment scope including recycling)*
C2Ga:	Cradle to Gate *(lifecycle assessment scope excluding End of Life)*
C2Gr:	Cradle to Grave *(lifecycle assessment scope excluding recycling)*
CFM:	Continuous Filament Mat (mats with randomly oriented)
CFRP:	Carbon Fibre Reinforced Polymer
CSM:	Chopped Strands Mat *(randomly oriented short fibres)*
EoL:	End of Life *(final phase in product lifecycle)*
FEM:	Finite Element Method *(numerical method for physics analysis)*
FRP:	Fibre Reinforced Polymer
GFRP:	Glass Fibre Reinforced Polymer
LCA:	Life Cycle Analysis / Life Cycle Assessment
LCC:	Life Cycle Cost
LCI:	Life Cycle Inventory *(standardised input data for an LCA)*
QI:	Quasi-isotropic *(fibre orientation for unidirectional reinforcement)*
RC:	Reinforced Concrete *(concrete with steel reinforcement)*
SLS:	Service Limit State *(at which the material stays serviceable)*
SOR:	Statement Of Requirements *(Dutch: Programma van Eisen, PvE)*
UD:	Unidirectional *(fibre orientation for directional reinforcement)*
ULS:	Ultimate Limit State *(at which the material yields)*
VA-RTM:	Vacuum Assisted Resin Transfer Moulding *(FRP production method)*
VOC:	Volatile Organic Compound *(evaporating fumes from curing resin)*
WR:	Woven Roving

Table of contents

Figures, images, tables & equations

1 Introduction

This master thesis revolves around the application and environmental performance of Fibre Reinforced Polymers (FRP) in movable bridge design. Currently, movable bridges are mostly designed in steel. FRP however, already being used in industries such as aerospace for decades, has recently been proven to also be a suitable material for the design and construction of movable bridges. Among other advantages are its material properties such as corrosion resistance, high strength and fatigue performance. Although FRP is not a new material, it is relatively new when concerning movable bridges, currently attracting interest from the industry. FRP bridge designs have already been realised around the world, with most of them fortunately performing well. Some exceptions exist however, where failure can be attributed to poor design and implementation of the material. The main question answered in this thesis is what factors are important when designing a movable bridge with FRP and how the material performs in terms of environmental sustainability compared to conventional materials.

1.1 Assignment

The initial assignment for this thesis was to investigate the mechanical, application and especially the environmental properties of FRP and ascertain its suitability as a replacement candidate for conventional materials such as steel in movable bridges. The main question at the start of the project was whether or not FRP is suitable at all for application in movable bridges, especially bascule bridges, as the directions of main forces change during bridge operation and are all transferred to a specific location around the axis of rotation. Two additional questions were whether FRP's environmental sustainability and its total Life Cycle Cost (LCC) outperform those of steel. These questions together formed the main question whether FRP should be used in movable bridge design and if so, when and where its application proves to be advantageous. Some design and engineering firms have already constructed parts of large-scale traffic bridges or entire medium sized traffic bridges out of FRP. Movares also has experience with the application of FRP in certain projects. Up until now, the material has proven to be a competitive lightweight replacement candidate for conventional materials. However, Movares still questions the material's applicability when concerning the entire lifecycle, especially with maintenance during the use phase and environmental impact during the production and End-of-Life (EoL) phase.

Several studies have been performed comparing FRP's environmental impact when applied in bridges to conventional materials. An example is a Life Cycle Analysis (LCA) ordered by leading Dutch FRP manufacturer FiberCore and performed by BECO in 2009, which stated FRP as environmentally beneficial compared to steel and concrete bridges.[1] In this study, two types of FRP bridges made with glass and carbon fibres were compared to concrete and steel bridges. Both FRP bridges scored significantly better in almost all three criteria: cumulative energy-demand (GJ), carbon footprint (103 CO2 equiv.) and Eco-indicator 99 (mPt). Another LCA however, this time ordered by Dutch agency RVO but also performed by BECO in 2013, stated a glass fibre bridge performs significantly worse compared to steel, concrete and wooden bridges.[2] The Functional Unit (FU: a quantified description of performance requirements for comparison of different design variants) in both LCA analyses was: providing a bridge for 100 years. The outcomes of these studies differ to such an extent that no solid conclusion can be drawn. One of the main factors for these large differences are the Life Cycle Inventory (LCI) data used in the studies, which are sometimes unavailable or estimated by the material producers. Additionally, when taking into account possible future beneficial advancements in polymer composition and material recycling technologies, such studies should be considered as a snapshot in time.

This thesis will provide recommendations concerning the suitability of FRP in movable bridge design. Key topics are environmental sustainability, mechanical properties, durability and in-service aspects concerning applications in movable bridges. An important factor is the material's environmental impact related to factors such as price, performance, production and maintenance efforts, etc. After thorough research, key issues are transformed in a proposed redesign to improve the applicability and reusability of the material.

1.2 Structure

First, in chapter 1, an introduction to the subject is given and the reasoning behind this thesis, the assignment, scope and approach are explained. In chapter 2, an introduction is given to the context of movable bridges and the application of FRP, concluding with the problem definition, research question and the aim and objectives of the project. In chapter 3, extensive desk research on FRP is summarized and presents the acquired insight into the important characteristics of the material. Based on this acquired knowledge, an FRP redesign is proposed in chapter 4 that exploits the benefits of the material and tries to minimize its downsides. The environmental impact of FRP application is then compared to that of steel in chapter 5. The proposed redesign and the environmental impact analysis are discussed in chapter 6 and finally, conclusions are drawn and recommendations are made in chapter 7, concluding this thesis.

1.3 Approach & methodology

This project has been conducted in four main phases. In the first phase, a literature study concerning FRP was conducted which is summarized in chapter 3. This involved the acquisition of knowledge concerning the characteristics of FRP: performance on sustainability, durability, material and mechanical property level. The research methods included: desk research using relevant literature, standards and regulations, additional sources from the internet, inquiries with manufacturers or raw material suppliers, interviews with FRP producers, experts, and engineers. At the end of this first phase, all relevant important factors have been identified, based on which an FRP bridge has been designed the second phase.

The second and third phase were executed largely in parallel and are summarized in chapters 4 and 5 respectively. For phase 2, interesting design alternatives were identified, explored and finally, one design direction was chosen and conceptualised into the proposed FRP redesign. In phase 3, durability and environmental sustainability of the proposed applications have been be assessed.

Finally, for phase 4, the outcomes of phase 2 and 3 are discussed in chapter 6 and recommendations, conclusions and an answer to the main question are presented in chapter 7.

2 Analysis

To understand the situation in and around a movable bridge; its context, basic design principles, operating mechanisms and related factors will be summarized in this chapter. An introduction to FRP is also given which is subsequently elaborated on in chapter 3. The problem definition, research question, aim and objectives that represent the subject of this thesis are presented at the end of this chapter.

2.1 Context

Current situation

Bridges are a common infrastructural phenomenon present almost everywhere in the world. In the Netherlands, a country with 26% of its land below sea level featuring many inland waterways, movable bridges are essential for the roads crossing these waterways. These bridges provide passage for pedestrians, cyclists, road and rail traffic, however also need to allow waterway traffic underneath, hence they have to be partially or completely movable.

A large amount of bridges currently in service in the Netherlands have been built around the 1960s and 1970s. As their lifespan progresses, three main factors influence their deterioration: fatigue, corrosion and traffic loads beyond the designed capacity.[3] A lot of these bridges have been built to last up to 50 years, current Dutch national guidelines such as NEN-EN 1993-2+C1 NB:2011 prescribe new bridges to be engineered to even last up to 100 years. For old bridges, if load bearing sub- or superstructure and foundations are still up to specifications and if conserved well, individual parts like the deck can be reconditioned. Bridges that are significantly degraded or loaded beyond their designed capacity however, will eventually need to be replaced.

The total amount of road vehicles in the Netherlands alone has risen 43% steadily from 7,6 million in 2000 to 10,9 million in 2016 [4], traffic intensity has also increased 14% between 2000 and 2011 [5] and the total transport weight has increased 217% between 1963 and 2007.[6]

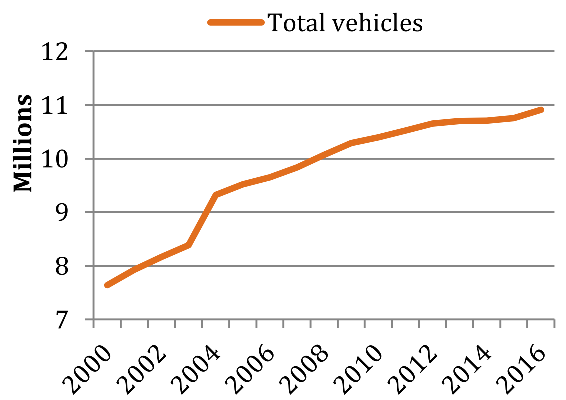


Figure 2.1 – Total vehicles in the Netherlands (Source: CBS 2017)

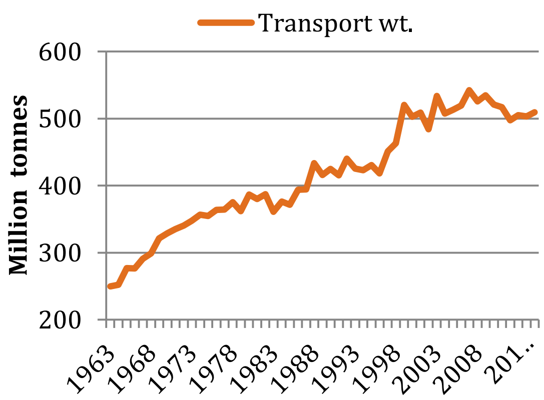


Figure 2.2 – Total transport weight in the Netherlands (Source: CBS 2017)

This increase of both traffic intensity and total transport weight poses a potential risk for the fatigue design parameters of old bridges, as loading cycles and cycle forces have increased significantly over time. When taking into account these effects on the bridges' fatigue parameters combined with the detrimental effects of corrosion; the structural integrity of a lot of these bridges is currently due for inspection. Next to the design and construction of new bridges, an enormous task lies ahead in evaluating and eventually reconditioning or replacing existing bridges.

Among conventional materials used in bridge design are: wood, steel and different types of RC. For movable medium and heavy traffic bridges, steel is mostly used due to its strength and stiffness to weight ratio. However, despite material advancements over the past decades, these materials still suffer from degradation issues such as corrosion and fatigue. Hence FRP has been introduced into the domain of bridge design; a strong, light and durable material whose properties can be tailored to different applications. Already being used in the aerospace and automotive racing industries for decades, the material science is already in a very mature state. Unfortunately for bridge design, the guidelines for FRP to which designs have to live up are limited. Only one design guideline currently exists in the Netherlands: the CUR96. This guideline is however being re-evaluated and expanded to be added to the Eurocode for better standardisation of design regulations.

FRP is an interesting material as its properties are competitive with those of conventional materials, even possessing properties that provide increased durability. Unlike steel, FRP does not suffer from corrosion and therefore does not require intensive conservation during its lifecycle. It also has very high strength compared to stiffness, requiring a stiffness-driven design approach resulting in high strength, making FRP structures less prone to fatigue. FRP's density on average is four times less that of steel, resulting in possible weight reduction. Weight reduction also means easier transport and installation, less complex and expensive foundations and operating mechanisms.

Two other significant reasons to investigate the application of FRP are the advantages of form freedom and property tailoring. The reinforcing fibres in FRP are very flexible during layup and the matrix resins are very viscous during impregnation, allowing complex shapes to be realised that can be directionally reinforced by using different fibre orientation and density in predetermined areas, reducing unnecessary material and in turn maintaining a low weight. However steel structures can also be made in a lot of shapes and sizes, a disadvantage is that moulds and forming processes like cutting and welding are very energy and labour intensive. For FRP, the required energy and labour are significantly less. Especially for a large product such as bridge when surface finishing is not a driving design aspect as is the case in consumer products. This form freedom also allows for different design approaches that might benefit the architectural and aesthetic value compared to steel girder designs. Since a bridge nowadays is not merely regarded a bridge but also a work of art.

The material also has disadvantages, especially concerning the EoL lifecycle phase of FRP products or parts made with thermosetting polymer matrices. Because it is a composite material, of which the original constituents cannot be separated easily, it is hard to recycle. Mechanical recycling currently results in very low quality recyclates such as powders, chemical recycling is currently not economically viable [7] and energy recovery by incineration leads to the loss of the material altogether. All valuable material properties that were created in the original product are completely lost in either of these recycling processes.

While the initial price of FRP might be higher compared to steel, FRP producers currently advocate that the total cost of ownership, including maintenance, known as Life Cycle Costs (LCC) will be at least equal or lower than steel variants. The LCC are important to take into account for an object as large and with a such a long lifespan as a bridge, as costs are part of the main governing factors in decision making for the client.

Current application

Some examples of FRP bridges already produced and currently in service are shown in Figure 2.3 to Figure 2.6. All these bridges are fixed bridges, with the exception of the Nelson Mandelbridge. However, as this is a lifting bridge, no drastic transitions in loads and directions take place during movement of the bridge, which is very different from other bridge types such as bascule bridges.

Figure 2.3 – Lleida pedestrian bridge, Lleida, ES
Made by Pedalta & Fiberline Composites.
Span: 38m, width: 3m. Pultruded GFRP superstructure with modular GFRP deck.
Image courtesy: Fiberline Composites A/S.

Figure 2.4 – Friedberg bridge, Friedberg, DE
Made by Fiberline Composites. Span: 27m, width: 5m. Steel girder substructure with modular GFRP deck.
Image courtesy: Fiberline Composites A/S.

Figure 2.5 – Nelson Mandela bridge, Alkmaar, NL
Made by Royal HaskoningDHV and Delft Infra Composites. Span: 22m, width: 12m. GFRP leaf deck.
Image courtesy: Royal Haskoning DHV.

Figure 2.6 – Bridge over A27, Lunetten, NL
Made by Heijmans, FiberCore & Movares. Span: 140m, width 6,2m. Steel truss superstructure with modular GFRP deck.
Image courtesy: FiberCore Europe B.V.

Case study

This thesis will revolve around one specific bridge as a case study: the Amaliabridge over the Gouwe canal in Gouda, a movable trunnion bascule bridge with its counterweight and operating mechanism inside a bascule basement that is situated partially below the water level as can be seen in Figure 2.7.

Figure 2.7 – The Amaliabridge over the Gouwe canal (Image courtesy: Hillebrand B.V.)

The bridge provides a 26,5 meter passage for the N451 county road over the Gouwe canal main waterway. One of the requirements for this bridge is an unlimited height clearance for waterway traffic in opened state. All other requirements originally stated in the Statement of Requirements (SOR) are not taken into account for this case study, to limit complexity and preserve openness in design approach. Although the Amaliabridge is a relatively tough subject for a case study, considering the size and loading requirements, viable FRP replacement concepts can be scaled down to cover multiple application scenario's.

2.2 Problem definition

Conventional materials like steel and reinforced concrete (RC) are currently the most used in bridge design. Especially for movable bridges, steel is still the dominant material of choice. However FRP would seem a close competitor for steel, considering it possesses good mechanical properties at a low weight, excellent durability and is currently also being adopted by the industry, its application is still in the early stages concerning movable bridges. Additionally, problems still exist at the EoL phase, where of the biggest challenges concerning FRP still exists: its environmental sustainability. As recycling processes currently do not yield similar results as with steel, for which the recycling process is relatively simple, the question is whether FRP's durability outweighs its possibly negative environmental impact.

All these aspects considered, Movares currently has no specific knowledge concerning the application and environmental aspects in relation to the question if, when and where the application of FRP is favourable when compared to conventional materials. The desired improvement is to analyse the material based on the aforementioned aspects and to seek innovation opportunities that can aid Movares in better decision-making concerning the choice for FRP application in the preliminary design phase.

2.3 Research question

The main topics in this thesis will be the applicability and environmental impact of FRP compared to conventional materials in the design of movable bridges. The main question is therefore formulated as:

"When taking into account its complete lifecycle, when and where should FRP be considered for application in movable bridges and how does its environmental impact compare to that of conventional materials?"

Three sub-questions are formulated to form the answer to this question:

1. When and where does FRP prove a suitable replacement candidate for conventional materials?
2. Can design improve the applicability or environmental performance of FRP?
3. How does FRP perform on environmental impact compared to conventional materials?

Sub-question 1 will be elaborated on in chapter 3. An FRP redesign is proposed in chapter 4 to provide an optional approach to answer sub-question 2. Finally, sub-question 3 will be answered in chapter 5 in the environmental impact analysis. All topics are then discussed in chapter 6 and finally concluded in chapter 7.

2.4 Aim and objectives

The aim is to ascertain whether FRP is a suitable material for use in movable bridges concerning its mechanical properties, durability and environmental impact compared to conventional materials. The four main objectives of this thesis are:

1. Generation of a clear summary of the ins & outs of FRP application in bridge design, taking into account: strengths, weaknesses, known issues, and expected (near) future developments.

2. Design of a conceptual design approach for the application of FRP, focused on efficiency, durability, sustainability form giving freedom and aesthetics.

3. Performing an environmental impact assessment where the application of FRP is evaluated and compared to an existing case study.

2.5 Scope

The scope of this thesis covers the entire lifecycle of a movable bridge. From the sourcing of raw materials to production, installation, maintenance, and for FRP in particular: End of Life (EoL). This lifecycle is evaluated on environmental impact performance and compared to the steel design of a case study to ascertain whether or not FRP is suitable for this specific case.

The scope of the case study will cover the analysis and redesign of the movable part of the bridge (the leaf) and its operating mechanism depicted in blue in Figure 2.8. The environmental impact assessment will also take into account materials and construction efforts of the bascule basement, as this is a significant part of the current design which has been excluded in the redesign.

For completeness, the mechanical, environmental and application aspects of FRP are covered in the research to fully grasp the context of the material. The environmental and design aspects will form the outlines of the scope for this thesis and the proposed redesign. The mechanical aspects are looked into during the research to provide an understanding of the principles of FRP, however no mechanical verification of the proposed redesign has been performed.

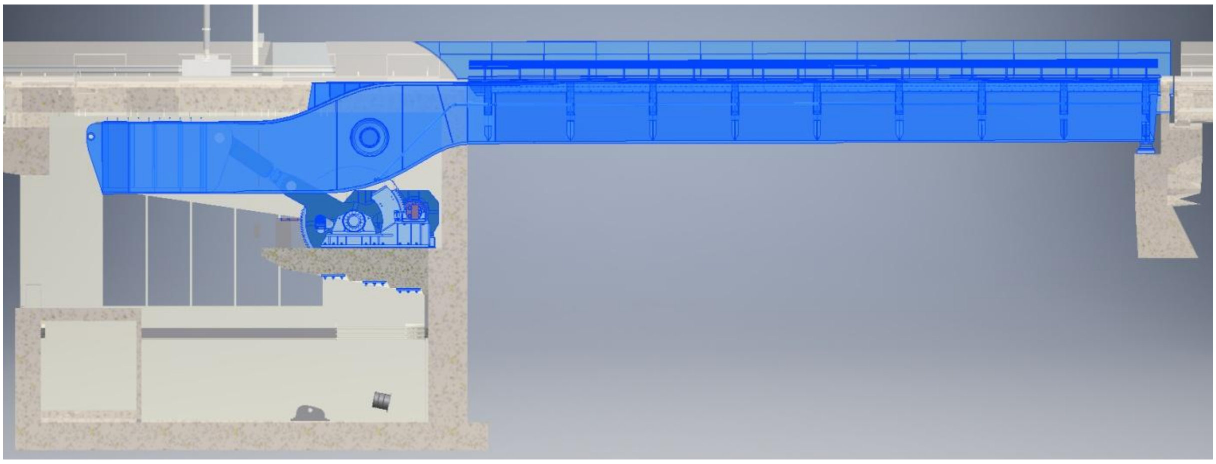


Figure 2.8 – System boundaries, blue components will be subject of investigation.

Limitations

The proposed redesign is not subjected to mechanical analysis due to time constraints and the level of complexity in relation to the graduation domain of Industrial Design Engineering. Instead, the design is focussed on the overall aspects of application of FRP in a movable bridge.

The environmental impact assessments are also based on data gathered from within Movares and available external sources. Some estimations however lead to problems with accuracy. Also considering the scope of the LCA, which comprises the entire lifecycle, not all processes, materials, etc. can be identified fully to make assessments that are perfectly accurate.

3 Fibre Reinforced Polymers

This chapter provides a summary of the research that was done to acquire insights into the different aspects of FRP: mechanical properties, durability, production aspects, etc. The aspects are mainly compared to steel as this is the primary competitor for application in movable bridge design.

3.1 Introduction

Fibre reinforced polymers are a combination of two main constituents: fibres (1) held together by a matrix (2), or in reverse: a matrix (2) reinforced by fibres (1). The fibres generally have high tensile strength and provide strength and stiffness, the matrix protects the fibres from external influences and provides toughness and impact resistance. Together they form a laminate, or composite, that has superior properties than the individual constituents. They come in various shapes and sizes, however two main types can be distinguished.

The first and most widely used type is reinforcement with very short discontinuous fibres, which provides high process compatibility as the fibres can be pre-mixed with the matrix, injection moulded, sprayed up or laid in the form of mats. The fibre reinforcement improves material properties like strength and stiffness, however no precise control exists over the exact placement, density and orientation of the fibres. This category of FRP is mostly applied in consumer and structurally low grade automotive or aerospace products.

The second type of FRP consists of directionally oriented long continuous fibres held together by a matrix. These long fibres can be oriented specifically to create directionally reinforced products. The fibres can either be wound around a mould, pulled through a mould or placed into, onto or around a mould. Multiple layers of fibres are often stacked on top of each other, which are individually called plies. Multiple plies stacked together form the final laminate. Commonly used fibre materials are aramid, glass or carbon fibres. Commonly used matrix materials are thermoplastic and thermosetting polymers. The composite nature of FRP makes it a heterogeneous anisotropic material, which means the material properties are not uniform throughout the laminate and that they are also directionally dependant (see Table 3.1).

Material type	Properties
Homogenous	Uniform composition and properties throughout the material *(e.g.: metals, plastics, glass, ceramics, etc.)*
Heterogeneous	Non-uniform composition and properties throughout the material *(e.g.: composites, wood.)*
Isotropic	Material properties are identical in all directions *(e.g.: metals, plastics, glass, ceramics.)*
Anisotropic	Material properties are directionally dependant *(e.g.: composites, wood and reinforced concrete.)*
Orthotropic (orthogonally anisotropic)	Material properties change along three mutually orthogonal twofold axes of rotational symmetry *(also wood.)*

Table 3.1 – Material property categories

It is interesting to note some structural member compositions in bridge design are also considered orthotropic. A deck consisting of a steel deck plate directionally stiffened with troughs or girders is referred to as an “orthotropic deck”, when the mechanical properties are similar in all directions, it is logically referred to as an “isotropic deck”.

3.2 Application of FRP

When considering the material properties of FRP, it seems to be an excellent candidate for application in civil structures. As laminates generally have a higher strength to weight ratio, superior environmental resistance properties and better fatigue behaviour compared to conventional alloys or RC. However promising the application of FRP might seem, a lot of design concerns and potential risks have to be considered. Design concerns are the failure modes of FRP laminates, of which the most common is delamination. An example of poor design and execution is the Morrison bridge in Portland, US, where pultruded I-beam profiles were used as decking material. Within two years, the I-beam flanges started to delaminate from the webs. Another risk associated with bridges in general is fire. An example is one that broke out in January 2015 underneath the Sloterbrug in Amsterdam, NL. Such a fire underneath or above the deck could have devastating consequences for an FRP deck, sub- or superstructure. Although the material may be fire-retardant, its material properties could degrade beyond the point of no repair.

Figure 3.1 – Sloterbrug, Amsterdam, NL
Fire underneath deck.
Image courtesy: De Telegraaf.

Figure 3.2 – Morrison Bridge, Portland, US
Inside view: delamination of pultruded deck elements. Image courtesy: Multnomah County.

3.3 Fibres

As stated previously, commonly used fibre materials in FRP products are glass, carbon and aramid. Glass fibres are the most used material in structural products due to the required volumes and its properties-to-price ratio. Carbon fibres have significantly higher stiffness, however are also the most expensive. Aramid fibres are generally not used in structural products due to low compression strength which would lead to the fibre buckling before the matrix when subjected to compressive forces.

Fabrics

For most production processes, the fibres are applied in the form of prefabricated fabrics. These fabrics are mainly randomly oriented short fibres or multi-axial stitched continuous fibres. The most common types are displayed in Table 3.2.

Non-woven fabrics		Woven fabrics
Chopped Strand Mat (CSM)	Continuous Filament Mat (CFM)	Woven Roving (WR)
		
Fibre length up to 5 cm	Fibre length up to 1 m	Fibre length more than 1 m

Table 3.2 – Different fibre fabrics

Fabrics generally consist of a single fibre type. However hybrids can also be produced, e.g. a glass woven roving consisting of glass fibres with a directional pattern of carbon fibres.

3.4 Plastics

Plastics are essentially polymers with additives of which there are two main types: thermoplastic and thermosetting polymers. Once these are mixed with additives and eventually polymerised (cured) into their final form, they can respectively be called thermoplastics and thermosets. The most commonly used materials for structural FRP matrices in civil applications are thermosetting cross-linked polymers: vinyl-esters, epoxies and polyesters. Thermoplastics are generally not used for structural design due to one significant disadvantage compared to thermosets: low heat resistance. Thermoplasts melt when heated, where thermosets do not. Although this might seem a significant advantage for thermosets, it poses a significant disadvantage for recycling at the End of Life (EoL) phase. Differences between the two types are shown in Table 3.3.

	Thermoplastic polymers		Thermosetting polymers
	Amorphous	Semi-crystalline	
Polymer bond type	Molecular *(reversible)*		Chemical *(irreversible)*
Morphology	Amorphous	Semi-crystalline	Cross-linked
Glass transition T_g	Yes	Yes	No
Specific T_m	No	Yes	No
Modulus retention (heat resistance)	Low (+/- XX° C)	Moderate (+/- XX° C)	Very good (+/- XX° C)
Volumetric shrinkage	Low	High	Low
Wall thickness transitions	Yes *(low in-mould shrinkage)*	No *(in-mould shrinkage)*	Yes *(very low in-mould shrinkage)*
Impact resistance	High	High	Moderate
Manufacturing	High temperature (+/- 200° C)		Room temperature (+/- 20° C)
Surface finish	Excellent		Good
Eco-friendly	Excellent *(recyclable)*		Moderate *(non-recyclable)*
Process complexity	Moderate		Low
Process control	Easy		Complex
Recyclable	Yes		No
Chemical resistance	Poor	Excellent	Excellent
Creep resistance	Poor	Moderate	Good
Cost	Low	High	Moderate
Market share	80%		+/- 20%

Table 3.3 – Different polymer properties

Additives

Polymers can be mixed with certain additives to improve material properties or to lower the amount of pure polymer for economic reasons. Examples of functions that can be improved by the use of additives are: surface finish, thermal degradation resistance, fire retardancy, fire resistance.

3.5 Bio-based materials

An interesting development concerning the environmental sustainability of FRP composites are bio-based polymer fibres and resins. Bio-based materials should not be confused with biodegradable materials, as the first has a biological origin and the latter decomposes biologically under specific environmental circumstances. The advantages of bio-based materials, is that any allocated CO_2 emissions are compensated by their CO_2 consuming biological origin. Unfortunately, the relevant data required concerning impact assessments is either not readily available or not compatible with common datasets.

3.6 Laminate composition

Fibres held together by a matrix are called a laminate or composite. When dealing with a laminate, the ratios of the used materials are one of the basic factors. Ratios can be defined as weight fraction (wt%) or volume fraction (v%). Logically, the relation between these two fractions depends on the densities of used materials.

Next to the material determination of the specific fibre, polymer, additives and their ratios, there is also the physical composition of the laminate. There are many production processes to combine the dry fibres with the resin and form them into a product. For convenience, the exact method of placing the fibres into, onto or around the mould will for now be generalised and referred to as "placement". Fibres are placed from a spool onto or around a mould, or are placed into, onto, or around the mould in the form of fibre fabric sheets. These sheets are sometimes already pre-impregnated with resin; so called pre-pregs.

Apart from the orientation of the fibres, there are two additional important factors for the mechanical properties: fibre length and fibre-matrix interface. Fibre length is an important factor for final mechanical properties and differs per type of fibre application and production process. Closely linked to fibre length is the fibre-matrix interface: the area of surface connection between the fibre and the matrix. If the interface quality is low, the fibres can only sustain low shear stresses and could move within the matrix under high stresses. High fibre length and high quality interface together lead to high laminate quality. Additional information concerning fibre orientation, Quasi-isotropic (QI) and Unidirection (UD) layup can be found in Appendix 9.4.

Hybrids

FRP laminates can be joined with other materials to achieve even greater product or part efficiency, for example increasing mechanical properties while maintaining low weight. An example of this is the sandwich structure, in which two FRP laminate sheets are adhesively bonded to a core material on the top and bottom. This core material generally consists of lightweight foam materials or vertically oriented shell structures such as honeycombs. This combination is based on the principle of placing the relatively strong material (FRP sheets) as far away from the neutral axis as possible, significantly increasing bending stiffness of the sandwich structure. A sandwich profile example can be seen in Figure 3.3.

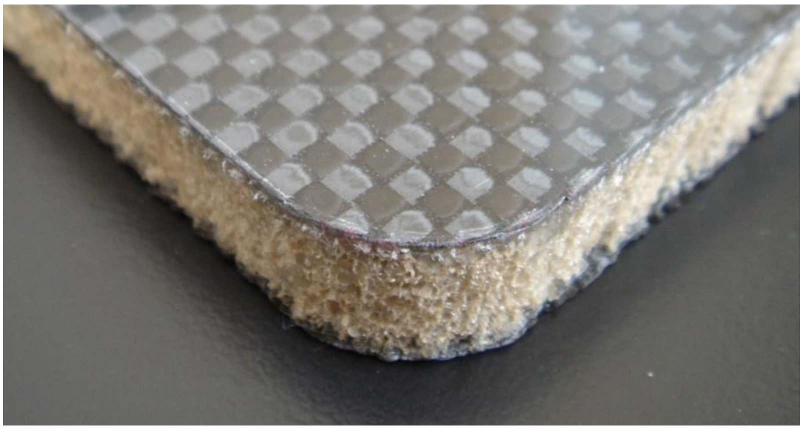


Figure 3.3 – CFRP and foam sandwich hybrid

3.7 Production processes

Production processes can determine whether or not a part or product can actually be produced. This also works the other way around, a specific product or part will determine or require a specific production method. For FRP, a the complexity of laminates and product size have a significant impact on the availability of suitable production processes. There are numerous processes available for fabricating FRP products. The most important aspects for a successful product are precise fibre placement and good resin impregnation of the fibres. For good impregnation, multiple factors determine the success rate: resin viscosity, pressure and flow resistance. These factors vary for all processes, which can be divided in two process categories: open- and closed-mould processes. Table 3.4 summarizes the aspects of both systems.

Closed mould system	Open mould system
✓ Closed system (better management)	✓ Low complexity machinery
✓ Less to no resin vapours (closed system)	✓ Low cost
✓ Faster impregnation (pressure)	✓ Easy to operate
✓ Less bubbles (pressure)	
- Complex system	- Low impregnation (no pressure)
- Sealing (needed due to pressurisation)	- Air bubbles (no pressure)
- Pressure leads to backflow (towards the fibre inlet side of the mould)	- Resin vapours (health concern)

Table 3.4 – Closed- and open-mould process comparison

Several processes, associated mould types, pressures, temperatures and other production aspects are summarized in Table 3.5 and Table 3.6. More information on open- and closed mould production processes can be found in Appendix 9.5.

Process	Process type	Mould type	Pressure		Mould temp.	
			Mould	Injection	T.set	T.plast
Hand lay-up	Open	Single sided	None	None	Low	n.a.
Filament winding		Rotational				
Pultrusion	Closed	Die	None	Medium	Low	High
Compression mld.		2-s	High	None		
Injection mld.				High		
HP-RTM						n.a.
(VA-)RTM		2-s or 1-s + film	Low	Vacuum		
RFI					n.a.	High
Vacuum infusion		1-s + film	None		Low	n.a.

Table 3.5 – Production process properties comparison
***1-s**: single-sided mould, **2-s**: two-sided mould, **n.a.**: process not applicable*

Process	Production				Product	
	Volumes	Automation	Complexity	Cost	Size	Complexity
Hand lay-up	Low	No	Low	Low	Large	Low
Filament winding	Medium	Yes		Medium	Medium	
Pultrusion	High	Yes	Medium	Medium	S-L	Medium
Compression mld.			High	High	Medium	High
Injection mld.				High		High
HP-RTM	Medium		1-s: low 2-s: high	1-s: low 2-s: high		High
(VA-)RTM	Low	1-s: no 2-s: yes				High
RFI						
Vacuum infusion	Medium				Large	

Table 3.6 – Production processes properties comparison
***1-s**: single-sided mould, **2-s**: two-sided mould, **S**: <15cm, **M**: 15-150cm, **L**: >150cm*

Key production aspects

There are several important aspects that have to be taken into account in general design and localised laminate composition. In shaping and moulding the product or part, resin rich zones should be avoided. Because of the lack of reinforcement, these zones are more susceptible to stresses and thus will fail more easily. Crazes or cracks can form locally and propagate into the reinforced zones leading to delamination.

As fibres are placed for reinforcement, the laminate should be optimized to provide maximum strength and stiffness. In some industries such as boat design, a unified laminate composition is used as the general pressures are equal. For structural parts, directional reinforcement laminate is preferred.

Temperature is one of the most important aspects in polymer processing, especially for semi-crystalline thermoplasts. Especially during in-mould cooling; the volumetric shrinkage can lead to local deformations, warping or even buckling of the final product. Thermosets generally do not require specific heated environments, so in-mould or post shrinkage is not an issue.

The temperature consequences for inserts should also be taken into account. Polymer processing temperatures generally do not significantly influence metal inserts, however stress concentrations will occur around the inserts upon cooling as the inserts are less sensitive to the temperature changes. The polymer's volumetric shrinkage and related stress distribution cannot progress through the insert and thus will concentrate around it.

When using high injection pressure either during processing or post processing (curing), its effects should be taken into account. Especially when considering structures susceptible to compression, buckling or collapse such as hollow inserts, foam cores and weak mould parts.

Regardless of the production process, the more complex the system and machinery, the more time it takes to clean, prepare, pre-heat and handle it. This goes hand in hand with the risk of production failure: the larger and more expensive parts or products become, the more attention is required to prevent these risks.

Additional production aspects concerning pre- and post treatment and surface finishing can be found in Appendix 9.6.

3.8 Joining techniques

FRP parts can be joined to other FRP parts or materials to form the final product. There are two main types of joining: adhesive bonding and mechanical joining.

Bonded joints

FRP can be joined to FRP or other materials by the use of adhesives. These adhesives provide a chemical bond between the mating surfaces. The advantages of adhesives are that loads can be transferred over a large area, minimizing localised stresses. The disadvantage is that it provides no mechanical locking by nature, unlike mechanical joints. Mating surfaces can however be designed to transfer loads primarily by their mechanical locking features, and that the adhesive bond ensures this mechanical locking stays in place and is not affected by primary loading.

Mechanical joints

FRP can also be joined to FRP or other materials by the use of mechanical fasteners such as bolts. Although bolting is relatively easy, secure and provides mechanical locking, there are numerous factors that can adversely influence the FRP structure. Bolting either requires inserts or holes in the FRP part. Inserts require more complex production and holes have to be drilled after the resin is cured. There are numerous disadvantages of drilling holes as this also cuts the reinforcing fibres and could lead to delamination due to pressure applied between plies inside the laminate by the drilling tool.[8] Another disadvantage is that stress concentrations will occur around the boltholes or inserts. Pre-stressing of bolts also leads to one of the disadvantages of FRP, as localized creep can occur. If the bolts are however pre-stressed on a steel structure surrounding an FRP part, the bolt only provides mechanical locking and no creep will occur.

When considering a modular approach in design, easy assembly and disassembly is one of the main desired features. It improves production times and also the ability to repair specific parts, sustaining the life of a product. A common method in structural engineering for joining parts is bolting. Unfortunately, two downsides are linked to this technique: reduced rigidity and creep properties of FRP. As bolts are tightened to a certain pretension, this means that if loading forces exceed this pretension, the joined parts can slip or move independently, leading to significantly reduced torsional rigidity. The governing disadvantage of bolting in this case however, is the creep properties of FRP, as the pretension in the bolt connection gradually reduces as a result from creep in the FRP part or parts. Fortunately, if the forces are within tolerances, inserts can be added inside the FRP product or parts which allow bolts to be used after all.

3.9 Mechanical properties

For the calculation and testing of material dimensioning, two limit conditions are determined: the Serviceable Limit State (SLS) up until which the material must perform and stay within its elastic range and the Ultimate Limit State (ULS) up until the material will not shear, buckle or in any other mechanical way fail its purpose. For steel, the yield strength is related to the SLS and the tensile strength to the ULS. However, FRP laminates exhibit linear elastic behaviour. They behave according to Hooke's law, where an applied force F equals a spring characteristic constant k multiplied by the displacement X.

$$F = k * X$$

Equation 3.1 – Hooke's law

This results in FRP laminates exhibiting linear elastic behaviour up until breaking (the ULS). Hence, no yield strength is defined for FRP laminates.

3.9.1 Strength & stiffness

For steel, three main values used in design are the elasticity modulus (E-modulus), yield strength and tensile strength. The E-modulus is the measure of a material's stiffness, determined by dividing an applied stress by the measured elongation. It should be noted that the E-modulus does not determine final product or part stiffness, as this is also governed by the second moment of area of the product or part's cross-section design. The yield strength defines the stress inside the material after which plastic deformation occurs. Tensile strength defines the stress inside the material at which it will break. The yield strength is related to the Serviceable Limit State (SLS) that defines the point up until which the material or product will keep performing within safety limits (e.g. no deformation). The tensile strength is related to the Ultimate Limit State (ULS) that defines the ultimate point after which the material or product will fail.

Volumefraction

The Young's modulus for a laminate E_{FRP} can be determined by adding the constituents' individual E-moduli multiplied by their respective volume fraction, see Equation 3.2.

$$E_{FRP} = E_{Reinforcement} * Vf_{Reinforcement} + E_{Matrix} * Vf_{Matrix}$$

Equation 3.2 – Young's modulus for FRP laminates

It should be noted that for steel, tensile strength is generally not used in design, only for determining failure modes and scenario's. FRP laminates generally do not show plastic deformation, rather exhibit linear elastic behaviour up until the tensile stress point, after which they will break. This means that for FRP, the yield strength is very close if not similar to the tensile strength point.

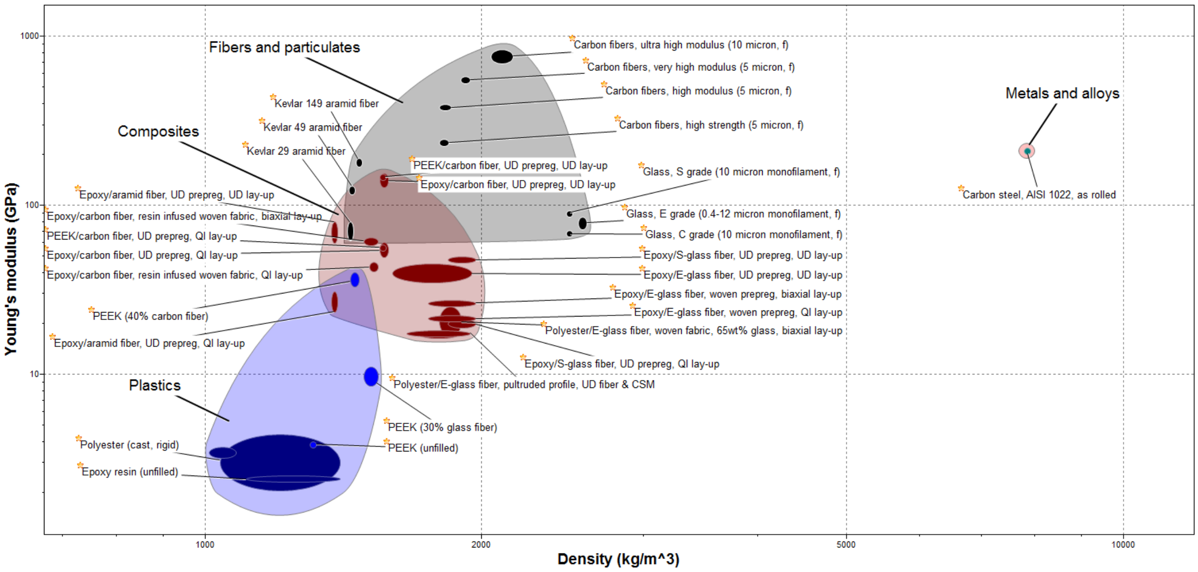


Figure 3.4 – E-modulus vs. Density (Source: CES EduPack 2016)

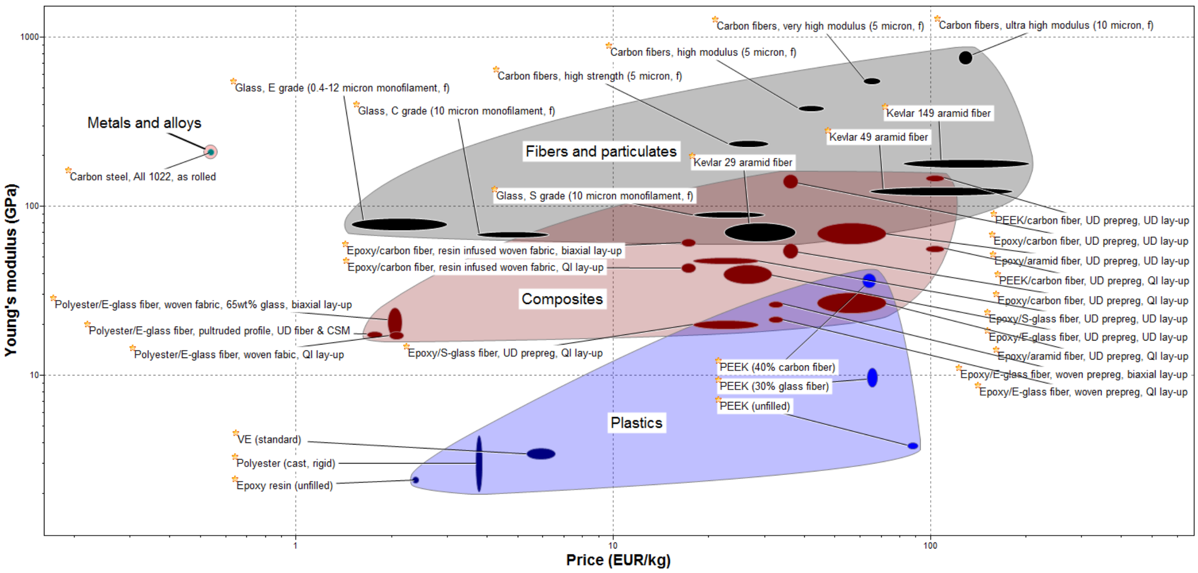


Figure 3.5 – E-modulus vs. Price (Source: CES EduPack 2016)

Figure 3.4 and Figure 3.5 use a logarithmic scale on both axes. They show that although the stiffness of steel is higher than most composites *(210 GPa for steel vs. 20 to 40 GPa for glass filled FRP)*, it is also 4 to 5 times more dense *(7850kg/m^3 for steel vs. 1800 to 2000kg/m^3 for glass filled FRP)*.

The price of FRP composites is however almost a factor 4 higher for glass filled polyester, a factor 40 to 60 higher for glass filled epoxies, a factor 60 higher for carbon filled epoxies and a factor 200 higher for carbon filled thermoplastic PEEK.

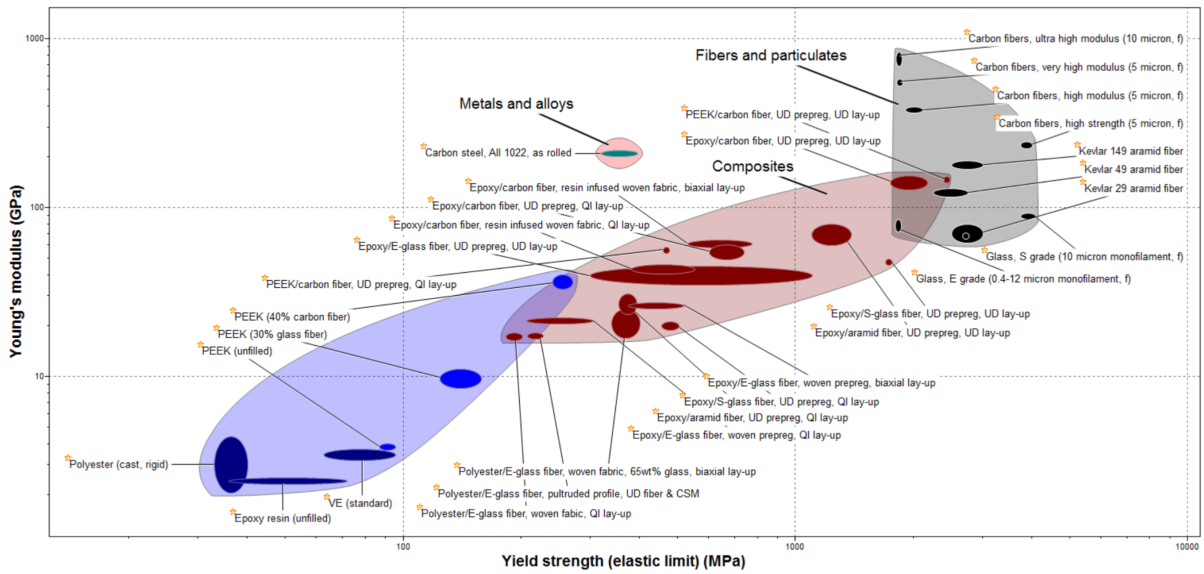


Figure 3.6 – E-modulus vs. Yield strength (Source: CES EduPack 2016)
(Note that for FRP, tensile strengths values are used.)

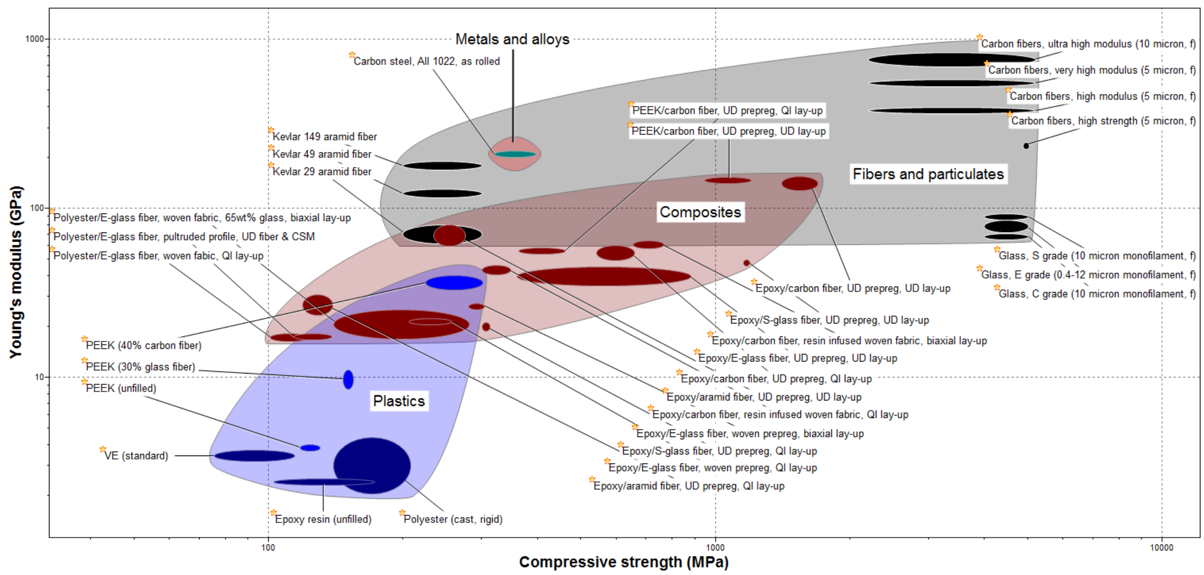


Figure 3.7 – E-modulus vs. compressive strength (Source: CES EduPack 2016)

Figure 3.6 and Figure 3.7 also use a logarithmic scale on both axes. Figure 3.6 shows that although FRP composites' stiffness is lower compared to steel, strength properties reach far beyond those of steel. Figure 3.7 again shows the higher possible compressive strengths feasible with FRP. Note here the low compression strength of Aramid fibres, making them only suitable in tension loading-governed regions of a part or product.

Additionally, it is interesting to note the differences between Quasi-isotropic and Unidirectional reinforced composites, where the latter can be around a factor 2,5 stiffer and up to a factor 7 stronger.

Stiffness	QI layup	UD layup	Ratio
Carbon filled PEEK	55 GPa	150 GPa	2,7
Carbon filled Epoxy	55 GPa	150 GPa	2,7
S-glass filled Epoxy	20 GPa	45 GPa	2,3

Table 3.7 – Stiffness values for different laminates

Strength	QI layup	UD layup	Ratio
Carbon filled PEEK	450 MPa	2500 MPa	5,6
Carbon filled Epoxy	650 MPa	2000 MPa	3,1
S-glass filled Epoxy	250 MPa	1800 MPa	7,2

Table 3.8 – Strength values for different laminates

For comparing steel to FRP alternatives, a conversion factor based on certain property ratios will be used throughout this thesis. This is a simplified representation of how much volume or mass of FRP is required to replace steel. Values used are from Table 3.7 to Table 3.9.

	Steel	FRP	
	S355	Unidirectional (UD)	Quasi-isotropic (QI)
Young's modulus E	210 GPa	47 GPa	20 GPa
Yield strength σ_Y	355 MPa	1730 MPa	480 MPa
Density ρ	7850 kg/m^3	1905 kg/m^3	1905 kg/m^3

Table 3.9 – Material property values of steel and GFRP

R_E = stiffness ratio Steel:FRP-UD

R_σ = strength ratio Steel:FRP-UD

R_ρ = density ratio Steel:FRP-UD

$$R_E = \frac{E_{Steel}}{E_{FRP-UD}} = 4{,}47$$

Equation 3.3 – Modulus ratio

$$R_\sigma = \frac{\sigma_{Steel}}{\sigma_{FRP-UD}} = 0{,}21$$

Equation 3.4 – Yield ratio

$$R_\rho = \frac{\rho_{Steel}}{\rho_{FRP-UD}} = 4{,}12$$

Equation 3.5 – Density ratio

When a certain steel cross-section is substituted for an FRP-UD one, the main structural requirement is that the FRP variant provides equal stiffness and strength. Two factors determine the FRP substitute's stiffness: E-modulus (1) and the cross-section's second area moment (2). As the E-modulus is a fixed material-related value and cannot be altered*, stiffness has to be provided by a different cross-section design. As the E-modulus of FRP is lower by a ratio R_E of 4,47, its cross-section has to become equally larger. To replace steel for FRP, a generalized cross-section substitution ratio is calculated as follows.

For any given cross-section from Figure 3.8, the second area moment I_{yy} is calculated by Equation 3.6. Another approach is to regard the cross-section as thin walled; see also Figure 3.9. The cross-section's second area moment I_{yy} is then calculated by Equation 3.7.

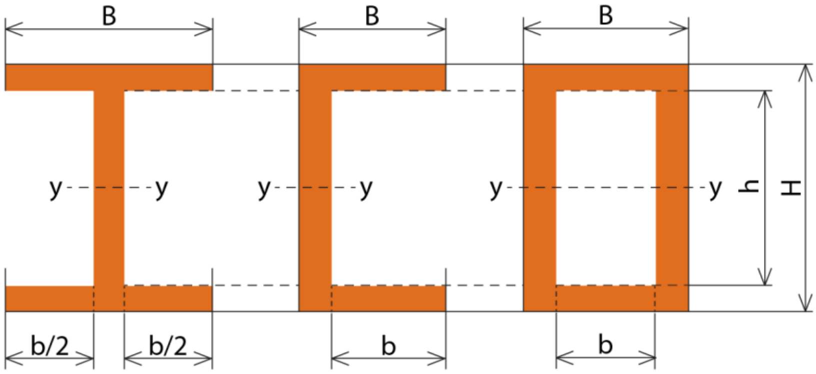


Figure 3.8 – Standard cross-sections

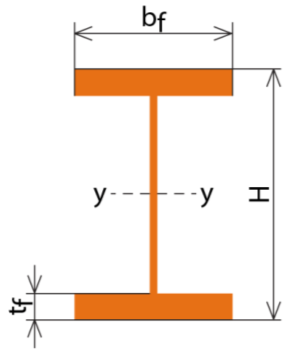


Figure 3.9 – Thin walled cross-section

$$I_{yy} = \frac{BH^3 - bh^3}{12}$$
Equation 3.6 – Standard cross-section's second moment of area

$$I_{yy} = b_f * t_f * \frac{H^2}{4}$$
Equation 3.7 – Thin-walled cross-section second moment of area

First, because the second moment of area in both cases is governed by four dimensions ($BH^3 - bh^3$ and $b_f * t_f * H^2$) the measurement ratio R_M is calculated by taking the 4th root of the modulus ratio R_E. This means that, to acquire FRP stiffness ($E * I$) equal to the original steel cross-section, the individual dimensions of the FRP cross-section (B, H, b and h or for thin walled: b_f, t_f and H) each have to increase by this ratio R_M:

$$R_M = \sqrt[4]{R_E} = 1{,}45$$
Equation 3.8 – Measurement ratio

Second, because the individual dimensions of the substitute FRP cross-section also govern its area, the area ratio R_A is calculated by squaring the measurement ratio R_M, as this ratio is applied in both x-, and y- direction. This means that, compared to the original steel cross-section, the total FRP cross-section area will increase by this ratio R_A:

$$R_A = {R_1}^2 = 2{,}11$$
Equation 3.9 – Area ratio

Third, ignoring the length of the both steel and FRP cross-sections, as the density of FRP-UD is lower than steel by a ratio of R_ρ, the area ratio R_A is divided by the density ratio R_ρ to calculate the final mass ratio R_M:

$$R_M = \frac{R_A}{R_\rho} = 0{,}51$$
Equation 3.10 – Mass ratio

Thus, the mass-ratio R_M for FRP substituting steel is 0,51. This means that, according to the simplified calculation, an FRP construction can be made at almost half the weight of a steel one. This is based on a (mostly) unidirectional laminate and does not take into account additional stiffening such as an improved cross-section (larger distance to neutral axis) or material improvements such as the use of foam cores or even stronger and stiffer reinforcing fibres. For the purpose of this thesis, the substitution ratio R_M will be increased to 0,6 for convenience and to be on the safe side. This means that an alternative FRP design would be 40% lighter than a steel design.

3.9.2 Fatigue

Due to the elastic nature of FRP laminates, they are generally modelled for stiffness rather than strength. FRP's yield strength is also substantially higher compared to steel. In almost all cases, when the product is stiff enough, it is also strong enough. This stiffness driven design of FRP also results in excellent fatigue resistance.[9]

3.9.3 Creep

Time-delayed stress relaxation, or creep, does not noticeably take place in the laminate's fibres. Polymers are however, by nature, very susceptible to creep. Fortunately, as both constituents are combined into a composite, the creep behaviour reduces to acceptable levels. The high strength properties of FRP also prevent creep from occurring in the direction of the fibres. Extreme loads or forces for long durations should be prevented however, as the resulting deformations can slowly deteriorate the interface between matrix and fibres, possibly leading to delamination. This is especially important when considering a bridge's counterweight that is commonly suspended in air.

3.9.4 Damage resistance/toughness

The toughness/hardness of a composite is mainly governed by the matrix, as the fibres themselves are relatively brittle, the matrix has the function of protecting them from impacts and ingress of foreign materials. Thermoplasts offer better impact resistance compared to thermosets, however thermosets are equally suitable for application in structural design. [9]

3.9.5 Thermal properties

Temperature mainly has a direct effect on the matrix. Short-term influences can lead to thermal expansion and are reversible. Long-term influences go along with chemical change and effects are thus non-reversible. Long-term influences are also part of the aging process of polymers.

Thermal expansion

Polymers have different thermal expansion coefficients compared to conventional materials. It is therefore important to take into account expansion margins when combining FRP with conventional materials to prevent dissimilar expansion leading to deformation of the structure. The level of crosslinking in thermosets is one main determinate for the thermal expansion coefficient.

Thermal conductivity

Polymers are generally good insulators, which means they do not conduct heat well. Additives can be added to facilitate better thermal conductivity. Also, when connected or joined to other temperature conductive materials such as metals, the heat transfer can be significantly higher resulting in distribution of temperature over larger areas.

Thermal degradation

If a polymer is exposed to certain high temperatures over a prolonged period of time, this can lead to thermal degradation. The degradation takes place on the molecular level where polymer chains are broken under the influence of heat. Stabilizers can be added to help prevent, slow down and contain degradation.

3.9.6 Failure modes

Where conventional homogenous materials mechanically only exhibit different forms of shear failure, FRP as a composite has multiple mechanical failure modes. Regardless of the cause, the following types are distinguished:

- **Delamination / matrix cracking**: interlaminar cracking of the matrix parallel to *(in between)* the fibres, resulting in separation of plies within the laminate.
- **Fibre cracking**: cracking of fibre perpendicular to fibre orientation.
- **De-bonding**: failure of either the adhesive layer itself or the bonding *(interface)* between other FRP or non-FRP materials *(common issue with sandwich panels due to shear failure of the adhesive layer)*.

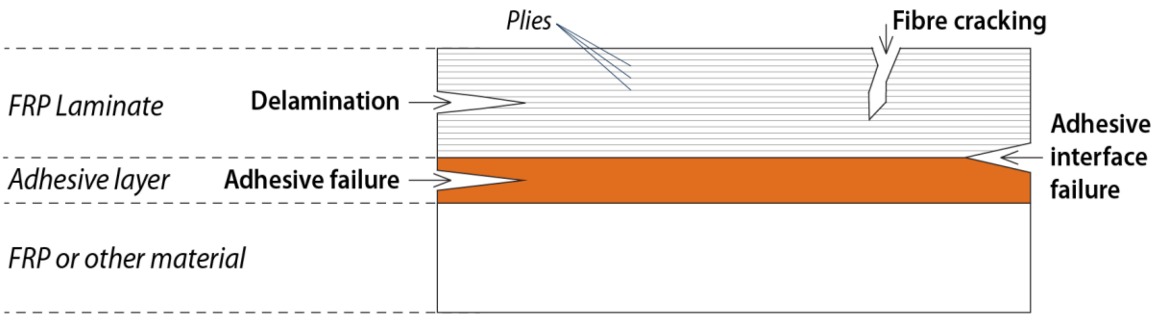


Figure 3.10 – FRP failure modes

Repair

If one of the aforementioned failure modes occurs either from the result of normal or abnormal use (an incident resulting in damage) the localised damage needs to be repaired or an entire part might need to be replaced. When a part is joined to connecting parts by adhesive bonding, replacement is not easy but feasible depending on the local shape complexity. Repair of independent parts in an FRP structure can be regarded both easy as well as difficult. Although a small puncture or localised damage can be repaired relatively easy by patching it using fibres and adhesives, this can only be done for small scale damage or in regions of a part or product where no significant loads and stresses are located. When this is the case however, thorough investigation of the laminate and the resulting impact of the damage is required. Even when damage is small, the detrimental structural impact can still be significant as broken long fibres result in reduction of the strength and stiffness of the overall structure.

3.10 External influences

As a bridge is exposed to the outside environment, there are a lot of factors to take into account in the design phase. Not only for the material selection, but also during design of water drainage and protection from influences that can occur by accident, such as physical damage resulting from a crash or a fire.

Fire

An extreme use scenario concerning temperature conditions is a fire. Unfortunately, the molecular composition of polymers provides the first of the three necessities for fire: fuel, oxygen and heat. The main concern in civil engineering is generally the structural integrity. However in a fire, next to this integrity, there is also the formation of hazardous combustion products, such as toxic fumes. Apart from extinguishing the fire by eliminating the other two necessities (oxygen and heat), it is also possible to mix flame resistant or fire retardant additives into the resin, essentially reducing the "fuel quality". An advantage of polymers is that they generally have good insulating properties, which means the heat from a fire is not transferred directly over a large area or volume, containing the damage resulting from a fire.

During time periods of prolonged high solar radiation and outside temperatures, the wear layer on the road deck surface (whether it be asphalt, epoxy or another type) can heat up significantly. Depending on the thermal conductivity of the wear layer, such heat can be conducted to an underlying FRP substructure. This could influence the mechanical properties of thermoset matrix resins and especially pose a threat to the mechanical properties of thermoplastic resins. Mechanical properties of fibres within the matrix are not significantly affected by high outside temperatures.

Especially in case of fire, the heat consequences are a main reason for the industry not to apply thermoplastics in structural design. Several manufacturers that were consulted stated that however the recycling advantages of thermoplasts offer a significant benefit, the same underlying property enabling this recycling also poses a risk that is deemed to great in case of fire.

UV-radiation

As many products are also used or in this case are permanently placed outdoors, they are exposed to sunlight. Among other wavelengths, the sun emits UV-radiation that over time can degrade the quality of certain matrix polymer materials. Fibres are less susceptible to UV-radiation as the polymer matrix surrounds and protects them. The polymers can be protected by the addition of UV stabilisers to the matrix resin or by adding a UV-resistant gelcoat during production. Gelcoats and paint layers are almost always added to prevent permeability. Even then, the sunlight would only penetrate the first millimetres of the product or part, not influencing the inner structure.

Permeability & chemical resistance

As stated, FRP laminates are generally protected by a layer of gelcoat, preventing the ingress of foreign materials. This reduction in permeability of the laminate increases the resistance to chemicals that either come into contact with the surface or penetrate the laminate. Possible chemicals are water, de-icing salts, alkalis, acids, bases, solvents, fuels and oils.

3.11 End of Life

As FRP is a heterogeneous material by nature, it should be separated to be brought back to the constituents virgin state. For thermoplastics, this can be achieved by subjecting the product or part to high temperatures, after which the reinforcement fibres can be extracted from the viscous matrix resin. Unfortunately, this process is not available for thermosets. The current state of art concerning the recycling of thermoset FRP consists of four main processes: energy recovery by incineration, mechanical recycling through powder aggregation, thermal recycling through pyrolysis and chemical recycling using solvents.

Energy recovery

This is a common EoL scenario for many materials and waste types. The materials are incinerated which results in a combustion reaction yielding heat that can be harvested for generation of energy. This process is not considered recycling, as it results in a complete loss of the material and its valuable properties.

Mechanical recycling

Powder aggregation is one of the main mechanical recycling methods used for FRP. The product of part is simply structurally broken down into smaller pieces or even ground to fine powder. This results in a total loss of mechanical material quality. The only purpose left for the recyclates is to be used as a filler in concrete or other plastic parts or products.[10] Although the recyclates can provide significant value for reuse as a filler in concretes, the major mechanical quality of the original laminate is completely lost.[11]

Thermal recycling

Thermal recycling is done through the process of pyrolysis,;where the material is placed inside a highly heated environment with an inert atmosphere resulting in decomposition of organic molecules, not affecting the fibres, which can then be extracted.[12]

Chemical recycling

Chemical recycling involves the dissolution of the matrix resins using chemical solvents, after which the fibres can be extracted. However the fibres extracted using this method can preserve high value[12], this method requires additional chemicals and ends up with a mixture of chemically solved (contaminated) resin.

3.12 Material summary

When considering application of FRP in movable bridges, the mechanical, environmental and production aspects reviewed in this chapter together form the most important aspects to consider when a part or the entire bridge is to be made from FRP. The application of FRP can be regarded interdependent either top-down or bottom-up from the tree diagram in Figure 3.11. Design is almost always governed top-down: the part's shape and function determine the type of FRP application *(shell, structural profile or a hybrid)*, the type determines the production process *(e.g. vacuum infusion or pultrusion)* and the production process determines the constituent types, compositions, ratios and layups. However, in the first stages of design when the product or part shape are not yet determined, the design can also be driven bottom-up.

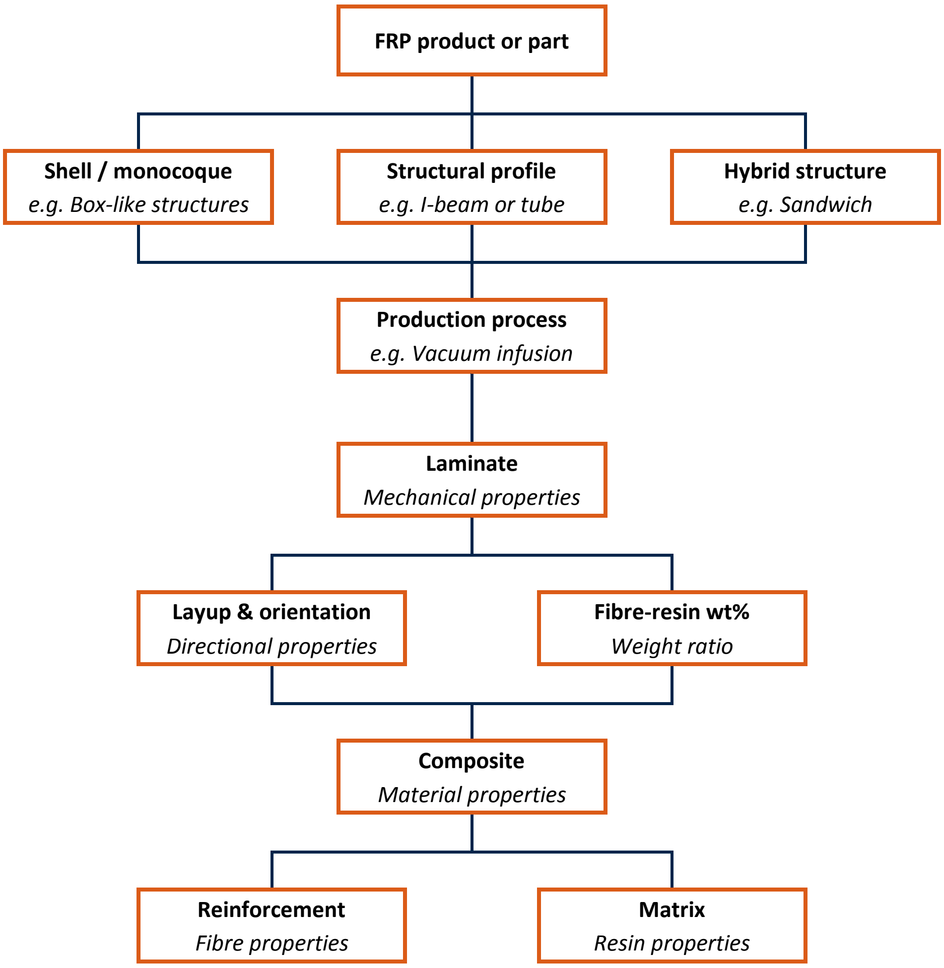


Figure 3.11 – FRP application interdependency tree diagram

4 Product improvement design

The advantages and disadvantages of the material have been explained in the previous chapter. For a movable bridge design in FRP however, there are more factors involved than merely the material's properties and its manufacturing aspects. Some factors that can be expected with an FRP redesign when compared to the current steel variant are: reduction in weight *(easier transport and installation)*, reduced maintenance *(less cost & downtime)*, increased form freedom *(alternate designs)* and the possibility of reuse *(due to the durability of FRP)*. This chapter proposes a design alternative for the leaf of the bridge out of FRP and its operating mechanism. The main feature of this redesign is to enable repurposing of the leaf, prolonging its lifespan.

4.1 Design objective

As stated previously in the aim and objectives, the scope of the FRP redesign is limited to the leaf and its operating mechanism. After exploring several design improvement options, the choice was made to design a leaf that eliminates the needs for a trunnion and bascule basement and that can eventually be repurposed. This effectively eliminates the need for complex connections with the trunnion, extensive labour and material use for the bascule basement. Additionally, when reused, the EoL stage is postponed, significantly increasing the lifespan. The main reasoning behind this choice are the durability and fatigue performance of FRP, both enabling this lifespan. The goal was therefore to design a leaf that is suitable for application in the Amaliabridge case study, but also in different scenario's, so that after decommissioning for reasons not related to the mechanical properties of the leaf, it can be repurposed elsewhere.

Function

The main function of the current Amaliabridge is to provide a four-lane road passing over a 26,5 meter wide waterway for 100 years. An additional requirement is that this road deck can be displaced sufficiently to allow large vessels to pass the road-waterway crossing, effectively meaning that in opened state, the bridge needs to provide unlimited waterway clearance.

The original design is due for replacement after 100 years. However, due to the durability and long lifespan of the proposed FRP variant, the required lifespan is increased to 200 years, meaning that the current Amaliabridge would have to rebuilt once, and the FRP variant could last the required lifetime.

Due to the long four-lane transversal span of the Amaliabridge that could result in excessive deflections of an FRP deck variant, the redesign consists of two separate independently operated two-lane leafs instead of the current Amaliabridge's single four-lane leaf. The requirements can now be translated to a product description essentially similar to that of the Amaliabridge: two 26,5 meter two-lane movable bridges with a 200 year lifetime and unlimited waterway clearance in opened state.

Target group & users

Form a functional perspective; the target group primarily consists of the road and waterway users, consisting of all sorts and weights of automobile traffic and waterway traffic. Secondary users can be considered the owner and or operator, as they also use the bridge by operating and maintaining it. For all these users, the primary requirement is safe and proper operation so that passage can be guaranteed for both parties.

Stakeholders

Multiple stakeholders are involved in a project like the Amaliabridge. Short term stakeholders are engineering firms and contractors responsible for design, manufacturing, installation and maintenance. Long term stakeholders are those that are dependent on proper operation: the client, users, businesses and residents in the vicinity of the bridge.

Short term stakeholders require proper design, careful planning, streamlined cooperation and a safe working environment during their activities. For the long term stakeholders however, durability and guaranteed safe and proper operation are most important during the bridge's lifecycle. Additionally, aesthetics and environmental impact can play a role in design selection by the client.

For Movares, an adequate business perspective is also required, as otherwise the design's implementation would offer no benefit. The main perspectives of the redesign are its durability, design simplicity, aesthetics and reusability. These perspectives eventually have to be translated into unique selling points for the client. These each have to be related to the Lifecycle Costs (LCC), as this is mostly the dominant decision factor.

Environment

The environmental impact of the design should be significantly lower due to the material's durability and the long lifespan enabled by the design, especially when it is used for as long as possible. The associated impact assessment results are presented later in chapter 5.

Requirements

Any bridge design has a certain set of prerequisites and demands stated in the SOR. The main requirements used for the FRP redesign of the Amaliabridge are stated below:

- Minimal waterway obstruction in closed state
- Unlimited height clearance in opened state
- Slenderness *(low sub/superstructure and deck height to length radio)*
- Stiffness *(minimal deflection in both longitudinal and transverse direction)*
- Lightness
- Overall energy and labour reduction *(environmental impact reduction)*
- Durability *(resistance to corrosion and fatigue and reduction of maintenance)*
- Sustainability *(environmental impact reduction)*

Some of these prerequisites, such as stiffness and lightness are not verified in the final design, due to the scope of the project and the main focus being the reduction of its environmental impact.

4.2 Analysis

When the bridge is operated, the leaf of the bridge will move, during which it will be rotated or translated in such a way that directions of dead loads and forces could drastically change. The centres of gravity of the deck and counterweight relative to the point of rotation could also affect the balance of the leaf. To analyze these transitions in loads and forces, an operation type has to be determined first to analyze the specific open/close scenarios. The six main operation types of movable bridges are shown in Table 4.1, together with their (dis-)advantages.

	Translation	Rotation
X-axis *(parallel to road direction)*	*(Retractable bridge)* - Two translations required: first lifting in Z-axis, then moving in X-axis.	*(Tilt bridge)* - Limited waterway clearance
Y-axis *(perpendicular to road direction)*	*(No practical use)* - Does not take away leaf obstruction.	*(Bascule bridge)* + Favourable as the deck moves up into "free space"
Z-axis *(vertical, up from the XY-plane)*	*(Lifting bridge)* - Limited waterway clearance	*(Swing bridge)* - Large space requirement in XY plane

Table 4.1 – Movable bridge operation types

As can be seen in Table 4.1; the tilt and lifting bridge do not provide unlimited height clearance for waterway traffic and are therefore unsuitable. The retractable bridge is less attractive due to the double translation required and corresponding operation mechanism complexity. Considering the length of the bridge (26,5 meters), the swing bridge would require a very large area on the abutment. The bascule bridge has the greatest advantage of all types: moving the deck up into the free space. The counterweight and operating mechanism are often placed in a bascule basement under the road surface, which can also be regarded as free space. The basement does however require excavation and extra construction efforts, which account for almost half the design and engineering efforts.

Bascule bridge components

A bascule bridge consists out of different components. It can be regarded as a fixed bridge, with two main differences: a part of the bridge deck can rotate about a rotation axis perpendicular to the road direction (Y-axis). The **sub- or superstructure** supporting the **deck** and **counterweight** together are called the **leaf**. The front end of the leaf that is lifted up and away is called the **toe**, the back end of the leaf is called the **heel**. The point of rotation and the toe are supported on either side by the **abutments**.

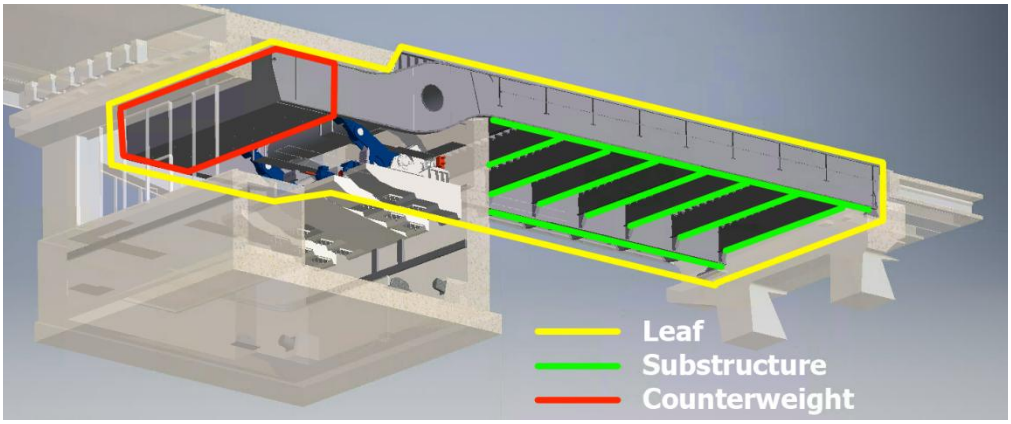


Figure 4.1 – Bascule bridge components

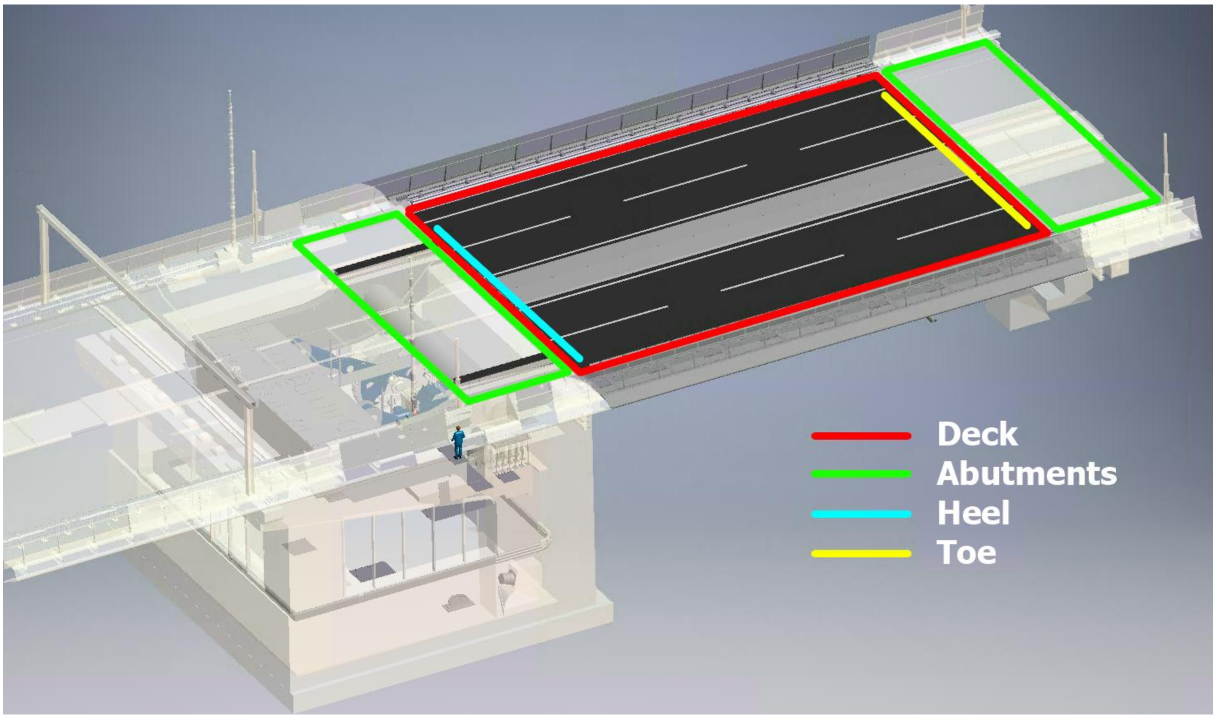


Figure 4.2 – Bascule bridge components

Bascule bridge types

There are two main types of bascule bridges: a trunnion and rolling type. The Amaliabridge is an example of a trunnion bascule bridge, which has its counterweight attached rigidly to the main load bearing girders with a trunnion shaft perpendicularly in between, resting on bearings that are fixed to the abutment. The leaf is connected to a mechanical operating mechanism that allows for rotation of the leaf around the trunnion (Y-axis). The counterweight is generally placed underneath the road deck in a bascule basement behind the abutment.

A rolling bascule bridge has a curvature in its main load bearing structure, over which the leaf rolls back and forth. Both mechanical as well as hydraulic operating mechanisms can be implemented, however no trunnion is required, as the structure already allows for rotation by rolling. An important aspect of a rolling bascule bridge is alignment; as the structure should not deviate from its predefined rolling path. Advantages are the design's simplicity, the absence of a trunnion and bascule basement and relative low maintenance. Another advantage is that as the leaf rolls backwards, it also translates in this direction, clearing the waterway. A significant disadvantage is the safety concerning the rolling motion; as objects, animals or humans can be crushed underneath the rolling structure. The risks associated with this disadvantage can be minimized however, using proper design and appropriate preventative measures.

During operation of both bascule bridge types, their dead weight forces will be transferred to the the point of rotation, resulting in high stress concentrations. When using a trunnion as a rotation axle, the problem will be connecting the FRP structure to this trunnion. As these forces will have to be transferred through this connection over to the bearings into the fixed environment, it is deemed as the weakest point in an FRP design. Hence the choice was made to eliminate the need for a trunnion in the redesign the Amaliabridge into a rolling bascule bridge type.

4.3 Design

The redesign is of the rolling bascule type, based on its advantages mentioned earlier. The main load bearing structure is made entirely out of FRP, with only a stainless steel rolling surface to minimize local wear and an internal counterweight made from heavy concrete or steel. The leaf's deck is placed in between the two main load bearing girders and inserted in slots inside the girders. This design requires only minimal modifications on both the abutments compared to the current Amaliabridge. The only main requirements are a rolling surface with adequate foundations, and sufficient clearance of the abutment's deck for the bridge's rolling motion.

Figure 4.3 – Artist impression of the bridge in an urban environment

Figure 4.4 – Artist impression of the bridge in opened "rolled back" state

Figure 4.5 – Front view of the bridge in closed state

Figure 4.6 – Side view of the bridge in half opened state

Figure 4.7 – Rear view of the bridge in open state

Operating mechanism

The operating principle of opening the bridge is by rolling the leaf backwards over its two main load bearing girders, each with a curved rolling face on the back side with an 8 meter radius and a stainless steel curved gear rack attached locally, following a matching linear gear rack mounted on the abutment. The rolling motion is enabled by pushing the deck upwards using two hydraulic cylinders attached to each leaf.
The rolling surface is placed lower than the road surface to allow greater structural freedom (height) of the girders to support the deck. This also prevents animals or humans from coming in the vicinity of the rolling track, which is dangerous during operation.

Enabling movement of the leafs requires several components. For the current Amaliabridge, a mechanical operating mechanism is used, where an electric motor powers a reductor gearbox, in turn moving the gear mechanism attached to the leaf. For the redesign however, a hydraulic system is used, where pumps power hydraulic cylinders directly connected to the abutment and the leafs. In closed state, the cylinders are covered by the deck to protect them from rain, dirt and other contaminants that can induce degradation. They are placed between the main girders, see Figure 4.8, so that they do not form an additional obstruction of the waterway.

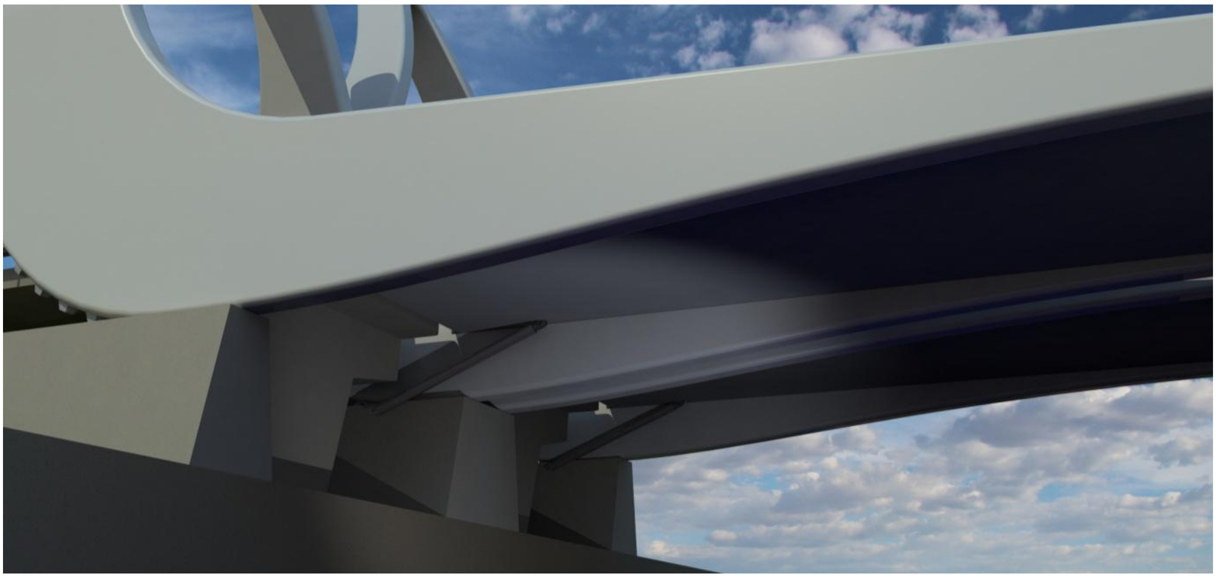


Figure 4.8 – Placement of hydraulic cylinders

The multiple components of a hydraulic operating system are shown in Figure 4.9. According to Dutch regulations, hydraulic systems have to be reconditioned every 25 years. This generally requires reconditioning of the hydraulic cylinder, valve systems, oil reservoirs and filters.[13] This interval is twice as short compared to a mechanical operating system, which has to be reconditioned every 50 years. However, next to the lower amount of labour and parts that need to be reconditioned in a hydraulic system, a significant advantage of this design is that both hydraulic systems can be reconditioned one at a time.

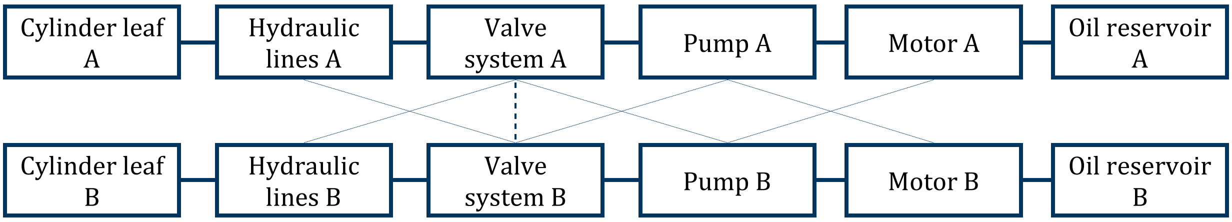


Figure 4.9 – Hydraulic operating mechanism

Another significant advantage of having two hydraulic operating systems is redundancy. If the motor, pump, or valve system of one of the leafs fails, the other can take over its function, preserving operation at half the normal speed. Interconnections are visualised in Figure 4.9; the dashed lines represent the alternative routes in case of failure of one of the main components.

Alignment

As stated previously, the bridge's rolling motion is guided by two matching gear racks. The teeth of the curved rack are shaped in the form of a square pyramidal frustum, see Figure 4.10. This shape provides alignment in both x- and y-direction.

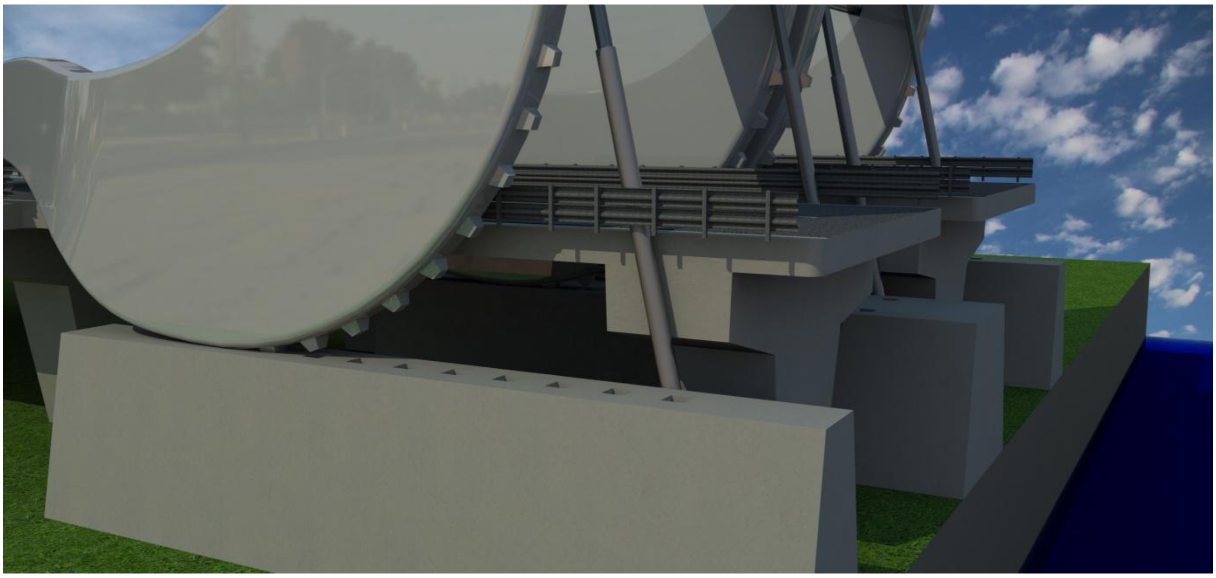


Figure 4.10 – Leaf alignment

Static analysis

During operation of both bascule bridge types, their dead weight forces will be transferred to the point of rotation, resulting in high stress concentrations. When using a trunnion as a rotation axle in an FRP deck design, the problem will be connecting the FRP structure to this trunnion, as these forces will have to be transferred through this connection over to the bearings into the fixed environment. This connection is deemed as the weakest point in such a design made from FRP. Therefore the choice was made to eliminate the need for a trunnion and redesign the Amaliabridge into a rolling bascule bridge type.

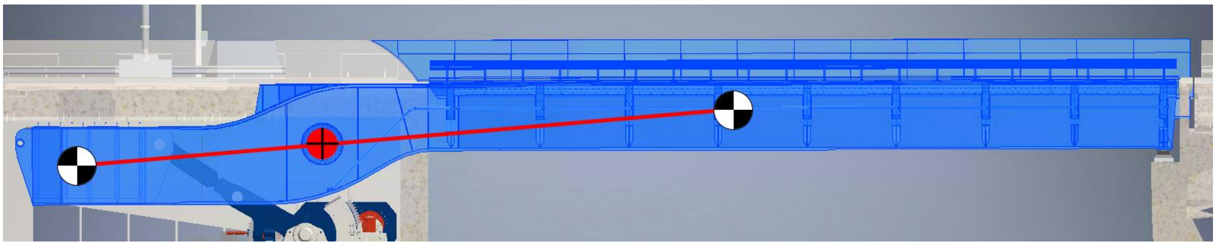


Figure 4.11 – Balanced centres of gravity in trunnion bascule leaf

Figure 4.11 shows a significant advantages of common trunnion bascule bridge leaf design: the centres of gravity of the deck and counterweight have a merged centre of gravity at the point of rotation. This results in an ideal balance of the leaf, requiring little energy for operation during no-wind conditions. For a rolling bascule basement, such balance can also be achieved, however requires a large spanning structure of the counterweight. One of the detrimental mechanical behaviours of FRP could prohibit this type of design: creep. When the counterweight is placed too far from the rotation point, gravity is constantly exerting a downward force that could result in permanent displacements over time. To overcome this problem, the counterweight is placed vertically close to the point of rotation, as can be seen in Figure 4.12.

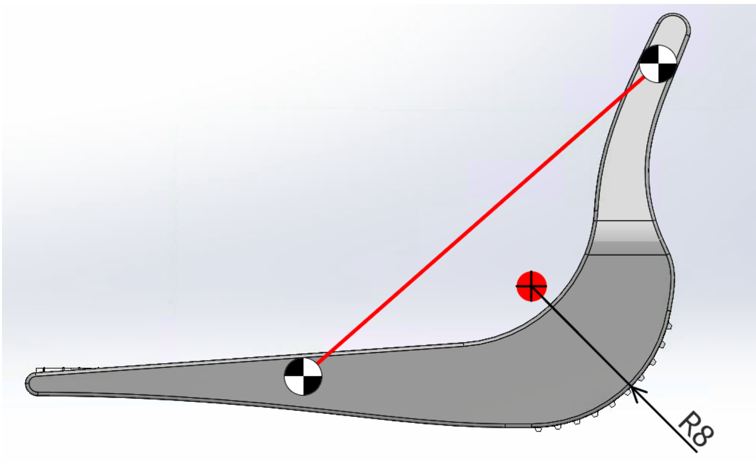


Figure 4.12 – Centres of gravity in rolling bascule leaf

Dimensions

The main load bearing structure is 25 meters high, 36,5 meters long and 11,5 meters wide. The deck of inside the leaf is 26,5 meters long and 10 meters wide, supporting two traffic lanes.

Balancing

The bridge is balanced using a counterweight that is incorporated inside the FRP load bearing structure. The two load bearing side structures join in the top of the leaf, providing rigidity for the overall structure preventing torsion and independent horizontal displacement of the main load bearing girders, which could lead to unnecessary and unwanted bending forces and displacement of the deck.
Originally, during the design process, an idea was to use water as balancing weight. As FRP is insensitive to corrosion, water could be pumped between different sections or pumped inside the leaf from outside. Unfortunately, for a bridge of this length (and corresponding weight), the weight of the deck and its distance to the point of rotation is too large compared to the weight of the counterweight and its relative small distance to

the point of rotation. This would lead to an immense required volume of water, since its density is just 1000 kg/m^3 versus common ballast materials such concrete (up to 3000 kg/m3) and steel (7850 kg/m3).

Safety

One significant disadvantage of this concept concerning the rolling principle is safety. Objects, humans or animals could be crushed by the rolling leaf underneath the main girders in opening or closing operation. The accidental presence of objects, humans or animals can never be ruled out, however preventative measures can be taken to minimize the risk. Fences and additional obstructing barrier design can ensure nothing large could be placed or present on the rolling track of the leaf. Sensors can also be added that can prevent operation if objects larger than a certain size are detected on the rolling track that are deemed significant or dangerous for safe and proper operation. Naturally, the appropriate safety and warning signs have to be placed to alert people and personnel of the potential dangers during operation.

4.4 Production

The main girders will be produced through vacuum infusion (VI). This process is currently also being used by manufacturers of large FRP products (primarily concerning bridge decks). VI requires a fair amount of manual labour, preparing the vacuum bags, lines and seals, placing the reinforcement fibres and foam cores and eventually infusing the matrix resin. Due to the sheer size of the girders, automated production is not economically viable, as it would require tremendous effort in engineering machines, only to be used for a very small production run. One significant disadvantage of manufacturing large parts such as the girders is that if a production failure occurs during the early stages of fibre layup or resin infusion, consequences can be very costly, possibly requiring disposal and manufacturing of a new part.
The modular ASSET profiles are produced through pultrusion, enabling mass production while ensuring a very high part uniformity and quality. Another significant advantage is that parts can be tested first before starting large production batches.

Joining

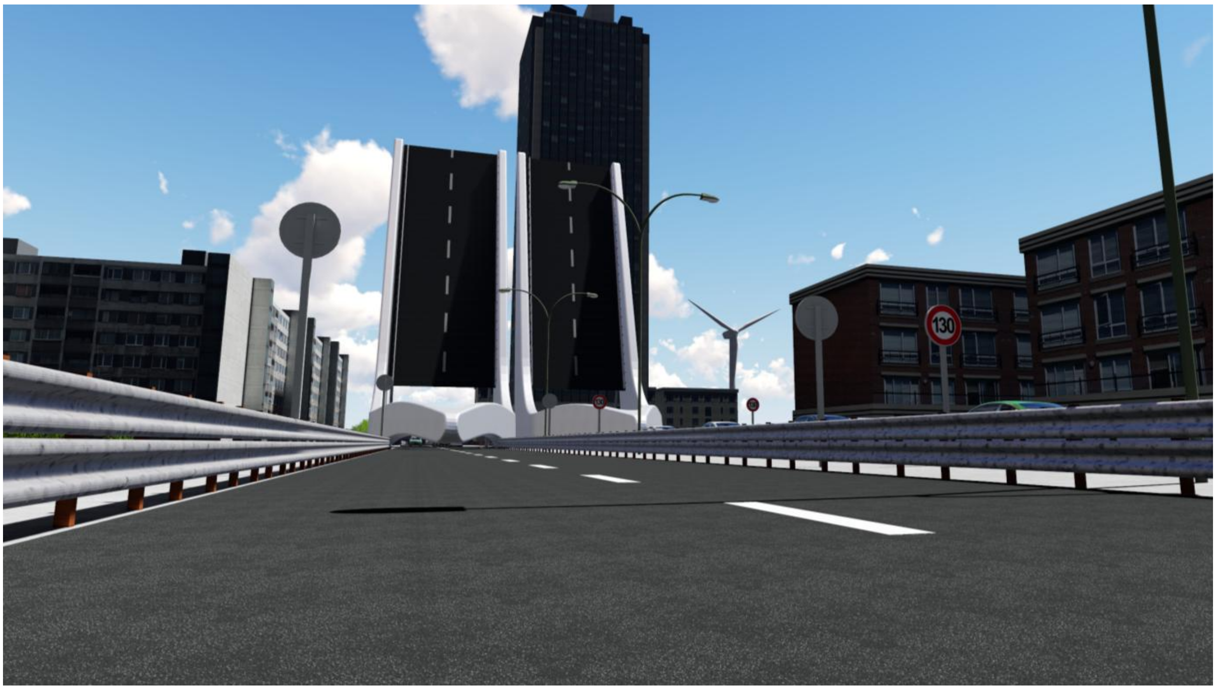
Adhesives will be used in this design to join both the ASSET pultrusion elements together to form the deck and respectively joining the deck to the main load bearing girders. It is important to note that when connecting the deck to the main girders, a large area is connected in one production step, requiring a proportionally large amount of adhesive that has to be applied to both surfaces and connected before it cures.

Repair

As explained previously in chapter 3, repair of FRP can be both easy and challenging. Small superficial damage can be repaired by patching the local area with new fibre mats and resin. However; if the leaf sustains large structural damage due to ships, cars or trucks colliding with the main load bearing structure, the damage could extend beyond possible repair, as broken fibres result in significant material property degradation. Proper measures should be taken to minimize collision risks with road traffic, such as guardrails. For waterway traffic however, moving perpendicular to the structure, collision prevention is not that simple. However this issue is present in all bridges, additional study to the repair options for FRP would be advisable when considering the proposed design.

4.5 End of Life

The main drivers for the proposed design are its operation simplicity and the possibility of repurposing. In the face of sustainable performance of the bridge related to its main material FRP, both the material and the bridge's design should allow for a long lifespan. The bridge requires minimal adaptations from its environment: only matching abutments, a rolling track and a hydraulic operating mechanism. Not only does this minimize construction times during initial installation, but also in the case of repurposing.



5 Environmental impact analysis

In this chapter, the environmental impact of the currently in-service steel variant of the Amaliabridge is compared to that of four FRP variants. First, an introduction is given concerning the subjects of sustainability and related concepts. Followed by an explanation of the impact assessment setup and analysis of the acquired results.

Durability

A product's durability can be regarded as a relation between the product lifespan and the product's performance during this lifespan. High durability can be defined as a long lifespan with a constant performance level. Low durability can either be a long lifespan with a degrading performance level, or a low lifespan with constant (or also degrading) performance level. When considering the demands for a bridge, both the lifespan and the performance level demand for a product with high durability. The schematic in Figure 5.1 is adopted from the SBRI report on sustainable bridges and depicts a summarized view of a bridge's lifecycle with factors influencing its durability. [3]

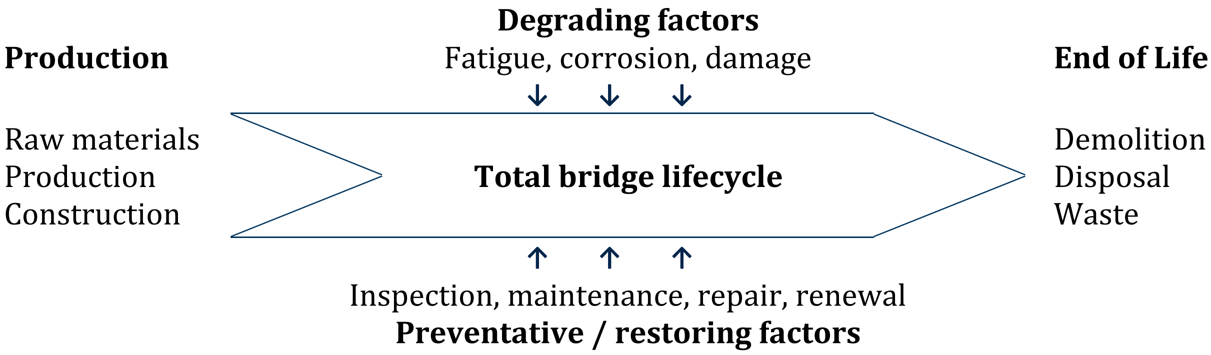


Figure 5.1 – Summarized lifecycle schematic of a bridge

Sustainability

A product's sustainability is closely related to its environmental impact, determining to what extent its entire lifecycle either adversely, neutrally or positively influences its environment. The United Nation's Brundtland Commission states the following about sustainability:

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

This definition of sustainability considers three categories of consideration: environmental quality (1), economic quality (2) and social and functional quality (3). For the outline of this thesis, only the environmental quality will be assessed for different design variants. Their individual environmental impacts will be assessed by performing a Life Cycle Assessment (LCA) for each variant.

Circular Economy

Closely linked to sustainability is the concept of the circular economy, which aims at keeping products, components and materials at their highest economic value and lowest environmental impact for as long as possible by designing for long product life and by looping back used products, components and materials into the economic system through repair, refurbishment, remanufacture and recycling. Although this might sound like an utopia, it is not as unfeasible as it seems. The only factor refraining society from fully embracing the circular economy is the economy itself. For a lot of materials, virgin sources are cheaper compared to recycled sources. Some well-known exceptions exists however, such as glass and metals, for which the recycling process is either relatively easy or for which the price of mining, refining, processing or synthesis far higher than recycling. Unfortunately, price is still one of the governing factors in product design when choosing for virgin or recycled sources, and when designing for long product life.

This circular design approach is also incorporated in the redesign from chapter 4; by mainly using a durable material in a product designed for reuse. As FRP's durability and excellent fatigue behaviour enable a long product life and the design enables eventual reuse, high economic value and lower environmental impact of the EoL phase are achieved.

5.1 Subject

The subjects of the environmental impact assessment in this thesis are: the current in service steel Amaliabridge, one variant where the steel troughs and deck are replaced by a modular thermoset composite system and three variants where the entire bridge is redesigned completely to better suit the application of FRP using both thermosetting and thermoplastic resins. For the thermoplastic resin variants, both energy recovery by incineration and recycling are modelled for their EoL scenarios. For the three all-FRP variants, the rolling bascule redesign concept from chapter 4 is used for the analysis, excluding the bascule basement.

Variant	Abbreviation	Description
Steel	**ST**	Original steel variant, including bascule basement
Hybrid	**HY**	Steel variant with thermoset modular deck, including bascule basement
Thermoset	**TS**	Thermoset rolling bascule variant, excluding basement
Thermoplast	**TP-I**	Thermoplast rolling bascule variant, excluding basement *(Incinerated)*
Thermoplast	**TP-R**	Thermoplast rolling bascule variant, excluding basement *(Recycled)*

Table 5.1 – Variants subjected to LCA and comparison

Although thermoplasts are deemed unfit for use in bridges altogether due to their poor resistance to high temperatures in case of fire, they are included in this analysis to provide insight whether or not their application should be further investigated for (movable) bridges.

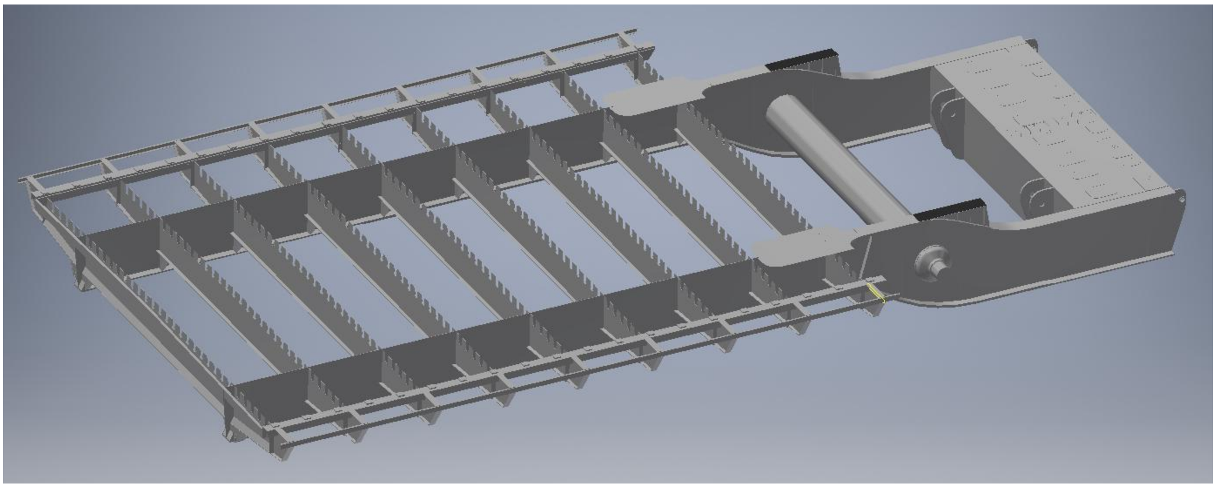


Figure 5.2 – Steel substructure of hybrid variant

Figure 5.2 shows the remaining substructure of the hybrid variant, of which the steel throughs and deckplate have been removed and are replaced by an ASSET FBD600 thermoset composite system by Fiberline Composites A/S. The weight of this replacement deck has been calculated and used as input for the LCA.

Figure 5.3 shows the foundations that have been constructed for the current Amalia-bridge. For the scope of this analysis, these foundations are not taken into account, however it should be noted that the redesign will require less foundations than the original design.

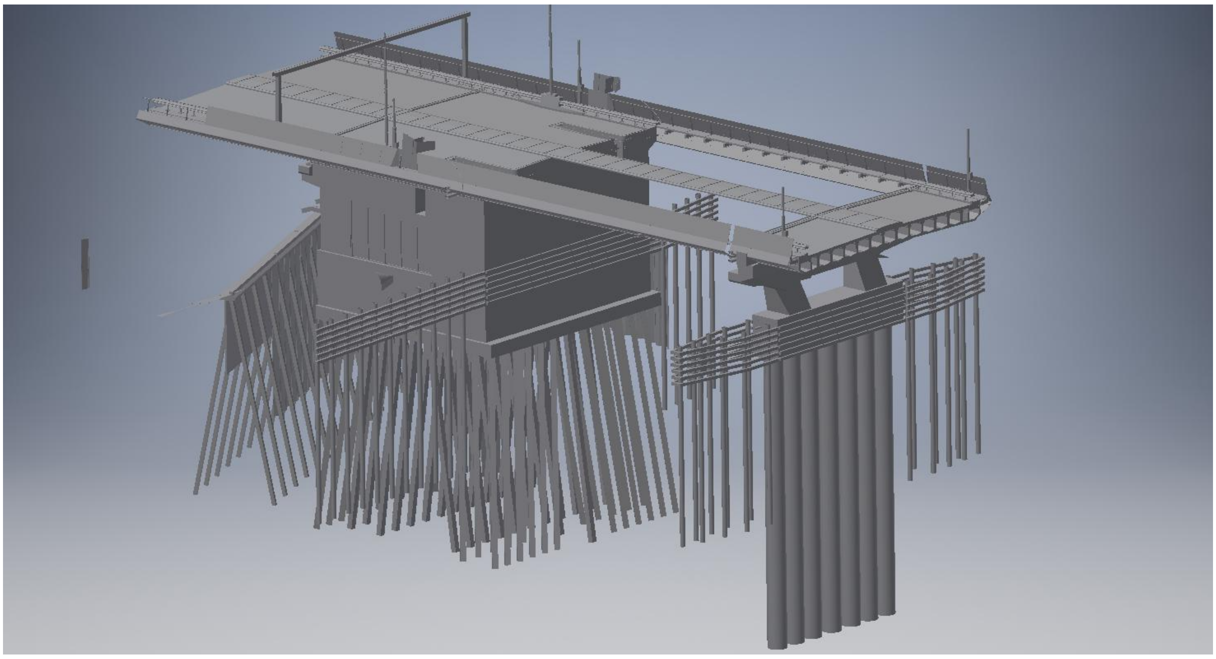


Figure 5.3 – Foundations of Amaliabridge abutments and bascule basement

5.2 Life Cycle Assessment

In an LCA, first the goal and scope have to be determined. After which all the materials, processes, forms of energy and generated wastes that are required or generated during a product's lifecycle have to be identified. These form the input data for an impact calculation, which is based on so-called Life Cycle Inventory (LCI) data: representing environmental impact scores of the input data. The combined impacts of all the inputs can be added up and aggregated using an LCA weighting method, which allocates weighting factors and aggregates certain values into specific damage categories (midpoints). After the results are weighted, they have to be interpreted to form a conclusion. In Figure 5.4, these steps are visualised in the LCA framework.

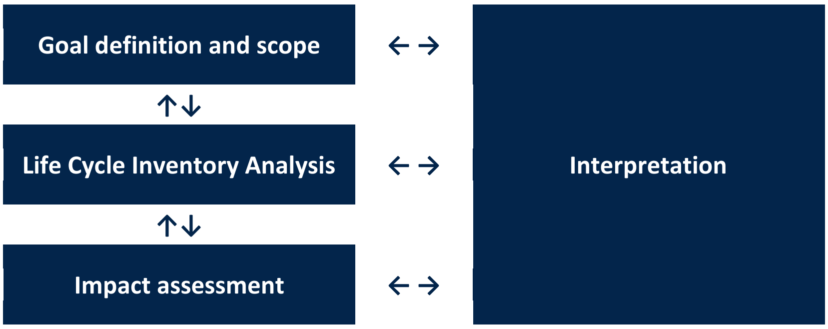


Figure 5.4 – LCA framework

5.2.1 Goal and scope

The goal of this analysis is to ascertain how FRP alternatives perform on environmental impact scores compared to steel variant. Four sub-goals are defined:

Goals

- Generate an overview of the environmental impact scores of each of the four design variants.
- Compare the environmental impact scores of the all-steel Amaliabridge design to alternative FRP designs.
- Identify the variant with the overall lowest environmental impact.
- Identify important impact phases for each design variant to allow for further optimization in design.

Scope

The scope of this analysis comprises all phases in the product's lifecycle *(see Figure 5.5)*. For the steel and hybrid variant, both the leaf and the bascule basement are included in the analysis. For each of the FRP variants, only the leafs are calculated in the analysis. The purpose is to show the difference between a steel bascule bridge requiring a large labour and material intensive concrete basement compared to FRP alternatives that do not require this basement. The operating mechanisms and all associated elements of a movable bridge are regarded similar for all variants and are therefore neglected.
Impacts of secondary impacts related to the lifecycle are not taken into account in the analysis. An example of such a secondary impact is the increase of emissions from traffic rerouting of both road and waterway traffic during installation and maintenance.

Functional Unit

The Functional Unit (FU) in an LCA is the unit that describes a product's function and performance requirements to enable objective comparison between multiple design variants. If a certain lifespan is integrated in a Functional Unit's performance description, it can greatly determine the difference between two variants.
In the case of the Amaliabridge versus FRP variants, the FRP variants are designed to last for up to 200 years, where the current steel variant is only designed for up to 100 years. If the FU would be set at 100 years, the FRP variants would be "overqualified". When it is set at 200 years, the current steel variant would be "underqualified" however can simply be built twice to live up to the FU. The description of the FU therefore is stated as: *Providing a four lane medium traffic movable bridge for 200 years.*

Assumptions

There are parameters for which no specific values exist yet which therefore have to be assumed. One of the critical values is material mass; for the steel variant, the steel and concrete masses are known. For the FRP alternatives however, the values have been calculated based on the mass property ratio of FRP substituting steel R_M defined earlier in chapter 3.9.1. This means that for the thermoset and thermoplast alternatives, the resin and fibre mass is calculated by multiplying R_M by the total steel mass of the steel variant. For the laminates' weightfractions, 0,6% is used for fibres and 0,4% for the resin.

5.2.2 Life Cycle Inventory

Depending on the goal and scope, a product's lifecycle can consist out of up to five main lifecycle phases, visualised in Figure 5.5. An assessment covering materials that are recycled from the EoL phase back to the raw material or production stage is called 'Cradle to Cradle', or 'C2Cr'. When the analysis does not cover recycling or when only waste is generated in the EoL phase and no materials are recycled back, the assessment is called 'Cradle to Grave', or 'C2Gr'. When the EoL phase is not taken into account altogether, the assessment is called 'Cradle to Gate', or 'C2Ga'. For all variants, both a C2Ga and a C2Cr assessment are performed. However, as some variants have no materials being recycled but incinerated instead, their C2Cr assessment will only yield results similar to a C2Gr approach.

Figure 5.5 – Main product lifecycle phases

For each of these phases, the relevant input data and the matching LCI data need to be gathered, calculated and summed to acquire the total environmental impact. For homogeneity in both LCA input and output, the LCI data used for this analysis are solely from the EcoInvent 3.1 library embedded in the SimaPro 8 analysis software. In this library, there are three system models available:

- Allocation Default *(Allocation cut-off by classification)*
- Allocation Recycled Content *(Allocation at the point of substitution)*
- Consequential *(Substitution, Consequential, Long-Term)*

Each of these three system models has two subsets available:

- Market *(Including transport, emissions and resource extractions)*
- Transformation *(Excluding transport, emissions and resource extractions)*

Each of these two subsets has two additional aggregation subsets available:

- System *(Unit values aggregated into one "black box" process. No detailed process tree.)*
- Unit *(Detailed data with separate values for each subsystem. With detailed process tree.)*

For the purpose of this study, the Consequential system model's Market Unit data are used to enable identification of high-impact processes or sub-processes. Material and process LCI data used for the analysis are summarized in tables Table 5.2 through Table 5.6. Detailed information concerning the parameters used in the assessments can be found in Appendix 9.8.

			Raw materials
Variant	Type	Material	Amount
Steel	Steel	Low alloy steel	$355*10^3$ kg (x2)
	Coating	Acrylic varnish	$42*10^3$ kg (x2)
	Concrete	Concrete	$4460*10^3$ kg (x2)
Hybrid Steel / Thermoset	Steel	Low alloy steel	$243*10^3$ kg (x2)
	Resin	Polyester resin	$8{,}8*10^3$ kg (x2)
	Fibre	Glass fibre rovings	$13*10^3$ kg (x2)
	Coating	Acrylic varnish	$42*10^3$ kg (x2)
	Concrete	Concrete	$4460*10^3$ kg (x2)
Thermoset	Resin	Nylon 6-6	$85*10^3$ kg
	Fibre	Glass fibre rovings	$128*10^3$ kg
	Coating	Acrylic varnish	$17*10^3$ kg
Thermoplast	Resin	Polyester resin	$85*10^3$ kg
	Fibre	Glass fibre rovings	$128*10^3$ kg
	Coating	Acrylic varnish	$17*10^3$ kg

Table 5.2 – Raw material LCI data

			Production
Variant	Type	Process	Amount
Steel	Steel	Cutting	250 m (x2)
	Steel	Forming	0,1 * Total steel mass (x2)
	Steel	Welding	3200 m (x2)
	Concrete	Mixing?	? (x2)
Hybrid Steel / Thermoset	Steel	Cutting	250 m (xw)
	Steel	Forming	0,1* Total steel mass (x2)
	Steel	Welding	3200 m (x2)
	Concrete	Mixing?	? (x2)
	FRP	Pultrusion (Injection moulding)	Total resin mass (x2)
Thermoset	Infusion	No process allocated, mostly manual labour	-
Thermoplast	Injection moulding	Injection moulding	Total resin mass

Table 5.3 – Production LCI data

During the life cycle of the design variants, all require one or more protective coatings and energy for operation shown in Table 5.4.

Variant	Type	Material / process	Amount **Life cycle**
Steel	Coating	Steel powder coating	4x Total steel area (x2)
	Energy	Electricity at grid, medium voltage	Calculated average
Hybrid Steel / Thermoset	Coating	Steel powder coating	4x Total steel area (x2)
	Energy	Electricity at grid, medium voltage	Calculated average
Thermoset	Coating	Steel powder coating	2x Total steel area
	Energy	Electricity at grid, medium voltage	Calculated average
Thermoplast	Coating	Steel powder coating	2x Total steel area
	Energy	Electricity at grid, medium voltage	Calculated average

Table 5.4 – Use phase scenarios

For the End of Life phases of all variants, both disassembly and reuse have been modelled according to the scenario's and processes in Table 5.5 and Table 5.6.

Variant	Disassembly	EoL scenario	Amount **Disassembly scenarios**
Steel	Steel	Reuse	Total steel mass
	Concrete	Reuse	Total concrete mass
Hybrid Steel / Thermoset	Steel	Reuse	Total steel mass
	Concrete	Reuse	Total concrete mass
	Resin & Fibre	Municipal solid waste incineration	Total resin & fibre mass of deck
Thermoset	Resin & Fibre	Municipal solid waste incineration	Total resin & fibre mass of structure
Thermoplast	Resin & Fibre	Reuse	Total resin & fibre mass of structure
	Resin & Fibre	Municipal solid waste incineration	Total resin & fibre mass of structure

Table 5.5 – Disassembly scenarios

Variant	Reuses	Additional process	Amount **Reuse scenarios**
Steel	Steel	Cutting (Process: Arc welding)	8000 m (2x)
	Concrete	Drilling / crushing (Process: Rock crusher)	Total concrete mass (2x)
Hybrid Steel / Thermoset	Steel	Cutting (Process: Arc welding)	7500 m (2x)
	Concrete	Drilling / crushing (Process: Rock crusher)	Total concrete mass (2x)
Thermoset	*No reuse*	*Either disposed or down-/recycled otherwise*	-
Thermoplast	Resin & Fibre	Melting the FRP (Process: Injection moulding)	Total resin mass

Table 5.6 – Reuse scenarios

Raw material phase

The raw materials are those directly required for production of the final product. For a steel bridge this concerns mainly raw steel or a specific alloy and protective coating paints. For FRP, this mainly concerns the fibres, polymer resin, additives, and the protective gelcoat. For both variants, a wear layer material is required, however, as the road deck area should be similar in all designs, the wear layer is left out of the analysis.
Any excess material that is used during manufacturing and/or installation that is not used in the final product is not taken into account in this study, as the efficiency of production cannot be determined specifically enough to enable an estimates.

Production & installation phase

During the production phase, the raw materials are converted into the final product using multiple production processes. For steel, this primarily concerns cutting and welding steel into the final form and conserving it with a protective coating.

For FRP, this involves production of the fibres and resin, hand layup of the fibres in the mould and finally the mould infusion process. The manual labour is not included in the analysis, but will also have a an environmental impact that is however estimated to be insignificant.

Use phase

During use, the only scheduled maintenance is reconditioning or replacement of the operating mechanism. Inspection is also performed at regulated intervals, which could lead to earlier mechanical maintenance to the operating mechanism. For steel there are additional inevitable activities such as conserving of the steel structure by reapplying a protective coating. Protective paint coatings for steel structures subjected to the outside environment generally last up to 20 years, depending on the maintenance intervals. For this analysis, four layers of additional protective coating will be allocated to the use phase in addition to the original coating during the production phase.
The use phase is where the FRP variant excels under normal use conditions. It does not require any additional coating as the gelcoat and paint layers that are applied should last the lifetime of the product. Although regular inspection is strongly advised and also mandatory by regulations, it should not come across damage from normal use. Nevertheless, two layers of paint are incorporated in the total lifecycle of the all-FRP variants.

Energy usage for operation of the bridge variants is based on a calculation provided by Movares on the average energy consumption during one opening/closing cycle. An assumption is made that the bridge will open an average of 10 times each day, 365 days a year, for 200 years. Considering all design variants are balanced and require similar overcapacity of the operating mechanism for wind loads, the energy use for all variants is kept the same but still included in this analysis to show its relevance in the overall impact assessment.

End of life phase

The EoL phase for steel primarily consists of removing the steel leaf off site and cutting it into recyclable pieces. The concrete bascule basement will have to be drilled, crushed and removed by heavy loader trucks. The same goes for thermoset and thermoplastic variants, they however require less energy to cut and transport, as they are easier to cut and do not have a bascule basement.

At the current state of art of FRP recycling processes, thermoset FRP composite materials cannot be recycled or reverted to their original virgin materials. The only viable option to retain as much value as possible is to reuse the product or parts entirely. However the recycling is still a very troublesome stage. At the current state of art of FRP recycling processes, thermoset FRP composite materials cannot be recycled or reverted to their original virgin materials. FRP waste is expected to be sent to landfill or incinerated. However, due to the non-biological and therefore non-biodegradeable nature of the material, incineration is used as a disposal scenario for thermoset FRP.

Thermoplast FRP is expected to be fully recycled, estimated to require similar energy amounts as during production. Therefore, identical process and amounts are used in its disposal scenario.

5.2.3 Impact assessment

In the impact assessment, the LCI input data and related amounts are calculated into outputs and weighted using a specific method multiplying these outputs with weighting factors into normalised results per variant. The method used in this thesis is the ReCiPe method, which calculates and normalizes the LCI outputs into eighteen distinct impact or "damage" categories called midpoints. These midpoints can be seen as environmental impact or damage units and are summarized in Table 5.7. The method also contains three analysis perspectives, differing in approach and the considered timeframe. The variants and their climate change timeframe are shown in Table 5.8. For the purpose of this thesis, the Hierarchist perspective is used, as this is regarded as the most common in analysis.[14]

Midpoint	Abbreviation	Unit
Climate change (GWP)	CC	kg CO_2 to air
Ozone depletion	OD	kg CFC-11 to air
Terrestrial acidification	TA	kg SO_2 to air
Freshwater eutrophication	FE	kg P to freshwater
Marine eutrophication	ME	kg N to freshwater
Human toxicity	HT	kg 14DCB to urban air
Photochemical oxidant form.	POF	kg NMVOC to urban air
Particulate matter formation	PMF	kg PM10 to air
Terrestrial ecotoxicity	TET	kg 14DCB to soil
Freshwater ecotoxicity	FET	kg 14DCB to freshwater
Marine ecotoxicity	MET	kg 14DCB to marine water
Ionising radiation	IR	kg U235 to air
Agricultural land occupation	ALO	m^2 / year of agricultural land
Urban land occupation	ULO	m^2 /year of urban land
Natural land transformation	NLT	m^2 of natural land
Water depletion	WD	m^3 of water depleted
Metal depletion	MD	Kg Fe depleted
Fossil depletion	FD	Kg of oil depleted

Table 5.7 – ReCiPe midpoints

Perspective	Timeframe	Description
Individualist	20 years	*Short-term interest only, 20 year timeframe for climate change impact*
Hierarchist	100 years	*Most common policy principles with regards to time-frame and other issues*
Egalitarian	500 years	*Precautionary perspective, taking into account the longest timeframe and impact types available*

Table 5.8 – ReCiPe perspectives

The LCA process can be visualised from data gathering to input, weighting, comparison and interpretation from the schematic visualised in Figure 5.6.

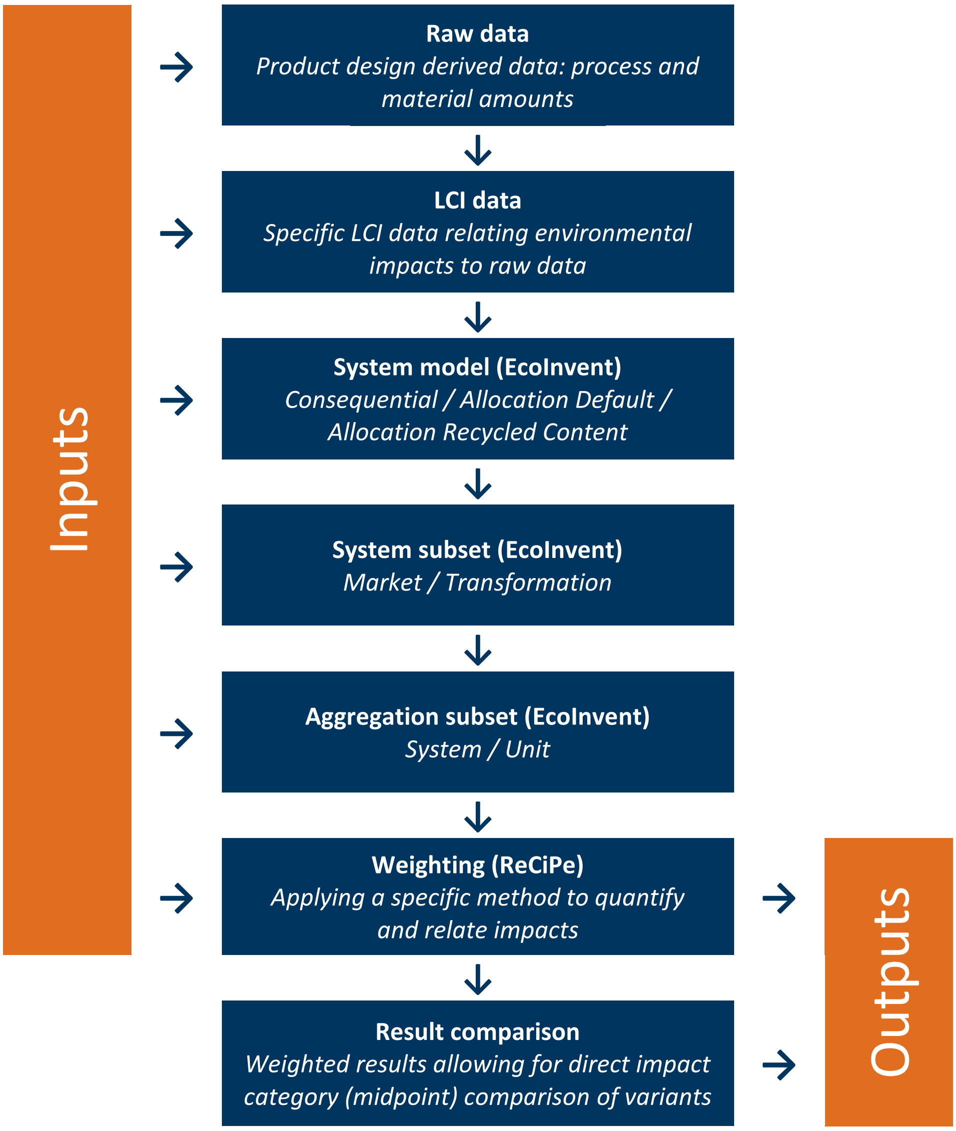


Figure 5.6 – LCA process

5.3 Results & interpretation

The results from the individual impact assessments are merged into graphs shown in Figure 5.7 to Figure 5.10. Please note that some midpoints were insignificant and have therefore been left out of the visualised graphs. The values on the Y-axes are the normalized impacts, meaning all midpoint impacts have been re-calculated into a single unit: CO_2 equivalent. The weighted results show the normalizes results multiplied by a weighting factor determined in the ReCiPe method.

What is interesting to note from these graphs is that steel variants have the highest impact in the C2Ga assessments compared to the FRP variants. However, when looking at the C2Cr (or C2Gr in case of incineration), the FRP incineration variants suddenly have the highest impact.

Another interesting result from both assessments is that the thermoplastic variant has the lowest impact in all cases and for all midpoints.

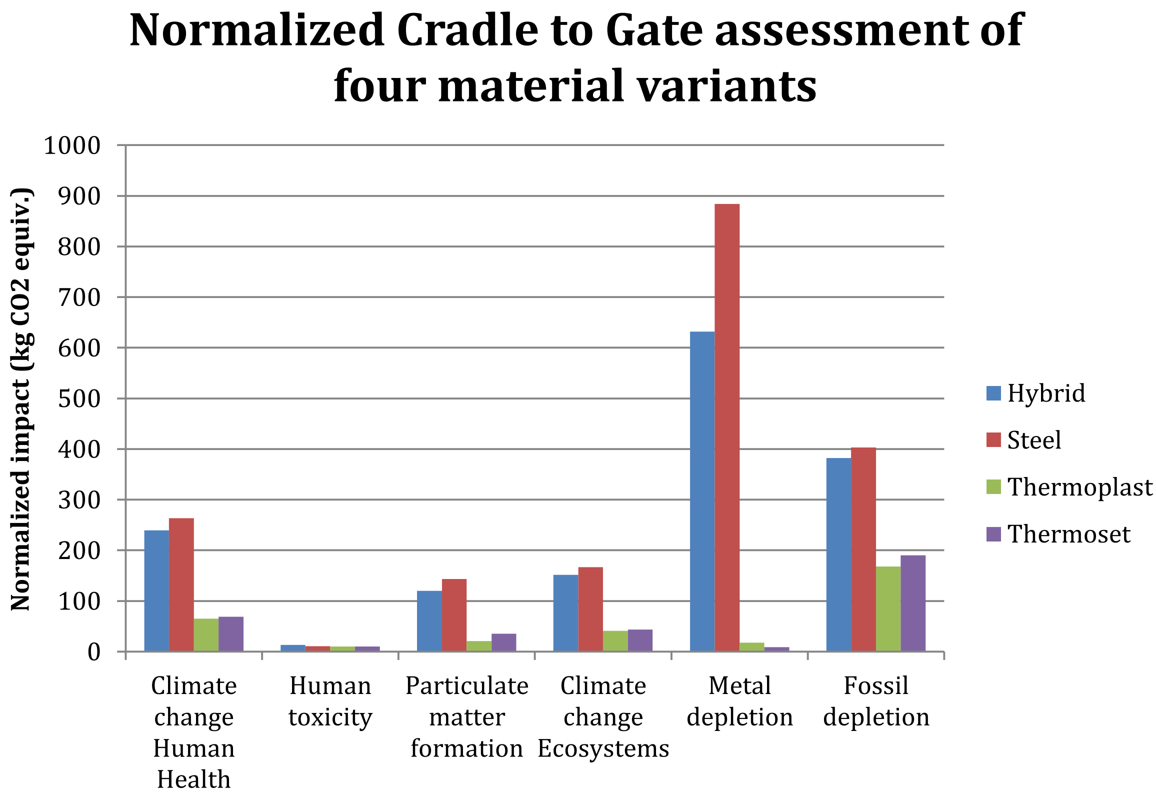


Figure 5.7 – Normalized Cradle to Gate assessment of four material variants

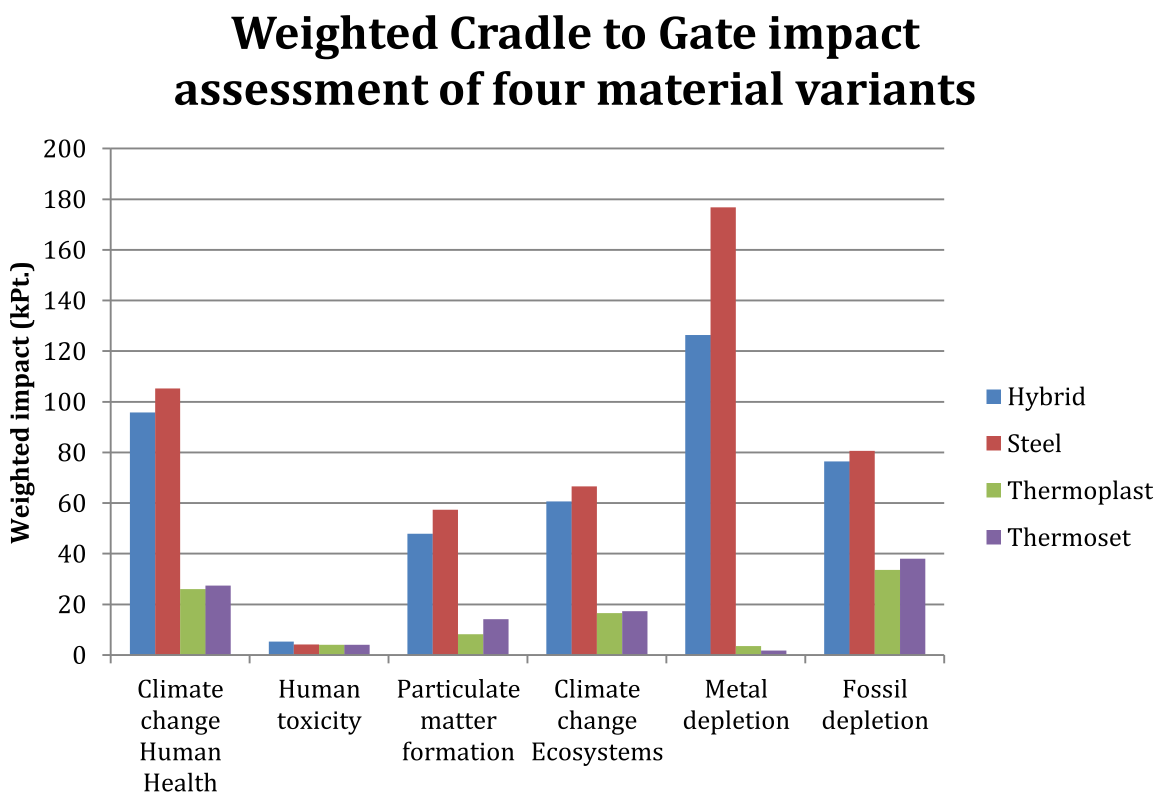


Figure 5.8 – Weighted Cradle to Gate impact assessment of four material variants

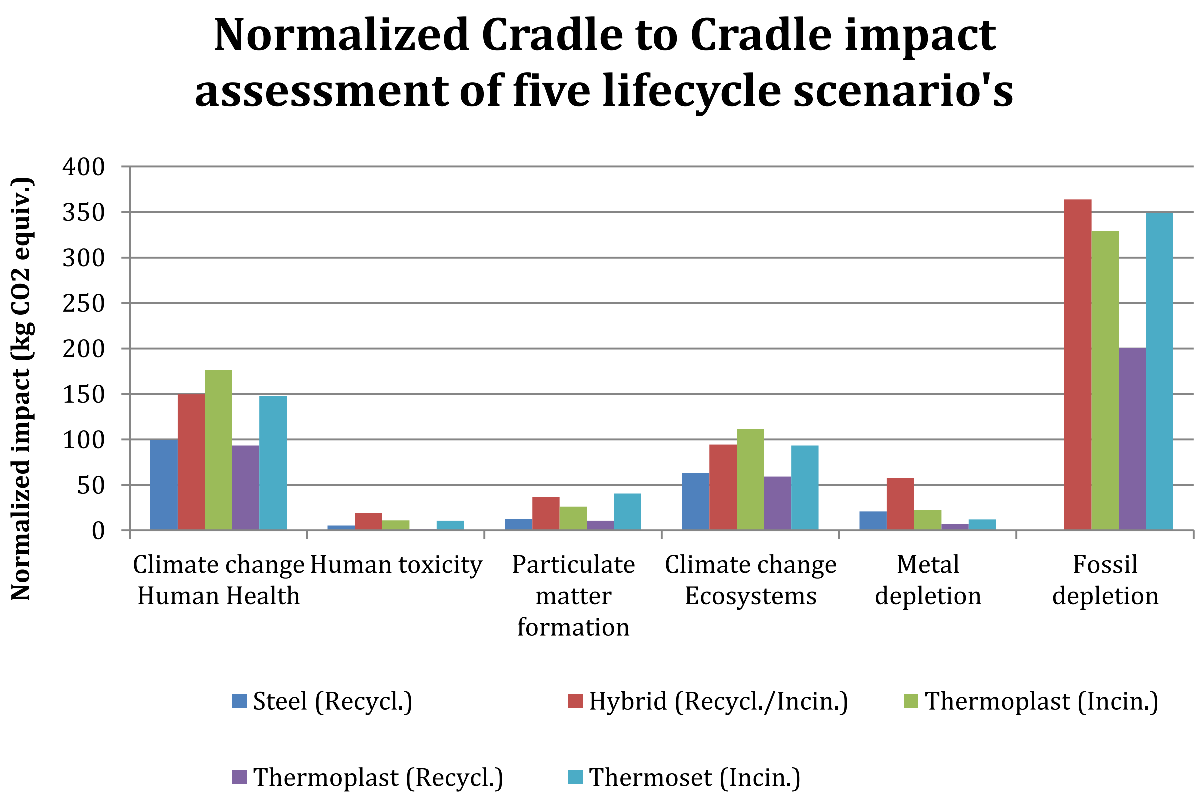


Figure 5.9 – Normalized Cradle to Cradle impact assessment of five lifecycle scenario's

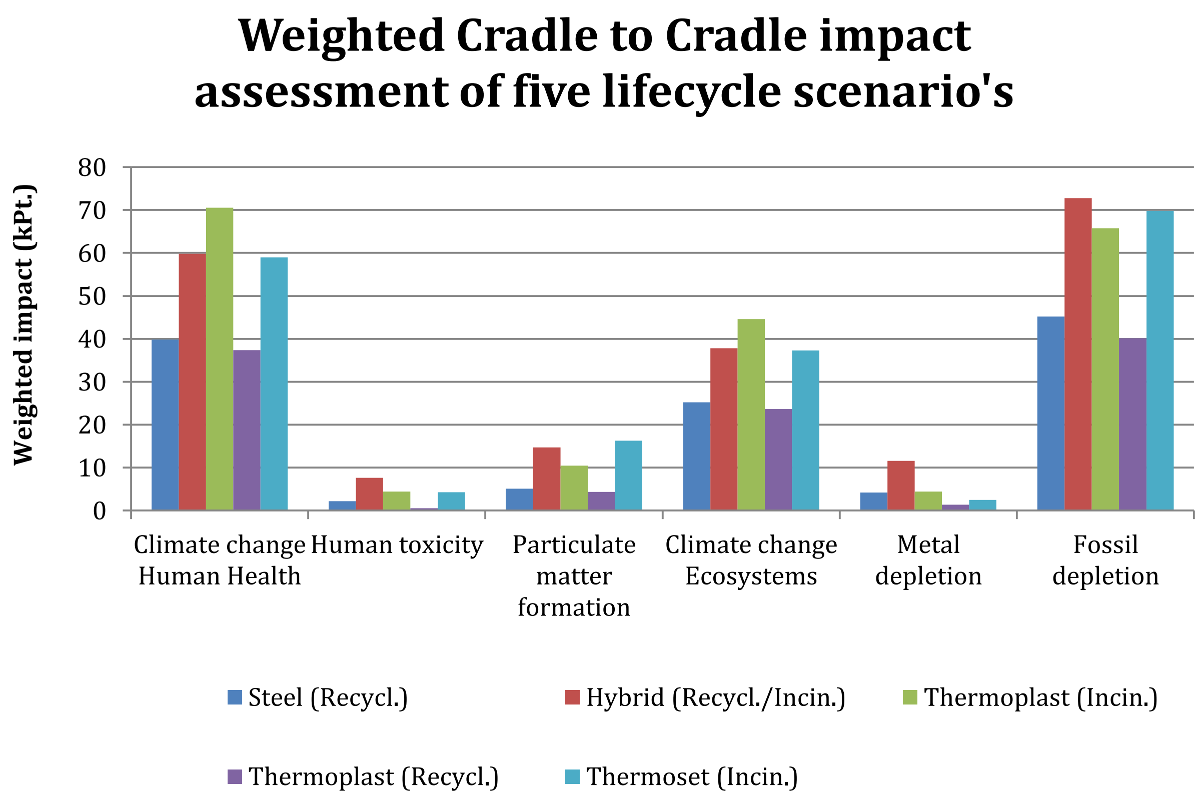


Figure 5.10 – Weighted Cradle to Cradle impact assessment of five lifecycle scenario's

5.3.1 Sensitivity analysis

Parameters

One of the most important parameters in the assessment are the weights of steel and FRP accounting for the most significant impact. As the weights are estimated based on a weight ratio compared to the steel design, this introduces great sensitivity in the assessment results. The solution would be to perform a detailed design and mechanical analysis to provide more accurate dimensions and weights. This can only be done after the design is sufficiently detailed, or if experience from other projects can provide significantly better estimates than the one in this analysis.

LCI Data

Detailed LCI data are very scarce. Any FRP laminate will use specific resin and fibres, requiring similarly specific LCI data. Also fillers, additives, etc. that are normally added to resin are not included in the LCI setup and could prove an additional influence on the assessment results. This goes for the accuracy of the steel input data as well, as only a few types of steel are available in the EcoInvent database used. The specific steel could be partially reused, and therefore having lower impact than a high grade steel that is required in the design of a bridge (sometimes virgin sources are demanded).
The level of detail in this analysis is also not as high as would be desired. Only main materials, production processes, transport routes, use processes are modelled. Where in a real project, contrary to a case study, significantly more detail is available for input in the analysis.

Method

The methods provided in the software initially caused problems with the assessment results. The ReCiPe Midpoint Hierarchist method caused unrealistic results, with high marine ecotoxicity and almost no climate change, something that is expected in an energy intensive product such as a steel bridge. When using the ReCiPe Endpoint method and displaying the individual unaggregated midpoints, the results were as expected. The exact problems were never found in the software, and the choice of the Endpoint method was not the one of choice for this assessment.

Allocation

Another issue with using the methods integrated in the software, is that it is not clear how the software allocates certain recycling activities. When the assessments were investigated individually, the diagrams were unclear whether or not the impacts were allocated according to expectations. Some material inputs even vanished from the analysis altogether, probably caused by a 100% reuse scenario, resulting in no impact allocated to a certain material.

Results

It was expected that the results would show the steel variant to have the most dominant impact in all cases, especially considering the FU of 200 years, requiring twice the construction of this steel variant. However, in the Cradle to Cradle assessment, the thermoset variants proved to have the most impact. Reasons could be the LCI data and allocation issues considering the recycling approaches employed by the method or the SimaPro software.

6 Discussion

In this chapter, the proposed redesign and the environmental impact assessment are judged with an objective view, discussing both positive and negative results.

Product improvement design

The product improvement design focused on sustainability by durable design and prolonged lifespan. The aim was to improve the environmental performance by designing an all-FRP bridge that would not only outlast the original steel design based on the durability of FRP, but could also eventually be repurposed. The repurpose feature also meant that both installation and re-installation should be relatively easy. The hydraulically powered rolling bascule design is an ideal solution, as this can be applied anywhere without significant modifications to a new location. The added redundancy is also beneficial in case of partial operating system breakdown, or during scheduled maintenance.

There are issues related to FRP application that still persist with the redesign: repair possibilities and engineering efforts. As FRP laminates are more complex than homogenous materials, the layup should be determined for each part of the design. Also, when repair is needed, the possibility of repair depends on the size of the damage. Small scale damage can be repaired fairly easy by patching. Large scale structural damage however is far more difficult to repair, especially in a non-modular structure such as the redesign.

Another issue that exists in all bridge designs is safety. However, when directly comparing the redesign to the original trunnion bascule type, the rolling bascule type has an additional crushing risk at the rolling track. This risk can be mitigated to a significant extent however, as explained earlier.

Environmental impact assessment

The impact assessments based on the Cradle to Gate approach seem realistic, with the steel variant having the most dominant impact. The Cradle to Cradle results however suddenly show all thermoset FRP variants to have the largest impact. This is against expectations. The problem is likely to be caused by incorrect allocation in the method or software due to reuse scenario's that were modelled for the recyclable materials such as steel and thermoplasts, versus the incineration scenario's for thermoset polymers.

The BECO study mentioned early in the introduction shows similar results compared to the impact assessment in this thesis. However, the time span of the functional unit in the BECO study (100 years) was twice as short as the one in this report (200 years). The purpose of doubling the functional unit was to see if FRP performed better when it's durability aspects could be exploited by simulating a lifespan twice as long as the steel variant. However, the results cannot be directly compared, as the functional units did not only differ on the time span but also the type of bridge (a fixed bridge in the BECO study, versus a movable bridge in this thesis).

7 Concluding summary

This is the final chapter concluding this thesis, providing conclusions from previous chapters, answers to the research question and recommendations related to the application of FRP, the proposed redesign and the impact assessments.

7.1 Conclusions

7.1.1 FRP in movable bridges

Significant advantages of using FRP for application in movable bridges are high strength, low weight, high durability and the ability of property tailoring. As designs are stiffness-driven, strength eventually becomes no issue which leads to good fatigue performance. Laminates have multiple variables that determine the final properties, such as fibre orientation, layup, density, etc. This allows every part in a construction to have different properties tailored exactly for that section's purpose. This is especially advantageous when loads and corresponding forces are present in predetermined areas and directions. Form freedom also enables enormous design freedom, as the material only requires manual labour in laying the fibres but requires little energy to be shaped in difficult forms.

7.1.2 Design

The proposed redesign has multiple advantages over the current Amaliabridge, such as long lifespan, significantly less construction work requirements, ease of maintenance, redundancy and scalability. A functional advantage of the redesign is the rolling motion, in which the bridge is rotated up and away, effectively creating an unlimited clearance for waterway traffic. On the other hand, there are also potential risks associated with the design, such as safety and production aspects. Designing with FRP also requires significant design and engineering efforts when compared to conventional steel girder designs.

Reusability

The reusability of the design tackles one of the main issues currently inherent to the use of FRP: recycling in the End of Life phase. By postponing this phase for as long as possible, the durability of the product goes up as its lifespan increases while performance is not expected to degrade significantly over time due to the good fatigue properties of FRP.

Construction efforts reduction

Another advantage of the design is the exclusion of the bascule basement by using a rolling bascule bridge design. Not only does this save tremendous amounts of construction materials and efforts, but it also makes reuse significantly easier. If the bridge is eventually repurposed, the main requirements would only be adaptations on the abutments to allow for the rolling motion. However the leaf's size is larger compared to a trunnion bascule bridge, it's additional size is situated mostly in the Y-direction, which is essentially free space that requires no excavation or area around the bridge.

Maintenance & redundancy

The operating mechanism is significantly smaller compared to the original trunnion bascule bridge design. A significant advantage during the use phase of the bridge is the ease of maintenance and the added redundancy, as the operating mechanisms can drive both leafs interchangeably and independently, resulting in lesser downtime.

Environmental impact

Although the design aims at prolonging the lifespan as much as possible, the bridge will eventually reach the EoL phase, where the material will have to be disposed of. The recycling processes currently yield low recyclate value or will result in complete material loss with partial energy recovery. Hopefully, recycling processes will have advanced sufficiently during the lifespan of the bridge, reaching higher recyclate value compared to the current state of art.

Scalability

The design can also be scaled down to be applied in other scenario's. As the span of the Amaliabridge case is very long compared to average movable bridges, shorter spans will allow for greater design freedom and better balancing options.

Safety

The primary concern with a rolling bascule bridge is safety during operation. The associated risks are therefore reduced as much as possible in the design and can be mitigated further by implementing proper precautionary measures such as safety barriers and signs. Additionally, sensors can be incorporated in the design to detect the presence of anything in the rolling path, mitigating the risks even further.

Design, engineering and production

Design and engineering efforts are higher with structural FRP designs; as the laminate composition and its directional reinforcement have to be determined for each section of the design, it will require high mechanical validation efforts.
Additionally, due to the size of the design, production will require high quality control as production failures in large parts such as the girders will require disposal of the failed part and costly remanufacturing.

7.1.3 Environmental impact

The conclusions have already been elaborated on in the sensitivity analysis and discussion. Unfortunately, the results proved thermoset FRP variants to perform significantly worse compared to conventional steel materials. Thermoplasts however had the least impact of all variants, however is less suitable for application in movable bridges. As mentioned earlier, the validity of these results are questionable, as there is most probably an allocation error that could not be identified in time for the conclusion of this project.

7.2 Research question

The only important aspect remaining is to answer the initial research question: *"When taking into account its complete lifecycle, when and where should FRP be considered for application in movable bridges and how does its environmental impact compare to that of conventional materials?"* To provide an answer, the individual sub-questions are answered independently.

1. *When and where does FRP prove a suitable replacement candidate for conventional materials?*
   FRP performs well in any application that requires either or more of the following aspects: durability, resistance to corrosive influences like water and de-icing salts, form freedom, directional reinforcement, high strength and low weight. Stiffness however is relatively low compared to steel. Especially in large spans such as the Amaliabridge. For this specific case study, the best option would probably be a combination of a steel substructure with an FRP deck.

2. *Can design improve the applicability or environmental performance of FRP?*
   For a direct replacement of steel maintaining the current design, FRP is probably not suitable, as the material's properties are different from steel and the design methods for steel (girder based designs) are not applicable to FRP. The proposed redesign gives a conceptual representation of an alternative that is possible with FRP. The resulting answer is that for a design in FRP, designers and eingineers should not think in conventional steel girder designs, however more in the relevant FRP structures built up from laminates in several possible compositions. As FRP is very durable and has good fatigue properties, long lifespan can be achieved, leading to a more sustainable design. The design should however be aimed at achieving this long lifespan, such as the reusability in the proposed design.

3. *How does FRP perform on environmental impact compared to conventional materials?*
   The results from the impact assessments presented in this thesis show thermoset FRP to perform better than conventional materials when only the Cradle to Gate approach was used, however worse when the Cradle to Cradle approach was used. There are multiple factors at play described in the sensitivity analysis and discussion that can negatively or wrongly influence this outcome. Although no proof can be given, the expectation is that the environmental impact of an all steel design like the Amaliabridge would be higher when compared to an FRP design, especially when based on the redesign proposed in this thesis.

7.3 Recommendations

The first recommendation is to further investigate the application, technical and economical feasibility of the proposed design. As with any design, several risks, dangers, disadvantages exist and have to be prevented or overcome. Although the key feature of possible reuse is not the first aspect that is considered during initial bridge design, when using materials with a long lifespan as FRP, a reuse scenario can significantly reduce environmental impact and is therefore interesting to look into.

Proper laminate documentation

In case repair of an FRP part or product is necessary, extensive documentation of the FRP laminate composition throughout the product is required for accurate determination of the repair approach. Not only does this alleviate the dependency on the FRP part's or product's producer, but it also enables third parties to form an expert opinion in case this is required. The laminate composition documentation can also aid in recalculations for possible repurposing or reuse elsewhere of the bridge.

Thermoplastic resins

Using thermoplastic polymer resins in FRP provides the significant advantage of possible recycling next to the overall lowest results in the impact assessments. Unfortunately, this advantage comes paired with a significant disadvantage: low temperature resistance. Which is also the main reason for the industry not to adopt thermoplastic polymers in bridge design, as the risk of structural failure at high temperature (e.g.: a fire) is relatively high. However, applications might be found in areas that are less prone to the temperature related risks of fire.

Acquisition of LCI data

If it ever becomes desirable to perform an accurate LCA of two or more bridge alternatives, both the input (dimensions, weights, amounts) and corresponding LCI data should be estimated with high certainty and accuracy. The current lack of detailed LCI data, also concerning bio-based fibres and resins provides an insufficient basis for a proper detailed impact assessment.

Improve LCA level of detail

The level of detail for the assessment should be increased to encompass detailed processes, materials and energy streams associated especially with production and construction. Currently, these efforts are only modelled to a very limited extent. Secondary impacts of both road and waterway traffic rerouting during installation and maintenance could also be taken into account if the obstruction takes considerable time or the reroute is significantly longer than the original route over or under the bridge.

Incorporating sensors

Several types of sensors can be included in the design for the purpose of monitoring forces, displacements, elongation and stresses during the use phase. These sensors can be included in the mould during the resin infusion/injection stage, and will permanently stay inside the product. The additional process step of including the sensors in the final part of product is relatively easy and low-cost compared to the total manufacturing efforts and costs. Sufficiently qualitative sensors must be used, as they cannot easily be repaired or replaced after the resin is cured.

8 Literature

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9 Appendices

9.1 Bridge types and examples

There are two main bridge types: fixed and movable bridges. Fixed bridges either do not pass over any road or waterway or are high enough not to require displacement of the road deck for passage underneath. Movable bridges however include a mechanism to partially of completely displace the bridge deck to allow passage underneath. There are multiple types of movable bridges, which can be categorised by the type and direction of deck displacement *(see Table 9.1)*.

	Translation	Rotation
X-axis *(parallel to road direction)*	- Retractable bridge - Folding bridge - Transporter (ferry) bridge	- Tilt bridge
Y-axis *(perpendicular to road direction)*	*Does not take away road-deck obstruction, therefore no practical use*	- Drawbridge - Bascule bridge
Z-axis *(vertical)*	- Lifting (table) bridge - Submersible bridge	- Swing bridge

Table 9.1 – Types of bridges

Table 9.1 shows that translation in the Y-axis is the only displacement type that provides no useful purpose, as the deck is not moved out of the way. Some examples of bridge types are shown below. It should be noted that not all bridge types have unlimited clearance in their opened position.

Image 9.1 – Millennium bridge, Gateshead, GB. Tilt bridge, limited clearance.

Image 9.2 – Den Ysere Ryve bridge at Bruinisse, NL. Retractable bridge, unlimited clearance.

Image 9.3 – Nelson Mandela bridge, Alkmaar, NL.
Lifting bridge, limited clearance.

Image 9.4 – Bridge at Sas van Gent, NL.
Swing bridge, unlimited clearance.

Image 9.5 – Gouderaksebrug, Gouda, NL.
Drawbridge, unlimited clearance.

Image 9.6 – Slauerhoff bridge, Leeuwarden, NL.
Bascule bridge, unlimited clearance.

Image 9.7 – Te Matau a Pohe Bridge, Whangarei, NZ.
Rolling bascule bridge, unlimited clearance.
Image courtesy: McKay

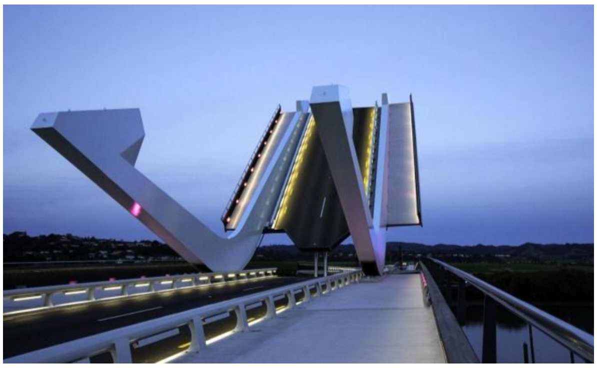

Image 9.8 – Te Matau a Pohe Bridge, Whangarei, NZ.
Rolling bascule bridge, unlimited clearance.
Image courtesy: Whangarei Marina

Amaliabridge, Gouda, NL.
Bascule bridge, unlimited clearance

9.2 In-depth information on polymers

Thermoplastic polymers have different states and properties that significantly change at two key temperatures:

T_g = Glass transition temperature

T_m = Melting temperature

When the temperature rises, thermoplastics will begin to soften at the glass transition temperature T_g. Between T_g and T_m, the material will be in a rubbery state. At temperatures above T_m, the material will melt.

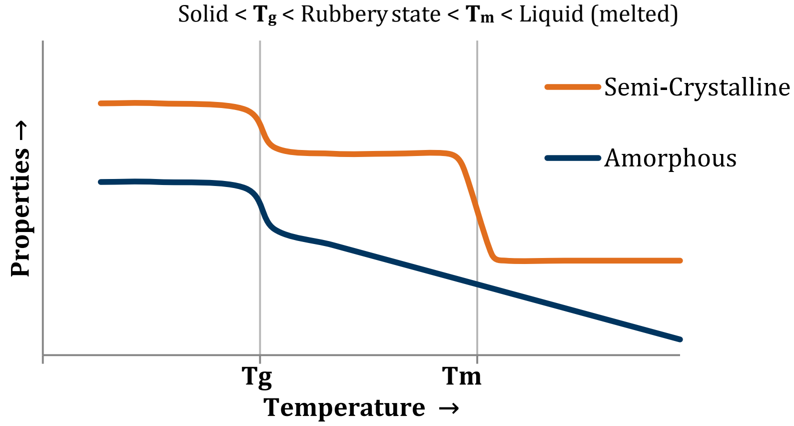

Figure 9.1 – Thermal transitions of thermoplastic polymers

9.2.1 Thermoplastics

Semi-crystalline polymers

Semi-crystalline polymers have a highly ordered molecular structure and a sharp melting point T_m. They therefore do not gradually soften with increasing temperatures, rather transform into a viscous liquid at a specific temperature. This fast transition results in higher volumetric shrinkage upon cooling when compared to amorphous polymers.

Amorphous polymers

Amorphous polymers have a structure consisting of randomly ordered molecules. These structures exhibit no sharp melting point and therefore soften gradually with increasing temperatures. This gradual transition results in low volumetric shrinkage upon cooling. Amorphous polymers however lose their mechanical properties above the glass temperature T_g, they also become viscous as semi-crystalline polymers.

9.2.2 Thermosets

Cross linked polymers

Thermosets differ from thermoplastics on the molecular level. Where thermoplastics have a molecular bond, thermosets have a chemical bond. Multiple molecular polymer chains are cross-linked by chemical bonds. This chemical bond is also responsible for the thermal behaviour, e.g. not melting at high temperatures.

9.3 Polymerisation

To achieve optimal matrix quality, and thus final laminate quality, the part where the matrix is finally formed during manufacturing is important to guarantee long service life. The process where the matrix transfers from a viscous liquid to a solid state is called polymerisation, or curing. This is where the monomers are bonded together to form large chains (polymers) that become entangled to form a dense and solid mass. An important aspect of the curing process is the ratio of epoxy resin and the added curing agent. If this ratio is out of balance or in any way suboptimal, either unreacted resin or curing agent will remain in the matrix, influencing final quality and properties of the laminate. There are two types of polymerisation:

> **Addition polymerisation**: the monomers are dissolved in a solvent, which later evaporates and allows the monomers to combine into large polymer chains. This has the advantage that no by-products remain in the final material.
> **Condensation polymerisation**: the monomers react into a polymer with the formation of a by-product such as water (H_2O).

There are also two condition types for curing of the polymer matrix:

> **Cold cured system**: the polymerisation is performed in ambient temperatures (around 10-30 °C) and thus can be done on-site. This low temperature however involves a longer cure time when compared to a hot cured system.
> **Hot cured system**: the polymerisation is performed in a heated environment (around 130 °C) mostly in a factory environment.

The composition of the resin determines the polymerisation type and whether it can be cold or hot cured. If the curing needs to be done on-site, the resin has to be compatible with a cold curing system. In general, automated processes use a hot curing system as this can be closely controlled and can speed up production times significantly. For larger products, the heat distribution is far more complex and if suboptimal can lead to non-uniform curing and thus material quality throughout the product.

9.4 Fibre orientation

One of the main advantages of an FRP laminate is that the fibres can be placed in any desirable direction within the matrix, referred to as: fibre orientation. If the fibres are placed in multiple directions in a symmetrical pattern the mechanical properties become more or less similar in all directions and the laminate is thus regarded Quasi-isotropic (QI). If the fibres are predominantly placed in one direction only, the mechanical properties significantly differ depending on the direction of analysis and the laminate is thus regarded Unidirectional (UD). UD orientation logically results in anisotropic material properties, which can and should be used as a design advantage when a uniform load scenario is present.

When fibre orientation follows a pattern, the recurring section is called the reference laminate. An example of a reference laminate layup is 0/45/90/-45/0, in which the first ply is placed in a reference (0°) direction, the second ply in a 45° angle respective to the first ply, the third ply in a 90° angle respective to the first ply, the fourth ply in a -45° (or 135°) angle respective to the first ply, etc. There are two ways of scaling the reference laminate: sub-laminate-level scaling and ply-level scaling. In sub-laminate-level scaling; the reference laminate is stacked multiple times, in ply-level scaling; the individual ply count within the reference laminate is increased.

	Ply no.	Orientation: Sub-laminate level scaling	Orientation: Ply-level scaling
Symmetrical	1	0°	0°
	2	45°	0°
	3	90°	45°
	4	-45°	45°
Mid plane	5	0°	90°
	6	0°	90°
Symmetrical	7	45°	-45°
	8	90°	-45°
	9	-45°	0°
	10	0°	0°

Figure 9.2 – Reference laminate orientation and scaling

There are two ways of scaling the reference laminate: sub-laminate-level scaling and ply-level scaling. In sub-laminate-level scaling; the reference laminate is stacked multiple times, in ply-level scaling; the individual ply count within the reference laminate is increased.

9.5 Open & closed mould systems

9.5.1 Open-mould

In open-mould processes, resin impregnation of the fibres and curing of the resin takes place in open air. For automated processes, impregnation takes place before or during shaping, for manual processes this can be either before, during or after shaping. A disadvantage of all open-mould processes is that factory workers require adequate respiratory and skin protection as they are exposed to Volatile Organic Compound (VOC) emissions (evaporating fumes from curing resin) and could come in physical contact with the resin. Two of the most used open-mould processes are described below.

Hand lay-up

Fibres are manually placed into, onto or around a mould and resin is also manually applied with a brush or roller. This is the most cost effective process, as large products can be produced with the least amount of required equipment. Product complexity is limited however, as the manual application and impregnation is bound to certain physical limits, e.g. hard to reach places like small crevices. Examples of products created with hand lay-up are boat hulls and bath tubs.

Filament winding

Fibres are wound around a mould. Impregnation takes place before winding, by passing the fibres through a resin bath. Additionally, resin can be sprayed locally over the mould where fibres are being applied. An advantage is the possibility of automation. Filament winding is generally used for cylindrical shapes, like tubes, shafts and vessels.

9.5.2 Closed-mould

In closed-mould processes, resin impregnation of the fibres and curing of the resin takes place inside the mould. For automated processes, curing can partially take place outside the mould, after the resin has hardened sufficiently to be taken out of the mould. One of the advantages of closed mould processes is that VOC emissions are essentially captured due to the closed nature of the processes.

Pultrusion

Fibres are arranged, impregnated and pulled through a die, partially similar to extrusion where material is pushed through the die. Fibres pass through a resin bath for pre-impregnation and are then pulled through the die. This makes it a partially open-mould process. Resin can also be injected inside the die under pressure for optimal impregnation and filling of the mould. The resin will cure inside mould while the laminate is being pulled through. Additionally, the mould can be heated for faster and optimal curing. Once the laminate cross-section leaves the mould, it can be cut to specific lengths. Advantages of pultrusion are the resulting high quality products with a constant cross-section, and the possibility of automation. Examples of pultrusion products are structural profiles such as beams and floor panels.

Compression moulding

Fibres are placed inside the mould cavity and preheated thermoplastic or resin is added. When the mould closes, the fibres and resin are subjected to high pressure and heat, which ensures good impregnation and curing. Advantages are very low cycle times, product uniformity, perfect two sided finish and the possibilities of adding inserts and automating the process. However, the moulds are very expensive and can be in excess of €100.000+ for large parts, also depending on the required level of surface finish and quality. Examples of compression moulding parts are consumer appliance housings, automotive and structural parts generally produced only on a large scale.

Injection moulding
Injection moulding is similar to compression moulding, except for the addition of resin, which is injected under pressure after the mould is closed. Advantages are similar to compression moulding, with the addition that more uniform pressure can be applied throughout the mould and that it will be filled precisely, which ensures optimal fibre impregnation and exactly matching parts. A disadvantage is additional waste material that has to be removed in post processing, such as the sprue (main resin feed), runner (resin distribution channel), and gate (final injection point into mould cavity), however this influence will be minimal for large structural parts.

Vacuum infusion
Fibres are placed into, onto or around a mould which is sealed off from the environment with a vacuum bag, generally by covering the laminate with an air-tight plastic film that is taped to the edges of the mould. One or multiple inlets are connected to a resin tank and one or multiple outlets to a vacuum pump. When the pump is activated, the generated vacuum on the outlet(s) will compact the laminate and infuse the resin from the inlet(s), which will ensure good impregnation and removal of excess resin. Vacuum infusion can be used to produce very large products, and requires minimal tools. Moulds and examples of vacuum infused products are similar to hand lay-up products: boat hulls, bath tubs and even larger products such as wind turbine blades and building cladding panels.

(VA-)RTM
Resin Transfer Moulding (RTM) is largely similar to injection moulding, except that resin is injected under medium to low pressure. An inherent prerequisite is a low viscosity resin, generally thermosets. In Vacuum Assisted Resin Transfer Moulding (VA-RTM) the resin is infused by a generated vacuum similar to the vacuum infusion process. Advantages of (VA-)RTM are lower tooling complexity compared to injection moulding, and higher surface quality parts compared to vacuum infusion. HP-RTM is a variant of RTM using high injection pressure to speed up production cycle times.

RFI
Resin Film Infusion (RFI) is similar to RTM, except that all fibre plies are separated by a thin thermoplastic resin film. When heat is applied, the resin film liquefies and will impregnate the fibres under vacuum pressure.

9.6 Production aspects

9.6.1 Pre- and post-treatment

For some processes (like injection moulding or RTM), it is desirable to pre-form the fibres to fit exactly inside the mould to accelerate production time. For manual moulding processes, it is preferred to apply gel coats before processing the laminate, as applying gel coat in post processing is far more labour intensive.

Some processes or resin types require specific heat and pressurized curing conditions, which generally takes place in an autoclave. Product or part dimensions are limited to the autoclave's size, where multiple products or parts might also be cured simultaneously.

For production processes that make use of vacuum bags, the resulting surface quality on the bag side is generally rough and could require sanding down to a smooth or coarse surface, depending on a final layer of paint or gel coat.

Paints and gel coats are generally applied to protect the laminate from external influences like UV-radiation and to prevent hydrolysis. Post application of paint is significantly easier compared to gel coat, as it is less viscous, can be sprayed on and finished more easily.

9.6.2 Surface finishing

Depending on the production process, surface finishing can vary from rough (when using vacuum bags) to smooth (when using polished metal moulds). Gelcoat is often first applied into or onto the mould to protect the final laminate from UV-radiation and prevent hydrolysis. If for economic reasons (wet)-sanding is preferred over an expensive mould, the gelcoat layer's thickness should be adequate to reach the desired surface finish.

9.7 Health hazards

There are potential health hazards involved with the application of FRP that are generally not addressed when considering aspects such as durability, sustainability and circularity. When processing FRP during production and in case of physical damage, factory workers and calamity response teams have to be cautious when dealing with the material, as it can generate possible physical and respiration risks.

Physical

Cracked or ruptured sections of FRP material can have sharp edges and fibres protruding from the remaining structure or debris. It should be handled with care to prevent puncture or cutting of the skin or eyes. If the remaining structure is unstable, falling pieces or pieces breaking and shooting away after a fall also form a hazard. In case of a fire, combustion products deposited on the fragments or sections can add to their toxicity. Proper body protection is required in all cases of physical damage, especially for the hands and eyes.

Respiratory

When processing FRP either in a factory environment or during a calamity, very small fibre particles can break off and become airborne. Fibres with a diameter less than 3 μm, a length of 5 to 80 μm and a diameter to length ratio greater than 3 are considered respirable. Again, in case of a fire, a well-known concern are general combustion products such as toxic fumes, soot, etc. which of course also provide a respiratory health concern. Deposited combustion products on the airborne fibres can also here add to their toxicity. Proper respiratory protection should be provided for workers to prevent possible inhalation of these small fibres and toxic fumes. Consequences of not using proper protection could include the deposition of fibres in the lungs, leading to acute effects like allergic reactions, or chronic effects like pulmonary fibrosis and cancer. Respiratory toxicity depends on the amount and size of ingested fibre particles and the deposition time in the lungs.[15]

9.8 LCI Parameters

Input parameters

Name	Value	Distribution	SD^2 or 2*SD	Min	Max	Hide	Comment
HY_A_FRP_Total	800	Undefined				☐	Steel/Thermoset Hybrid: Total area in m2
HY_A_Steel_Total	2320	Undefined				☐	Steel/Thermoset Hybrid: Total area for protective coating in m2
HY_Fibre_wt_frac	0,6	Undefined				☐	Steel/Thermoset Hybrid: Total fibre weight fraction %
HY_L_Cutting_Reuse	5000	Undefined				☐	Steel/Thermoset Hybrid: Total hybrid cutting length for reuse in m
HY_M_Adhesive	1000	Undefined				☐	Steel/Thermoset Hybrid: Total required adhesive mass in kg
HY_M_ResinAndFibre	22050	Undefined				☐	Steel/Thermoset Hybrid: Total FRP mass in kg (Calculated based on Fiberline Composites ASSET FBD600 dimensions and data)
HY_M_Steel_Total	243000	Undefined				☐	Steel/Thermoset Hybrid: Total raw steel mass in kg (Exported from CAD file, including ballast casing, troughs and deckplate, excluding concrete ballast)
n_OpenClosePerDay	15	Undefined				☐	Realistic number of open/close cycles per day #
ST_A_Steel_Total	4230	Undefined				☐	Steel: Total area for protective coating in m2
ST_E_OpenClose	1,17	Undefined				☐	Steel: Total required electric energy per open/close cycle in kWh (Calculated average by Movares in 5 BFT wind conditions counteracting the movement)
ST_L_Cutting_Reuse	8000	Undefined				☐	Steel: Total steel cutting length for reuse in m
ST_L_Cutting_Total	254	Undefined				☐	Steel: Total steel cutting length in m
ST_L_TransportFactoryToSite	157	Undefined				☐	Steel: Total inland waterway transport length from factory (Hillebrand Rotterdam) to site (Gouda) in km
ST_L_Welding_Total	3200	Undefined				☐	Steel: Total steel welding length in m
ST_M_Steel_Total	355000	Undefined				☐	Steel: Total raw steel mass in kg (Exported from CAD file, including ballast casing, excluding concrete ballast)
ST_p_Concrete	2400	Undefined				☐	Steel: Density of concrete in kg/m3
ST_t_OpenCycle	70	Undefined				☐	Steel: Total opening and closing cycle time in seconds
ST_V_Concrete	1857	Undefined				☐	Steel: Total concrete volume in m3 used for bascule basement (Exported from CAD file)
ST_V_Excavation	2000	Undefined				☐	Steel: Total excavation folume in m3 for bascule basement (Exported from CAD file)
SW_AllocDef	0	Undefined				☐	Calculation switch: IF [SW_AllocDef]=1 THEN [SW_Conseq]=0 AND [SW_AllocRec]=0 and vice versa
SW_AllocRec	0	Undefined				☐	Calculation switch: IF [SW_AllocRec]=1 THEN [SW_Conseq]=0 AND [SW_AllocDef]=0 and vice versa
SW_Conseq	1	Undefined				☐	Calculation switch: IF [SW_Conseq]=1 THEN [SW_AllocDef]=0 AND [SW_AllocRec]=0 and vice versa
T_DesignLife	36500	Undefined				☐	Total design life (100 years) of the steel variant in days, for FRP this parameter is multiplied by 2
TP_A_Total	1500	Undefined				☐	Thermoplast: Total estimated area for protective coating in m2
TP_Fibre_wt_frac	0,6	Undefined				☐	Thermoplast: Total fibre weight fraction %
TP_L_TransportFactoryToSite	23	Undefined				☐	Thermoplast: Total inland waterway transport length from factory (FiberCore Rotterdam) to site (Gouda) in km
TP_wt_fraction_of_ST	0,6	Undefined				☐	Thermoplast: Estimated weight percentage of steel variant %
TS_A_Total	1500	Undefined				☐	Thermoset: Total estimated area for protective coating in m2
TS_Fibre_wt_frac	0,6	Undefined				☐	Thermoset: Total fibre weight fraction %
TS_L_TransportFactoryToSite	23	Undefined				☐	Thermoset: Total inland waterway transport length from factory (FiberCore Rotterdam) to site (Gouda) in km
TS_M_Adhesive	1000	Undefined				☐	Thermoset: Total required adhesive mass in kg
TS_wt_fraction_of_ST	0,6	Undefined				☐	Thermoset: Estimated weight percentage of steel variant %

Calculated parameters

Name	Expression	Comment
ST_E_Operating_Total	ST_E_OpenClose*n_OpenClosePerDay*T_DesignLife = 6,41E5	Steel: Total required electric energy for physical operation during design life in kWh
ST_L_TransportFactoryToSite_tkm	(ST_M_Total/1000)*ST_L_TransportFactoryToSite = 5,57E4	Steel: Unit conversion from km to tkm
ST_M_Total	ST_M_Steel_Total = 3,55E5	Steel: Total product mass in kg
TP_E_OpenClose	ST_E_OpenClose*1 = 1,17	Thermoplast: Total required electric energy per open/close cycle in kWh
TP_E_Operating_Total	TP_E_OpenClose*n_OpenClosePerDay*T_DesignLife*2 = 1,28E6	Thermoplast: Total required electric energy for physical operation during design life in kWh
TP_L_TransportFactoryToSite_tkm	(TP_M_Total/1000)*TP_L_TransportFactoryToSite = 4,9E3	Thermoplast: Unit conversion from km to tkm
TP_M_Fibre_Total	TP_M_Total*TP_Fibre_wt_frac = 1,28E5	Thermoplast: Total glass fibre mass in kg
TP_M_Resin_Total	TP_M_Total*TP_Resin_wt_frac = 8,52E4	Thermoplast: Total thermoplastic resin mass in kg
TP_M_Total	TP_wt_fraction_of_ST*ST_M_Steel_Total = 2,13E5	Thermoplast: Total product mass in kg
TP_Resin_wt_frac	1-TP_Fibre_wt_frac = 0,4	Thermoplast: Laminate weight fraction of resin %
TS_E_OpenClose	ST_E_OpenClose*1 = 1,17	Thermoset: Total required electric energy per open/close cycle in kWh
TS_E_Operating_Total	TS_E_OpenClose*n_OpenClosePerDay*T_DesignLife*2 = 1,28E6	Thermoset: Total required electric energy for physical operation during design life in kWh
TS_L_TransportFactoryToSite_tkm	(TS_M_Total/1000)*TS_L_TransportFactoryToSite = 4,9E3	Thermoset: Unit conversion from km to tkm
TS_M_Fibre_Total	TS_M_Total*TS_Fibre_wt_frac = 1,28E5	Thermoset: Total glass fibre mass in kg
TS_M_Resin_Total	TS_M_Total*TS_Resin_wt_frac = 8,52E4	Thermoset: Total thermosetting resin mass in kg
TS_M_Total	TS_wt_fraction_of_ST*ST_M_Steel_Total = 2,13E5	Thermoset: Total product mass in kg
TS_Resin_wt_frac	1-TS_Fibre_wt_frac = 0,4	Thermoset: Laminate weight fraction of resin %
ST_M_Concrete	ST_V_Concrete*ST_p_Concrete = 4,46E6	Steel: Total concrete mass in kg used for bascule basement
HY_M_Resin	HY_Resin_wt_frac*HY_M_ResinAndFibre = 8,82E3	Steel/Thermoset Hybrid: Total resin mass in kg
HY_M_Fibre	HY_Fibre_wt_frac*HY_M_ResinAndFibre = 1,32E4	Steel/Thermoset Hybrd: Total fibre mass in kg
HY_Resin_wt_frac	1-HY_Fibre_wt_frac = 0,4	Steel/Thermoset Hybrid: Total resin weight fraction %