Composite materials and their integration in bridges

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Summary

This bachelor thesis is about the usage of composite materials in bridges. Composite materials are fairly new and therefor we've only scratched the surface of what these materials can achieve. These materials are starting to get integrated in buildings and structures, but a lot of their properties are still unknown due to the limited time of their integration and lack of standardized design codes. In this thesis I have tried to examine the advantages of composite materials and if their usage in structures such as bridges, which have a designed lifetime between 80-120 years, is superior to traditional materials such as concrete. In order to do this an explanation on what the composition of composite materials is about has been made, such as the matrix, the fibres and the resins. The subdivision of bridges as well as an examination of an existing FRP bridge has been made.

Key words: Bridge; Composite; Fibres; FRP; Resins

Resumen

Esta tesis de licenciatura trata sobre el uso de materiales compuestos en puentes. Los materiales compuestos son bastante nuevos y por eso sólo hemos arañado la superficie de lo que estos materiales pueden lograr. Estos materiales están comenzando a integrarse en edificios y estructuras, pero muchas de sus propiedades son aún desconocidas debido al tiempo limitado de su integración y la falta de códigos de diseño estandarizados. En esta tesis he intentado examinar las ventajas de los materiales compuestos y si su uso en estructuras como los puentes, que tienen una vida útil de entre 80 y 120 años, es superior a los materiales tradicionales como el hormigón. Para ello se ha explicado en qué consiste la composición de los materiales compuestos, como la matriz, las fibras y las resinas. Se ha realizado la subdivisión de puentes así como un examen de un puente FRP existente.

Palabras clave: Puente; Compuesto; Fibras; FRP; Resinas

Abstract

The project examines the use of composite materials in bridges. Here the classification, the manufacturing processes, advantages and disadvantages of the composites are explained. Also the different structures of a bridge, as well as an example where a composite deck of a 21m span bridge is compared to the same bridge but redesigned with a concrete deck.

Abstracto

El proyecto examina el uso de materiales compuestos en puentes. Aquí se explica la clasificación, los procesos de fabricación, las ventajas y desventajas de los compuestos. También las diferentes estructuras de un puente, así como un ejemplo en el que se compara un tablero compuesto de un puente de 21m de luz con el mismo puente pero rediseñado con un tablero de hormigón.

Thanks

Firstly I would like to express my gratitude towards universitat politècnica de valència for receiving me as an Erasmus exchange student and giving me the chance to write my bachelor thesis here. I especially want to extend my gratitude towards mentor Mr. Javier Orozco and Mr. Javier Calvo, as well as the international office, for guiding me through this thesis. In the period I have spend here I have met a lot of people who have helped me develop as a person and supported me throughout the writing of this thesis. Therefore I also want to thank my newly made friends and extend special gratitude towards Hogeschool Vives Oostende, especially Ms. Lien Velghe, for giving me the opportunity to do an Erasmus exchange program. As well as my parents and friends, who stayed at home, who have supported me no matter what happened!

Acronyms used

ASSET	Advanced structural systems for tomorrow
B.C.	Before Christ
CFM	Continuous filament mat
CMC	Ceramic matrix composite
CSM	Chopped strand mat
e.g.	Exempli gratia
etc.	Etcetera
FRP	Fibre reinforced polymer
GFRP	Glass fibre reinforced polymer
LCC	Life cycle cost
LUSAS	London university stress analysis software
MMC	Metallic matrix composite
PMC	Polymer matrix composite
RC	Reinforced concrete
SLS	Serviceability limit state
ULS	Ultimate limit stress
U.S.	United States
UV	Ultra violet
WR	Woven rovings
$\sigma_{x,t,k}$	Tensile strength (long.)
$\sigma_{y,t,k}$	Tensile strength (trans.)
$E_{x,t,k}$	Tensile modulus (long.)
$E_{y,t,k}$	Tensile modulus (trans.)
$\sigma_{x,c,k}$	Compressive strength (long.)
$\sigma_{y,c,k}$	Compressive strength (trans.)
$E_{x,c,k}$	Compressive modulus (long.)
$E_{y,c,k}$	Compressive modulus (trans.)
$\tau_{xy,k}$	Shear strength (in-plane)
$G_{xy,k}$	Shear modulus (in-plane)
$\sigma_{x,b,k}$	Flexural strength (long.)
$\sigma_{y,b,k}$	Flexural strength (trans.)
$E_{x,b,k}$	Flexural modulus (long)
$E_{y,b,k}$	Flexural modulus (trans.)

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Inhoud

Chapter 1.

Introduction

A bridge is more than a crossing point. Villages throughout the ages have settled next to rivers because this has numerous advantages. These rivers sustain the village with water, food such as fishes and protection due to the geographical features of rivers. The village of Yaxchilan is an example of this. The village is surrounded by the Usumacinta River, which acts as a natural fortress for Yaxchilan. Yet in order to become a viable city they needed an easy way to cross the river throughout the year, without to many risks in order to transport wares from the farms and villages to the city centre. Therefore, they constructed a bridge with a length of 113 meters divided over 3 spans. The bridge was made from 2 towers composed out of stone and concrete. Which are connected through a wooden decking suspended by rope cables made of henequen.

Figure 1 Location village of Yaxchilan

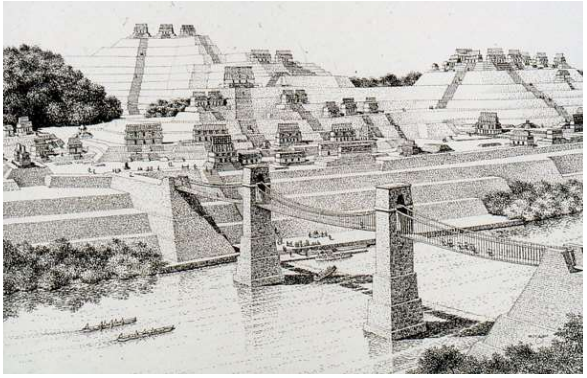


Figure 2 Bridge of Yaxchilan

These bridges provide the city with easy accessibility for their own inhabitants, as well as for travellers and traders. The less efforts and risks these traders had to take, the likelier they would travel to the city too trade. Which resulted in a lowered price for the villagers since the traders need less time and people to get to the city. So, these bridges provided the city with an increased traffic which caused it to thrive.

The peak period of the Inca empire is an example of the multifunctionality and providence of bridges as well. The length of the Inca empire was at his peak the length of the United States of America. Due to the road and bridge system the Inca's where able to cover great distances in a fairly limited time. They had runners (chaski or chasquis) stationed every 8km-12km in resting stations alongside the roads. These people had the job to take important messages and highly spoilable food such as fish for the nobles over great distances. With this system the Inca's where able to convey messages and wares over distances up to 240km in a single day. The biggest reduction in travel time was because of the bridges along the way. It's estimated that there were over 200 suspension bridges spanned above the ravines. Without these bridges the travellers would have had to make huge detours in order to find a reasonable crossing point. Since the Inca's hadn't developed the stone arch or iron tools yet, they used the techniques where they

Figure 3 The length of the Inca empire

were accomplished in. Namely the usage of natural fibres. They used natural fibres for clothing, boats, ropes for the bridges and even as a communication method with a system of knots (a quipu). The fibres used for the suspension bridges were woven together from ichu grass and could be as thick as a man's torso. The span that could be accomplished was at least 45m, which was longer than the European masonry bridges. Because of the massive number of bridges, the local populations were given the responsibility for the maintenance of the structure as their imperial tribute. For this an entire village works together once a year in order to create a new bridge to replace the old one or make structural improvements to the old bridges.

Figure 5 Fibrous suspension bridge

Figure 4 Quipu

Bridges are one of the signatures of the intellect and prosperity a culture has achieved. The pursuance of comfort can only be strived for when a city is thriving and able to provide for the basic needs of the villagers. Bridges are constructed in order to make the daily life more comfortable, but they have a lot of additional advantages such as described above. The techniques used for the construction of these structures are nowadays refined and improved. The modern-day goal is to create structures that are durable, guarantee safety, are practically maintenance free and have an ecological impact that is as small as possible. A lot of the now existing bridges must cope with increased traffic volumes and loads, exposure to environmental influences like de-icing salts, etc. Almost 40% of the damage in concrete bridges in due to corrosion of the reinforcement. The costs to repair this as well as the costs for traffic jams, detours, accidents during erection are a few of the reasons why these techniques could be improved. This is where composite bridges should play their part. Due to their high grade for prefabrication, good durability and fast assembly they offer a few advantages to the usages of traditional materials.

History of composite materials

The first composite materials already existed way before the evolution of the humans. Nature has developed composites such as wood (the combination of lignin and celluloses), bone (the combination of collagen and hydroxyl apatite), teeth, plant leaves and bird feathers.

Recent attempts to grow artificial bones have proved successful. The human body has the ability to regenerate fractured bones, yet when the injury is severe or caused by a disease this becomes more difficult. In such cases artificial bone composites can be used to replace the missing or damaged bone areas.

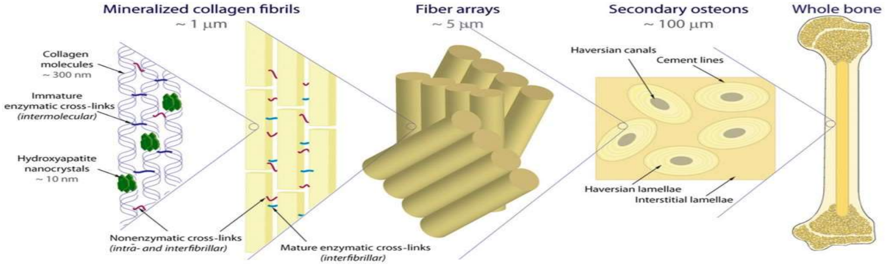


Figure 6 Natural composite material (bone)

One of the earliest composite usages by man was made by the Mesopotamians around 3400 B.C. They glued strips of wood in different angels to create plywood. Even the first ancient builders used straw reinforced mud bricks to build their walls. In the 12th century Mongols made a composite archery bow made from cattle tendons, horn, bamboo, silk, and natural pine resin. Some of the remaining bows were tested and proved nearly as strong as the modern-day composite bows. The bows proved accurate at distances of almost 450 meters.

Figure 8 Mesopotamian composite bow

Figure 7 Modern composite bow

Between 1870 and 1890 a revolution took place with the first synthetic resin. This polymer resin could be converted from liquid to solid using a chemical process called polymerization. (This is a process of connecting monomers together and creating large macromolecules of different sizes and shapes. The repeating units that serve as the building blocks of a polymer are small molecules called monomers.)

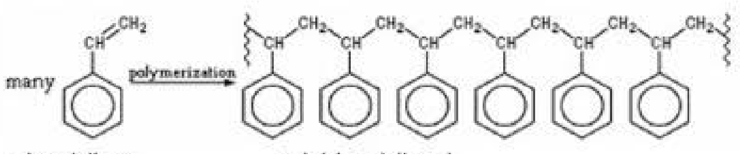


Figure 9 Polimerization

During the same period fibre glass was used to create a woven textile fabric which was being used on a commercial basis. In the early 1930s the two inventors of the first synthetic resin, the U.S. chemical companies American Cyanamid and DuPont, further developed polymer resins. The composites industrial revolution began in the late 1940s and expanded rapidly in the next 15 years. These developments where stimulated by Wold War II as the military searched for ways to reduce the weight of common building materials, yet at the same time increasing their mechanical properties, durability and weather resistance. Composites were being used as building materials for aircraft components, underground storage, boats, car bodies, truck parts, tanks and buildings.

In the present days the usage of composite materials is widely spread in the manufacturing of all the previous examples, but as well in infrastructures (buildings, bridges, roads, railways), pressurised vessels (fire extinguisher, scuba tanks), body armour, energy harvesting systems based on solar and wind power, transportation (busses, trains), sports (bikes, surfing boards), etc.

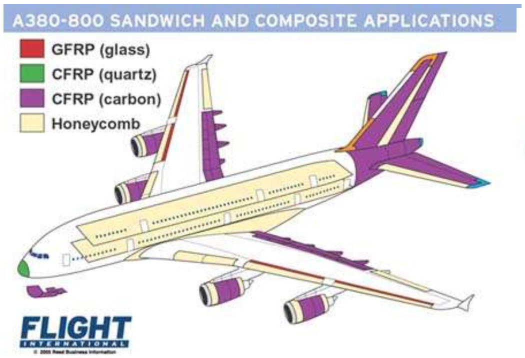


Figure 11 Composite parts of a plane

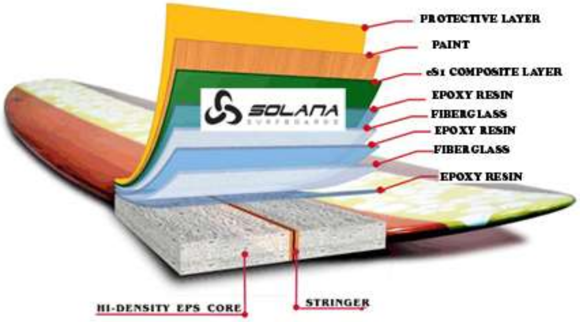


Figure 10 Composite surfboard

Chapter 2.

Classification of composites

A composite is a material formed by two (or more) materials in two (or more) distinct phases with different shape and chemical composition in order to obtain properties that significantly differ from the ones in the individual components.

Composites can be divided in a matrix phase and a dispersed phase. The matrix phase has a continuous character and is usually more ductile and less hard. The matrix phase holds the dispersed phase and shares a load with it. The dispersed phase is embedded in the matrix phase in a discontinuous form. The dispersed phase is usually stronger than the matrix phase. Therefore, it's also referred to as the reinforcement phase.

Many common materials have a small amount of dispersed phase in their structure as well, but since their properties are similar to their base components they are not called composite materials. For example, the physical properties of steel are similar to those of pure iron.

Composites are classified by their matrix or by their material structure. The matrices are classified as ceramic matrix composite (CMC), metal matrix composite (MMC) or polymer matrix composite (PMC).

2.1 Matrix

2.1.1 Metal matrix composite (MMC)

Metal matrix composite (MMC) are composed of a metallic matrix (aluminium, copper, lead, magnesium, titanium, zinc, iron, cobalt) and a dispersed phase of metal (lead, tungsten, molybdenum) or ceramics (oxides, carbides). The generally used matrix materials are aluminium, magnesium and titanium. However cobalt and cobalt nickel alloy are preferred for applications involving high temperatures. The reinforcement can either be continuous in the form of volumes which gives the composite the highest properties in the direction of the fibre orientation (anisotropic) or discontinues in the form of short fibres, particles or whiskers which give the composite isotropic properties. Isotropic properties have identical values of a property in all directions.

2.1.2 Ceramic matrix composite (CMC)

Ceramic matrix composite (CMC) are composed of a ceramic matrix and a ceramic dispersed phase. The ceramic matrix composites are reinforced by continuous long fibres or discontinuous short fibres. Discontinuous composites are composed through the conventional ceramic processes from an oxide or non-oxide matrix reinforced by ceramic fibres. Reinforcement of ceramic matrix composites are often done by silicon carbide fibres due to their high strength and stiffness (a good modulus of elasticity). Ceramic matrix composites were designed to improve the toughness of conventional ceramics to improve the brittleness, which is the main disadvantage of ceramics.

2.1.3 Polymer matrix composites (PMC)

Polymer matrix composites (PMC) are composed out of a polymer matrix and a fibrous reinforcement dispersed phase. The polymer matrix can consist out of thermoplastics (Low Density Polyethylene (LDPE), High Density Polyethylene (HDPE), polypropylene, nylon, acrylics) or thermosets (epoxies, phenolics). The reinforcing fibres may be arranged in unidirectional fibres, roving's (long and narrow bundles of fibre), a veil mat (a thin pile of randomly orientated and looped continuous fibres), Chopped strands (a thin pile of randomly orientated and looped short (3-4 inches) fibres) or a woven fabric.

The main disadvantages of polymer matrix composites are the low thermal resistance and a high coefficient of thermal expansion.

2.2 Thermosets

The thermoset composites have a reactive nature and are easily impregnated. The thermoset composite use glass, carbon or aramid fibres in the dispersed phase. This is to improve the properties of the young's modulus, impact strength, heat resistance and creep resistance. Some of the disadvantages of fibre additions are more costs, a higher viscosity, anisotropy, and abrasiveness on moulds and machineries. The orientation of the fibres defines the final properties of the composite.

The majority of the thermoset composites are based on epoxy resins and polyester resins.

2.2.1 Epoxy

Epoxy resins have a low molecular weight and are cured with hardeners in order to cross link the thermoset. These hardeners become a part of the finished structure and help develop the final properties of the product. Epoxies can also be cured at room temperature, but high temperature curing give superior properties. Polymer composites with an epoxy resin as thermoset matrix have good electrical properties, high wear resistance and outstanding adhesive properties, which are desired for laminated structures. Cured resins have better resistance to solvents and alkalis than polyesters, but their resistant to acids is also not good.

2.2.2 Polyester

Polyester resins are cured at room temperature and at an atmospheric pressure. The catalysis in polymer composites with a polyester resin as thermoset matrix are only used to initiate the curing process. They don't become part in the finished structure. Polymer composites with a polyester matrix have good mechanical, chemical and electrical properties. These polymer resins can be used as a compound for hard, brittle, flexible and resilient materials. Glass is frequently used as a reinforcing material for thermoset composites. The glass fibres are available in different forms. roving's (long and narrow bundles of fibre), a veil mat (a thin pile of randomly orientated and looped continuous fibres), Chopped strands (a thin pile of randomly orientated and looped short (3-4 inches) fibres) or a woven fabric. Long fibres give a greater strength to the composite, but shorter fibres give more uniform properties. There are different classes of glass fibres: E-glass the E is used because of its initial electrical applications. This glass is alkali free. S-glass ("S" for "Strength") is used when high young's modulus is important. In Europe S-glass is called R-glass ("R" for "reinforcement"). T-glass ("T" is for "thermal insulator") is a North American variant of C-glass and are resistant to chemical attack.

2.3 Thermoplastics

Thermoplastic composites use a thermoplastic polymer as a matrix and fibres (glass, carbon, aramid or metal) or particulate fillers as reinforcement for the dispersed phase. Depending on the preferred properties of the composite material a variety of fillers can be used. The addition of fillers can have multiple advantages such as density control, reduction of the thermal expansion coefficient, a higher thermal conductivity, improved mechanical properties and cost reduction. One of the important parameter to check the effectiveness of a filler is the aspect ratio (surface area to volume), which should be as high as possible. Discontinuous additives (reinforcing fillers) are used in order to obtain better mechanical properties. The properties of fillers are affected by their particle size, shape and surface chemistry. The role of additives in a polymer composite cannot be underestimated. Some of the features obtained by fillers are cost reduction, high melt viscosity, property enhancement (electrical, magnetic, fire resistance, degradability), lower mould shrinkage and thermal expansion and faster moulding cycles (due to the higher conductivity).

Polymer matrix composites are very popular due to their low cost and simple manufacturing methods.

Chapter 3.

Manufacturing processes

3.1 Open moulding

Open moulding, or contact moulding, is the simplest method of fabrication it is usually used for the manufacturing of large individual parts such as pools or boats. With this technique the resins and reinforcements are exposed to air while they cure or harden. Open moulding utilizes different processes such as hand lay-up, spray-up, casting, and filament windings.

3.2 Hand lay-up

This is the most common and least expensive method due to the low equipment costs. The hand lay-up method is suitable for a wide variety of products in different sizes. This method is a slow, manual and time-consuming method. In order to increase the quantity more moulds can be used. This method involves the cutting (by hand or powered devices) of the reinforcement materials. These pieces are placed on a mould that has been coated with an anti-adhesive layer and a resin coating. The pieces now have to be impregnated with the resin matrix after which they are hand rolled to create a uniform distribution of the reinforcement and to remove the entrapped air. In order to achieve the wanted thickness for the material, resin and reinforcement can be added until it is adequate. When the preferred thickness is reached the composite needs to cure. This can take place at room temperature (often with heated air assistance), ovens (with heated platen presses) or autoclaves. This curing can take up to an hour, a half day or longer. Curing can also be accomplished by moulding through a vacuum bag. Here a non-adhesive material is placed around the lay-up material and mould, after which a vacuum is slowly created to extract all the excessive air and resin. This method can also be used by using pre-impregnated reinforcements (prepreg). This eliminates the manual handling of the reinforcement and resin. This can improve the quality due to the consistent control of the uniformity of the reinforcement and resin. Prepreg must however be refrigerated when stored in order to prevent premature curing.

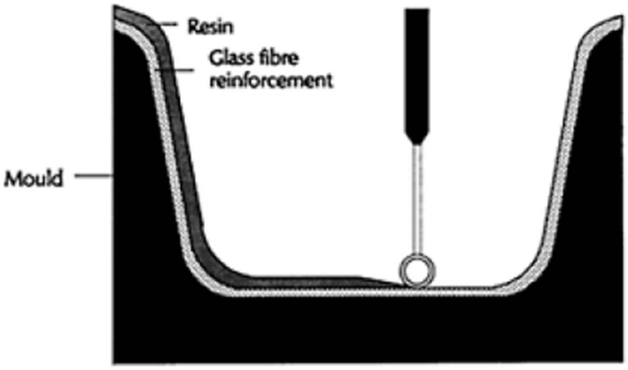


Figure 12 Hand lay-up

3.3 Spray-up

This method involves the usages of a specially designed spray gun. This gun simultaneously chops the reinforcement in small pieces while spraying the resin on the mould. This mould has been coated with an anti-adhesive layer and a resin coating just as in the hand lay-up method. The with resin saturated fibres are sprayed with a predetermined ratio of reinforcement and resin. In this process the uniform thickness and consistency of the composite is determined by the operator of the spray gun unless the spray gun is used by a machine. This method permits a rapid formation of a uniform composite coating. The mechanical properties are however lower than in the hand lay-up method since this method is unable to use long continuous reinforcement fibres.

3.4 Filament winding

Filament winding is a method were narrow reinforcement fibres are wrapped around a spindle which has the shape of the requested product. The resin can be applied on the fibres prior to the winding (wet filament winding) by going through a bath of resin just before being woven or the resin can be sprayed onto the fibres after being woven on the spindle. When the spindle is removed a hollow shape is the result. This method is mostly used for tubing, pipes, tanks, pressurised vessels and items of similar shapes.

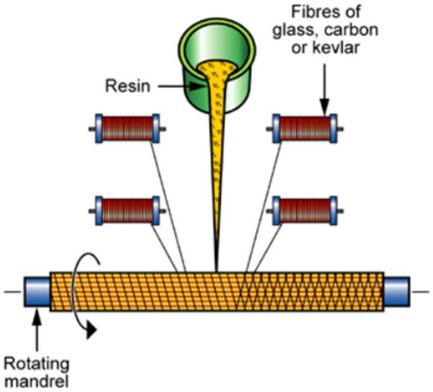


Figure 13 Filament winding

3.5 Closed moulding

Closed moulding is a process that is usually automated and requires special equipment. Therefore, a closed moulding process is normally used in industrial processes where high quantities are desired. In this moulding system raw materials are cured inside a two-sided mould (in order to create smooth surfaces on both sides) or a vacuum bag.

3.6 Compression moulding

This is a moulding process where a preheated split mould attached to a hydraulic press is used in order to shape a moulding charge. The charge takes the form of the mould during the compression and will start curing as a result of the increased heat and pressure on the material. The charge consists out of a pre-weighted amount of resin mixed with chopped reinforcement fibres, a hardening and anti-adhesive additive. This may be in the form of powders, pellets, plastic masses or pre-formed sheets. The charge is usually preheated before being placed in the mould to shorten the moulding cycle time since this makes the charge softer. When the upper half of the mould has come down and applied pressure on the charge, the cavities of the mould are filled up after which a heating system is implemented in order to start the curing. When the curing process has finished the mould is opened and the composite is removed with the help of the ejector pin. The cycle time for 1 piece is about 1-6 minutes.

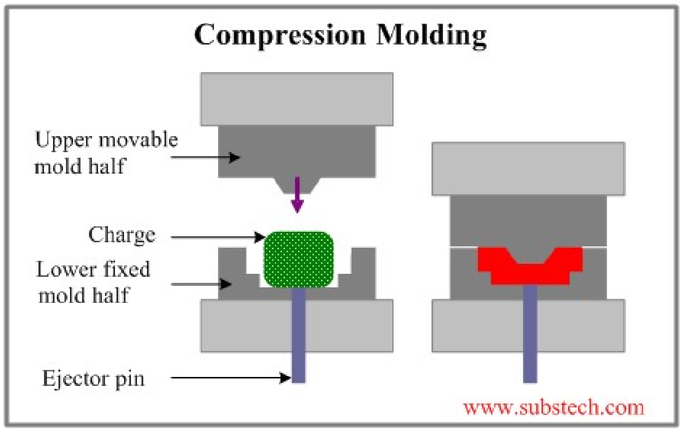


Figure 14 Compression moulding

3.7 Injection moulding

This is a moulding process in which a molten resin mixed with very short reinforcement fibres is forced into a mould cavity under high pressure. A mixture of resin and reinforcement is supplied to an injection moulding machine in the form of pellets. A hopper feeds the pellets into the injection machine where a screw pushes the pellets forward towards to mould. There are heating elements installed on the barrel of the injection moulding machine which cause the pellets to melt. The molten pellets are being pushed under high pressure into the mould by the screw which is called a reciprocating screw because it doesn't only rotate but moves forwards and backwards as well. After the cavity of the mould is filled with the heated resin the, in the mould equipped, cooling system provides a controlled cooling and solidification of the material. When the material is solidified the mould opens and ejects the composite with the ejecting pins. This method is mainly used for thermoplastic matrices, but they can also be used for thermoset matrices. In this case curing occurs in the heated barrel during the heating and melting of the material. This process is highly productive in the manufacturing of parts with the same shape and provide a high accuracy in the moulded shape of the produced parts.

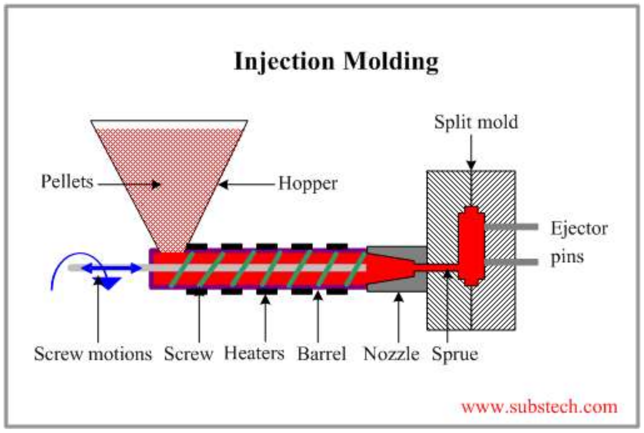


Figure 15 Injection moulding

3.8 Transfer moulding

Transfer moulding is a moulding process in which the reinforcement fibres are being placed inside a preheated mould cavity after which a hydraulic press pushes the heated charge, which consists out of a pre-weighted amount of resin mixed with additives and fillers, into the cavity. The charge may be in the form of powders, pellets, plastic masses or pre-formed blanks before it is heated in the transfer pot. The high pressure of the press ensures that the cavity is completely filled. The reinforcement fibres become impregnated with the resin, meanwhile the curing process is started due to the heat and pressure that is applied on the material. This method is primarily used on composites with thermoset matrices, but some thermoplastic parts are also produced by transfer moulding. After the curing the mould is opened and the moulded part is removed by the ejector pin. If a material with a thermoplastic matrix is moulded, the mould and manufactured part are cooled down before opening the mould.

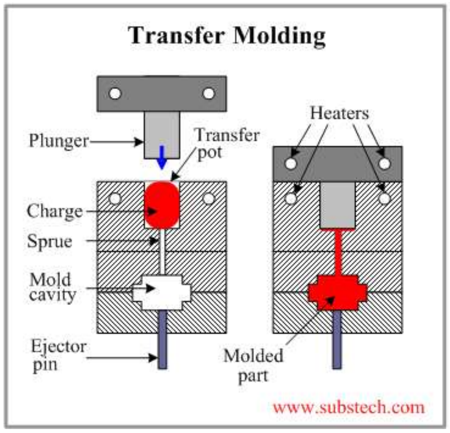


Figure 16 Transfer moulding

3.9 Pultrusion

Pultrusion is a moulding process primarily to produce long and straight shapes with a constant cross-section. It produces profiles with high structural properties due to the extremely high fibre loading. Pultrusion is almost the same as extrusion but the composite material is pulled through a mould instead of pushed. In this process continuous reinforcement fibres are impregnated in a resin bath after which they are pulled by a powerful tractor mechanism through a mould. The mould strengthens the saturated reinforcement and controls the resin/fibre ratio. The mould is heated by electricity or hot oil in order to rapidly cure the composite material. The latest pultrusion technology uses direct injections, in which the resin is introduced inside the mould, rather than through an external resin bath.

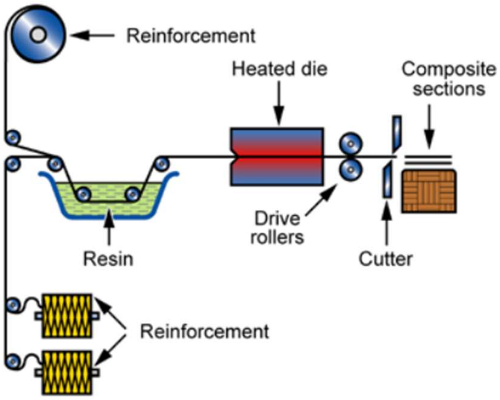


Figure 17 Pultrusion

Chapter 4.

Materials

4.1 Fibres reinforcements

Fibres are used in order to transmit strength and structural stiffness to the composite materials. The selection of the volume fraction of fibres in the composite determines the strength, stiffness and stress-strain properties. The influence of external loads is also defined by the used matrix resin and the direction of the fibres. The volume fraction of the fibres have a direct relation to the mechanical properties of the composite material. The theoretical maximum of the volume fraction for fibres is around the 90%, yet it is more realistic to expect around 70%. In practical applications due to the manufacturing process the fraction lies between 50%-65%. When the volume fraction is to low the properties of the composite material will not meet the expectations. When there is too much fibre reinforcement the strength properties of the composite will decrease because the matrix resin won't be able to fully surround and bond with the fibres.

The reinforcement fibres are made out of glass fibre, carbon fibres or aramid fibres.

The production of glass fibres can be divided in a few steps: batching, melting, fiberization and coating. Glass is made of silica sand (SiO_2) that is heated above 1720°C, which is the melting point of the silica sand, and cooled quickly to prevent crystallization which would form quartz instead of glass. To produce glass fibres the silica sand is combined with other ingredients in order to reduce the working temperature and add other properties that are useful in specific applications. In the batching phase these ingredients, who are carefully weighted, are mixed together. The melting of the glass happens in a high temperature natural gas filled furnace (1400°C). When the molten glass has passed through different stages in the furnace it is ready to be fiberized. This happens through extrusion and attenuation. During the extrusion the molten glass passes through a bushing that is preheated in order for the glass to maintain its viscosity. The attenuation is the process where the melted glass is mechanically pulled into fibrous elements with a diameter ranging from 4 µm to 34 µm called filaments. In order to draw these filaments a high-speed winder catches the stream of molten glass after which it revolves with a speed of 3km per minute. This is much faster than the glass exits the bushier which causes an applied tension on the glass which draws it into filaments. In the final stage a chemical coating is applied which may include lubricants, binders and/or coupling agents for the fibres to be protected and achieve an affinity for the resin chemistry.

Carbon fibres are classified by their tensile modulus. They are classified as low modulus, standard modulus, intermediate modulus, high modulus and ultrahigh modulus. The low modulus carbon fibres have a tensile modulus of 240 million kPa, while the ultrahigh modulus a modulus of 500 million to 1 billion kPa has. This means that the strongest carbon fibres five times the tensile modulus of steel have (200 million kPa). 90% of the carbon fibres are made out of polyacrylonitrile. The other 10% is made from rayon or petroleum pitch. The production process can be divided in the following steps: spinning stabilizing, carbonizing, surface treating, sizing. In the first step acrylonitrile plastic powder is mixed with other plastics after which a catalyst is added in order to start the polymerization process to form polyacrylonitrile plastic. The plastic can now be spun into fibres using a range of different methods. For example: The plastic can be heated after which it is pumped through tiny jets in a chamber where the solvent evaporates in order to leave a solid fibre. These fibres are then washed and spun. During this spinning the filaments are stretched into the desired diameter. The spinning and stretching is important because the internal atomic structure of the fibre is formed and aligns during this process. For the fibres to achieve a thermally stable bonding during the carbonization the fibres need to be stabilized. This is accomplished by heating the fibres in air. This way they fibre molecules pick up oxygen and rearrange their atomic bonding pattern. Once the fibres are stabilized they are heated, to 1000°C-3000°C, in a furnace filled with a gas that does not contain oxygen. This gas has been put under a pressure that is greater than the air pressure in order to keep oxygen from entering the furnace. In order to achieve this the entrance and exit of the fibres are sealed of as well. The lack of oxygen keeps the fibres from burning. Instead, these high temperature causes the atoms of the fibre to vibrate violently until most of the non-carbon atoms are repelled. This process is called carbonization. This leaves a fibre composed of long, tightly inter-locked chains of carbon atoms with only a few non-carbon atoms remaining. The surface of the carbonized fibres do not bond well with epoxies. This is why the surface is treated by oxidation. This etches and roughens the surface of the fibres which cause it to have better (mechanical) bonding properties. After oxidizing the fibres, they are coated to protect them from damage during winding or weaving. This is called sizing.

To produce aramid fibres filament yarns are prepared by dry-jet wet-spinning a liquid solution of PPTA polymer in sulfuric acid. After which the solution is extruded through spinning holes. The liquid filaments passes through an air gap and enters a coagulation bath containing water. Here the filaments are washed, neutralized, dried and wound onto spools. In the spinning solution, the stiff aramid molecules form a liquid crystalline structure in which the polymer molecules are well aligned. During the spinning process itself, the elongational stretching of these structures in the air gap induces the structure and the orientation of the polymer molecules to align with the direction of flow.

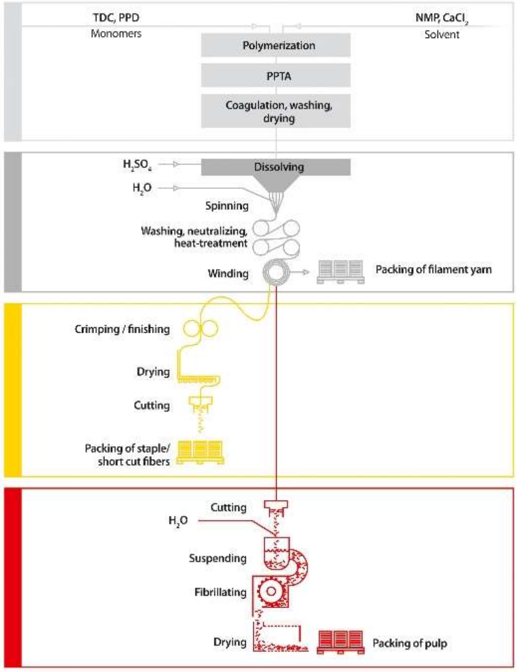


Figure 18 Fibre production process

4.2 Fibre arrangements

The composites can be assembled with different fibre arrangements. The way the fibres are used influence the volume fraction used in the composite. The arrangement of the fibres determines specific increases or decreases in the properties of the materials.

4.2.1 Rovings

Rovings are continuous strands of multifibres, supplied on creels and used directly and extensively in automated composite processes such as pultrusion and filament winding. The use of rovings is restricted to processes where tension can be applied to control orientation and fortification. The fibres strength properties are the highest in rovings, but decrease when these materials are used as woven reinforcements.

4.2.2 Mats

Chopped strand mat (CSM)

This is a non-woven two-dimensional material with randomly orientated fibres, chopped into short strands and fairly evenly distributed. The mat is held together by a binder which may separate during the impregnation phase. Due to the nature of this material, with randomly overlapping fibres, the fibre volume fraction cannot exceed about 25%. The manufacturing process of the composite will determine the exact level. The fibre fraction that determines the structural reinforcement effect in the internal-plane directions is usually not more than 10% of the volume. The use of discontinuous fibres leads to a greater dependency on the load conveyance of the resin. This also affects the long-term strength properties, which are lower than those of continuous fibres. The composite materials manufactured from chopped strand mat are mostly limited to low stress and low stiffness applications.

Continuous filament mat (CFM)

The continuous filament mat is similar to the chopped strand mat, with the exception that the fibres are randomly rotated and continuous. The properties and application potential are similar as well.

Woven rovings (WR)

Woven rovings are bidirectional reinforcements constructed from untwisted, parallel tows of fibre. These woven reinforcements allow for an easy to handle material for the construction of large area composites. Woven materials provide a higher strength and stiffness for the composite, but due to the presence of crimp the volume fraction of fibres is restricted to 40% unless when the process compactation is high. This volume fraction is divided in 2 sets of 20% volume fraction in the weft and in the warp. The material is woven in several layers of parallel roving strands, oriented in the machine direction (0° or warp), perpendicularly (90° or weft) or diagonally (+ or -45°). These woven materials are considered when the advantages of continuous fibres and the aligned bidirectional character of the reinforcement are preferable for the loading cases of the application.

4.2.3 Fabrics

Woven fabrics are constructed by weaving warp (longitudinal 0°) and weft (transversal 90°) fibres or filaments in a range of patterns in order to form a fabric style such as plain, unidirectional, twill, satin and others. These fabrics are usually lighter than rovings and have less crimp. This provides the fabric with more space which results in a higher fibre volume fraction. Depending on the method of compaction the volume fraction may exceed 50%. Non-crimp materials should be considered when the highest material properties are required. A low crimp material is also beneficial for the creep-behaviour of the material.

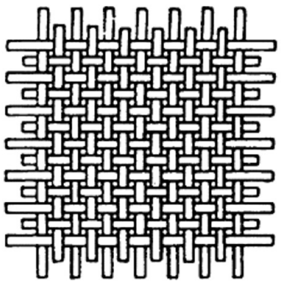


Figure 19 Plain weave fabric

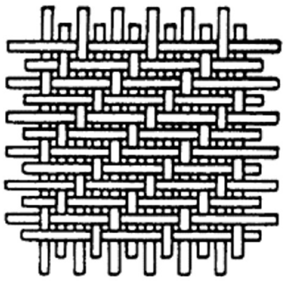


Figure 20 Till weave fabric

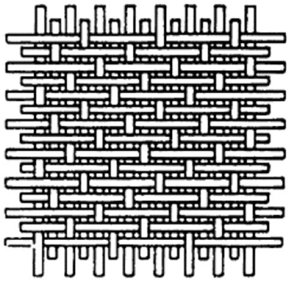


Figure 21 Satin weave fabric

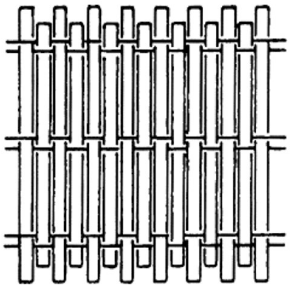


Figure 22 Uni-directional weave

4.2.4 Prepreg

Prepreg are fibre reinforcement that have already been saturated with resin, but the resin hasn't been cured fully. Depending on the resin system the required temperature for the manufacturing has to be between the range of 70°C and 150°C provided that consolidating pressure has been applied. The fibre volume fraction should easily exceed 50%. In order to cure these materials elevated temperatures are essential. The usage of prepreg materials should be considered when the material needs optimum properties, a low void content and a high fibre volume. When the curing is correctly executed the mechanical properties and environmental resistance can achieve its highest values.

4.3 Resins

The properties required of the resin are ordinarily dominated by the need of strength, stiffness, toughness and durability. Before selecting the resin the application, service temperature, method of fabrication, environment, level of required properties and curing conditions should be taken into account. Knowledge about the service temperature is necessary in order to correctly use the composite material. When the composite temperature gets close to the glass transition temperature a loss in stiffness and a significant creep will occur. When the temperature of a polymer gets below the glass transition temperature, it will become hard and brittle. Some polymers are used beneath their glass transition temperature, others will be used above it. Control of the curing process and thoroughly and accurate blending of the components is paramount for the attainment of a fully cured polymer. When this happens correctly the material will attain its optimum mechanical properties, reduce moisture diffusion, limit creep, prevent heat softening and minimise plasticisation effects.

4.3.1 Polyester resin

There are a few polyester based resins, all with specific properties. The most commonly used resin is the orthophthalic. This is the least expensive polyester system, but has a reliable combination of good mechanical properties and a chemical resistance. Isophthalic resins should be considered when there is a need for better water, chemical or fire resistance. This system has a more rigid structure and superior mechanical properties. They are more expensive then Orthophthalic resins. bisphenol A systems are considered when the most durable composite is required. They are almost exclusively used in high performance applications where the higher cost can be explained due to the sustainability. Chlorendic systems have a high fire resistance, but the strength and toughness properties are lower than the isophthalic resins.

4.3.2 Epoxy resin

The mechanical properties and water resistance of epoxy resins are superior to those of polyester resins, with less shrinkage during curing. The price is of the standard epoxy resins are 2-3 times higher than the polyester resins and up to 10-15 times higher for the higher performance prepreg materials. These resins are generally more frequently used in automated fabrication processes. Epoxy resins should be considered when the application requires good mechanical properties and durability during elevated temperatures or when a higher shear strength is required than the polyester resins can provide. Epoxy resins should only be used when elevated temperature curing can be used. The Optimum properties of the material are not met until a curing temperature between 60°C-150°C has been reached. Some epoxy resins have a low UV-resistance and need an appropriate surface protection.

4.4 Cores

Cores may be used as a load bearing structure or in order to shape the composite material. These cores may be foams, honeycombs or solid materials. Structural cores should be used efficiently in sandwich construction materials. The properties required for good structural cores should be a low density, high shear modulus and shear strength, thermal and dimensional stability, fatigue resistance, impact strength, resistance to moisture, ease of shaping and good bonding strength.

4.4.1 Foams

Foam consists of open or closed cell materials made from a wide variety of plastics. These foams may be used in prefabricated sandwich panels or can be foamed in situ. With panels foamed in situ more problems are presented, the attainment of properties is harder to achieve. Commonly used core materials include polyurethanes, rigid polyvinyls and polymethacrylimides available in lightweight and industrial grades.

Reinforced foams

Some plastic foams may be reinforced with glass or other short fibres. The improvement of the physical and mechanical properties depends on the fibre arrangement, type, amount. The consistency of these properties is harder to control.

Other foams

Syntactic foams offer higher strength properties than other foams. This foam is produced by mixing microspheres of glass, ceramics or polymers with other liquid polymers in order to cast or form a moulding compound. These materials are mostly lightweight and strong. They can be shaped or pressed in cavities and moulds where rigid foams are not practicable.

4.5 Honeycombs

Honeycombs are formed by almost any thin sheet material. These materials are joined together in the same shape a bee’s honeycomb is designed. The structural performance of honeycombs is exceptionally high for direct compression and shear. These materials should be selected when weight efficient structures are wanted.

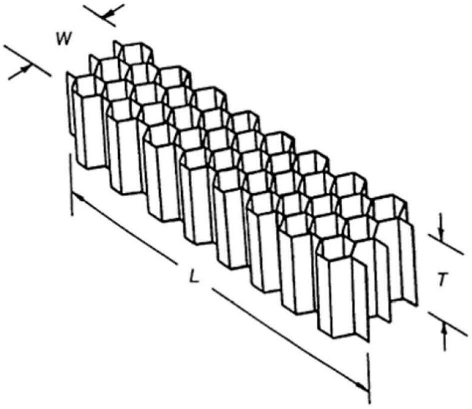


Figure 23 Honeycomb matrix

4.5.1 Aluminium

Aluminium honeycombs can be used with the prospect of a composite with electrical conductivity properties. In order to prevent internal galvanic corrosion problems in wet environments the honeycomb is electrically insulated from the core by a glass fibre interlayer.

4.5.2 Aramid

Aramid fibres can be dipped in different resins to form a paper that can be used to form a honeycomb. The properties depend on the thickness of the paper, the cell geometry and the size. The advantages of non-metallic honeycombs are that they don't corrode and are impact resistant.

4.5.3 Solids

Solids may be used as cores, but in sandwich construction only the strong lightweight materials will be efficient. Balsa wood has been widely used because it can offer advantages to foams in compression or with a critical shear loading.

4.5.4 Others

Other non-metallic honeycombs such as glass FRP, aramid FRP and Kraft paper have to be considered for specific applications.

4.6 Gel coats

Gel coats are included in the total composite system specifications because it can have advantages for the durability of the product, but are regarded as non-structural. Selection, specification and thickness of these gel coats depend on the desired prime function of the material. When gel coats of top coats are used the combability with the structural layers underneath should be researched. During the construction the coating should be controlled in order to insure a good adhesion. A good quality of the gel coat is necessary to prevent penetration of water and blistering due to osmosis. Gel coats can be used in order to improve weathering, to add flame retardancy or provide an increased thermal barrier, to filter out ultraviolet radiation, to improve chemical resistance, to prevent erosion, to provide electrical insulation (relevant to carbon fibre composites), to provide an increased barrier to moisture or to provide a colour scheme and improve general finish.

4.7 Surface veils

C-glass materials are commonly used as surface veils. These veils should be used when the appearance and properties of the surface layers need to be improved or when a high chemical resistance is required. Surface veils shouldn't be used on surfaces intended to be joined by bonding.

4.8 Additives

In fibre reinforced polymers the additives form an important part since this substance that is compounded into the FRP defines its characteristics. In some cases the additives can account for 15%-20% of the total composite weight. Some of these additives are purely used with an aesthetics purpose, while others are focussed on the property modification of the material. A few examples of additives and their functions are: marble dust/silicone dioxide (enhances compressive strength), antimony trioxide & alumina trihydrate (improves fire retardancy), ultra violet stabilizers (reduces UV-degradation & discolouration), thixotropes (thickens resin, reduces drainage).

4.8.1 Fillers

Fillers are non-structural components of a composite and should be limited to the body of the composite because they usually degrade the long-term structural properties and durability. Fillers are inorganic particulates that can be added to the resin in order to reduce shrinkage, to increase viscosity, increase local hardness, reduce flammability, reduce the peak of the exotherm reaction during the curing and to reduce costs. These fillers can also increase the modulus and compressive strength.

4.8.2 Pigments

Pigments can be used in the resin or gel coat systems. They are used in order to obtain a desired colour scheme. These pigments need to be analysed in order to confirm if it will affect the properties of the material. Some pigments affect the long-term structural stability of the composites. Metallic salt-based pigments may seriously lower the adhesion between the matrix and the fibres.

4.8.3 Flame retardants

The usage of flame retardants should be analysed before the composite is used, because these additives can result in lower than expected mechanical properties and weather resistance. These fire retardants can be incorporated in the resins or in the coating form.

Chapter 5.

Polymer properties

The general properties of fibre reinforced polymers depend on the fibre properties, the matrix properties, the fibre volume fraction and the orientation and geometry of the fibres.

5.1 Fire resistance

The experimental testing of fibre reinforced polymers has not been persuaded as much as tests for the mechanical properties of composite materials. After being exposed to an excessive heat the properties and stiffness value of the composite materials are greatly affected. The comparison of the reaction between fibre reinforced polymers and steel after being exposed to excessive heat can be found in the following graph. Here the relationship between heat and tensile yield stress are shown. FRP are faster affected by an increasement of heat than steel. When the temperature rises to 1000°F (538°C) the polymer loses all tensile yield stress, while the temperature needs to rise to 1500°F (816°C) in order for steel to lose all its tensile yield stress. When the fibre reinforced polymers are exposed to a temperature between 100°C – 200°C the composite will soften. As a result, it will start to creep and warp while this often leads to the buckling of the load bearing fibre structure of the polymer. When the temperature rises to 300°C - 500°C the polymer matrix will melt and release heat and toxic gases. Thermal analysis is an important aspect in the usage of composite materials in structures. The thermal expansion coefficient of FRP is higher than those of steel or concrete. The expansion rate of the polymer depends on the fabrication materials, especially of the plastic resin. Before combining these materials an analysis has to be done. The stiffness of steel and a GFRP are compared when being subjected to heat. When the temperature reaches a value of around 200°C the GFRP loses all its stiffness properties. The heat reaction is a big disadvantage for composites in construction applications and infrastructures. This has to be researched before being integrated in a structure.

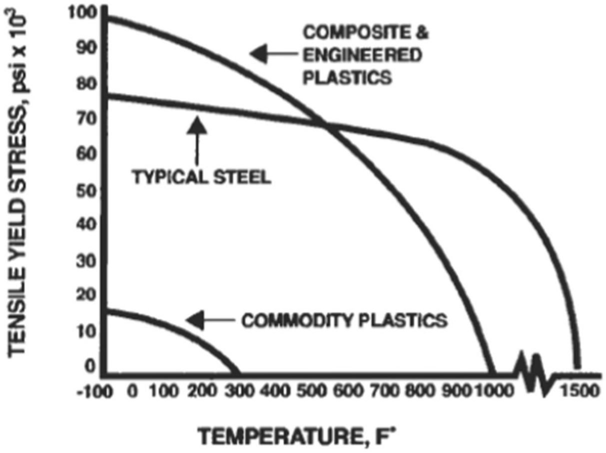


Figure 24 Fire resistancy

5.2 Permeability

The permeability of FRP can’t be guaranteed. The matrix resin encloses the reinforcement fibres inside the composite, but it is not 100% moisture proof. In order to acquire a material that is fully moisture proof a gel coating polymer needs to be applied on the outer surface of the FRP. A coupling agent directly applied to the reinforcement fibres may also protect the fibres from penetrating moisture.

5.3 Creep & stress ruptures

Creep is the deformation of a material that has, for a time, been under a constant load. Creep is therefore time dependant. The occurring creep under high and low loads is shown in following graph. The main component that triggers creep in a composite material is the matrix, since the reinforcement fibres display nearly no creep. The creep of the matrix is nonetheless determined by properties of the composite itself and external influences such as the resin type, volume fraction of the fibres, fibre orientation and the bonding conditions for the internal properties and temperature, loading, chemical action and moisture content for the external factors. The resistance to creep depends on the alignment of the fibres to match the direction of the external loading and hence to minimise stresses in the matrix.

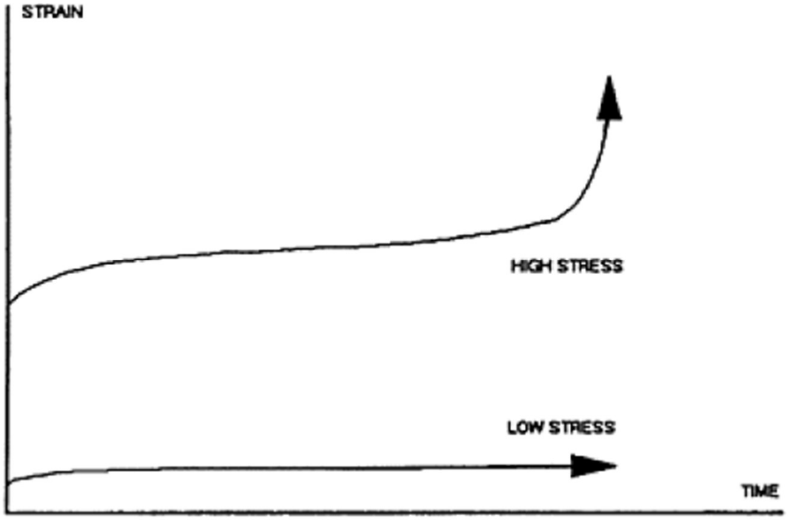


Figure 25 Creep under high and low stresses

5.4 Fatigue strength

In composites fatigue is highly dependent on the resin properties and laminate quality. The first steps of fatigue failure begin with fibre deboning and resin cracking. FRP structures can be prone to fatigue failure in both compression and tension unlike steel and metals. The general consensus amongst researchers who have examined the fatigue strength is that fatigue failure in composites is generally caused by damage to the matrix, such as debonding and cracking. This area is still an un-researched detail of FRP's and requires further testing.

5.5 Corrosion

When composites are compared to conventional construction materials such as reinforced concrete, steel, timbre, etc. it is clear that the composites possess a substantially higher resistance to corrosive chemical agents. This makes them an attractive solution when corrosion is a concern.

A comparative test was carried out by a Russian composite manufacturer "Apatech", between a composite and reinforced concrete drainage channel used in order to remove water from a roadway. After two years the experiment was evaluated, the effects were very clear. The reinforced concrete channel was broken and had started to crumble. The composite channel had virtually no signs of disturbance, discolouration or surface texture disruption.

5.6 Failure types

The ultimate limit strength of a laminate is usually in terms of how much load it can withstand before complete failure. At first the resin breaks down and the internal reinforcement fibres break, causing a complete failure. However, before this ultimate failure occurs, a certain stress level will be reached where the resin will begin to crack/debond away from the fibres that are not aligned with the load direction. Voids will be created in the resin matrix due to the spread of these cracks. This is called “transverse micro-cracking” and is the beginning of the composites failure process. As the ultimate strength of a laminate in tension is governed by the strength of the fibres, these micro-cracks don’t immediately reduce the properties of the laminate. Yet, in a location near water or an environment with a lot of moisture in the air, could allow the ingress of moisture into the resin through these cracks. This increases the weight, reduces the stiffness and eventually drops the ultimate properties.

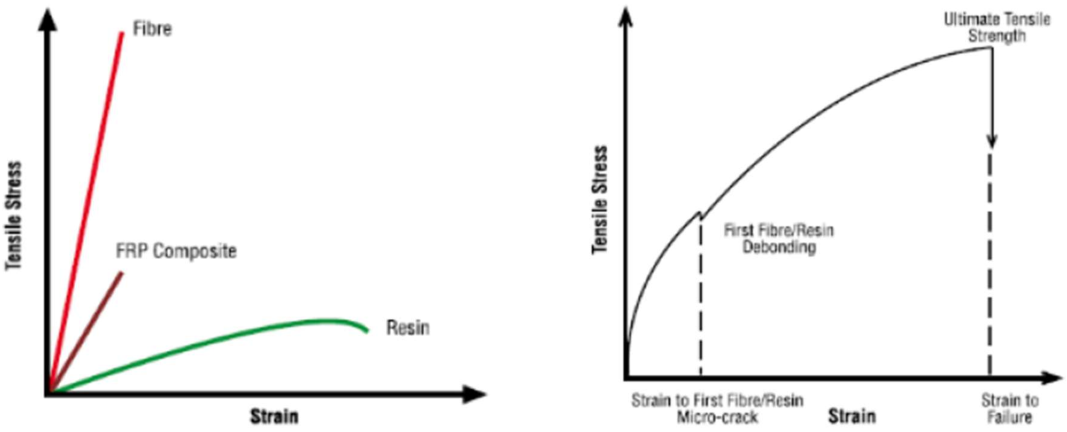


Figure 26 Failure per composed material/Stress strain curve

Chapter 6.

Advantages and disadvantages of fibre reinforced polymers

6.1 Advantages

6.1.1 Reduced mass

Normally FRP are lighter than their reinforced concrete equivalents. (for example: with FRP decking the weight is reduced by 10%-20%). This weight reduction saves money and time in multiple disciplines. A lighter construction means an easier and quicker installation process as well as a lighter lifting construction (e.g. small crane instead of a big one). The transport from the manufacturer to the building site will require a smaller amount of energy. The reduced total weight also reduces the measurements and cost for the supporting structure (bearings, abutments/foundations). This can be especially beneficial when the ground conditions, or similar, limit the practicable foundation and supporting elements. With large scale bridges or old bridges that need to be rehabilitated where the own-weight of the bridge is an issue, the usage of FRP is a viable alternative.

6.1.2 Pre-fabrication and site modulation

Composite materials can be pre-fabricated which improves the control quality and guarantees conformity with the manufacturing specifications for every piece of the construction. This quality control can't be guaranteed for in situ concrete, where the quality can vary. The quality of pre-fabricated concrete can be monitored better, but the fabrication, transportation and assembly will consume more energy than with composite materials since there is no need for formwork, rebar laying, pouring concrete and drying time for the concrete. Due to this time gain the substructure groundworks can take place concurrently with the manufacturing of the composite materials. A quick installation will also reduce the disruption in traffic, diverting of traffic and closing time of the roads.

6.1.3 Superior durability

FRP are highly resistant to most aggressive chemicals. This in contrary to steel, which is sensitive to rusting. This rusting can even be accelerated by coming in contact with de-icing salts. This can partially be prevented by periodically recurrent painting of the structure. For concrete the corrosion of the internal reinforcement steel is also a main cause of the deterioration of the structure. The durable nature and resistance to atmospheric degradation are one of the most influencing properties in the choice of FRP as a construction material in bridges. These properties are especially applicable in environments with harsh conditions. (e.g. bridges located near the coats or in very cold climates)

6.1.4 Minimum maintenance & life cycle cost

The usage of composite materials in bridge designs is relatively new. The manufacturers claim that the composite materials do not require any maintenance throughout their lifespan. These materials would only require occasional cleaning. Yet, due to the brief time these materials are used in bridges, especially bridges that have to endure heavy loads, few study cases have been made in order to confirm this economical advantage of composites. There are however a number of cycling and pedestrian bridges that can be examined to get a general idea of the need for maintenance. For example, the Kolding pedestrian bridge in Denmark. This bridge was entirely constructed out of FRP by “Fiberline Composite” in 1997. In the last 21 years this bridge hasn't had any need for maintenance. This bridge has minimal trafficking since it is a pedestrian bridge, but it is situated in coastal location which still makes it a good example for the durability properties due to the harsh environment.

The predicted life cycle costs according to Fibercore Europe can be seen below.

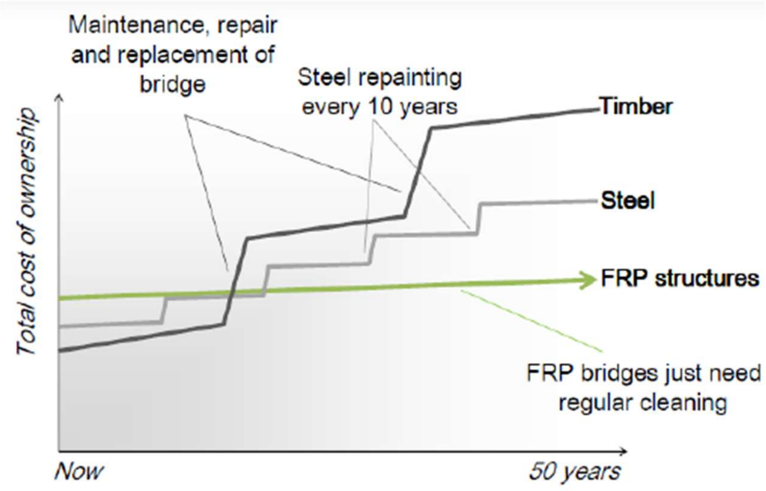


Figure 27 Predicted life cycle costs

6.1.5 Electrical properties

Depending on the manufacturing materials some forms of the FRP can be electrically non-conductive. This can be an advantage if the bridge is located near hazardous power sources or power lines.

6.1.6 Complex moulding forms

Due to the large quantity and flexibility of the manufacturing methods the aesthetic, shape and dimensional possibilities of FRP are almost endless. With manufacturing techniques as pultrusion a production line can be set up in order to produce uniform elements with a great efficiency and speed. Because of the almost limitless shaping possibilities more efficient solutions to structural problems can be found provided that more research, in the geometry and others, is conducted. Another economic benefit is that because of the pre-fabrication of the materials the to be expected loads and stresses per element can be calculated. As a consequence, the constructors of these elements have the ability to choose where and how much reinforcement fibres need to be placed. In high and low stress regions the fibres quantity can be balanced for the optimal reinforcement amounts.

6.1.7 Environmental

According to the study of Veltkamp, M. (2012) “Fiber Reinforced Polymer Bridges” the environmental impact of FRP bridges is up to 66% less than traditional materials during their lifespan when looking at the life cycle analysis (production, construction and maintenance). An environmental study of the energy consumption of FRP and traditional materials was also made. The study was based on two separate usage groups, energy required on delivery and throughout the maintenance. This includes the energy consumed during the manufacturing of the elements, the transportation to the site, the water pollution and air pollution during the installation. The former dealt with painting, construction maintenance, replacement of components, etc. This study shows that in the overall lifetime of the composite element it requires less than half of the energy compared to the other materials. This can be seen in the following graph where the energy consumption (MJ) of a few materials is compared.

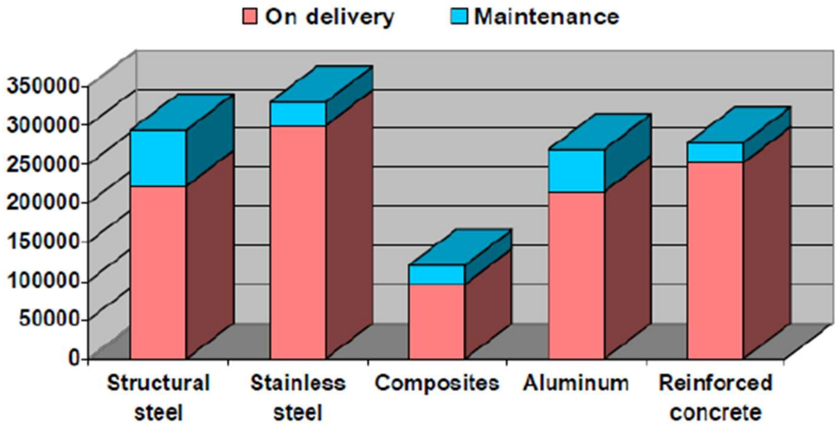


Figure 28 Energy consumption (MJ)

6.1.8 Recycling

The company “Fiberline composites” are able to fully recycle all of their produced sections. They use a resource where the composites are used within the manufacturing of cement. They use 30% of the composite as an energy source and 70% as a raw material. In order to acquire the raw materials, the composite is reduced to granulates by grinding it in a mill. After the grinding the granulates are blended with other recycled materials and finally used as a substitute raw material. This happens in “Zajons” a German based company that works in co-operation with “Fiberline”. The substitute raw material is then processed by the company “Holcim”. According to “Fiberline”, when one thousand tonnes of composite elements is recycled in cement the manufacturer saves 450 tonnes of coal, 200 tonnes of chalk, 200 tonnes of sand and 150 tonnes of aluminium oxide. While no by products such as ash or dust are produced in the process.

6.2 Disadvantages

6.2.1 Initial costs

The initial cost of composite materials is substantially higher than that of traditional materials such as concrete or steel, which is why it is difficult to justify at first impression for the designers and engineers. This is why the decision of the usage of such an expensive material must be justified and specified on specific projects or client requirements. For the maintenance of bridges there is almost always a limitation on the economical expenses that can be provided by the caretakers of these bridges. This is why the designers can't let the initial costs of these materials overshadow the projects life cycle costs, which are more favourable for fibre reinforced polymers. Fortunately the costs are expected to decrease as the material becomes more well known, widespread and awareness of the long-term benefits increase.

6.2.2 Structural instability

The reduction in weight (e.g. in the bridge decking) usually elicits in a reduction in size for the girders and other superstructures. Yet the opposite can be true as well. If the FRP is not strong enough in order to act in balance with the existing superstructure, the girders may have to be able to make up for the stiffness deficiency and hence have to be increased to prevent failure in induced deficiencies such as lateral torsional bucking. This would increase the total costs of the project and therefore cancel out the benefits obtained by the FRP. A low weight can also affect the dynamic instability of the bridge. In order to increase this dynamic instability additional dampers or weights would be required in order to increase the mass of the bridge. This is in order to reduce the chance on wind oscillation and resonance.

6.2.3 Design standards

Until now there is no universally used standard procedures for the design or production of composite materials. There are however several publications, manuals and books on the designing procedures and properties of composite structures. This is one of the reasons that engineers tend to be more inclined to use standard materials of which they know they are safe and of which there are procedures that outline the current day standards. One of the publications that has its eye on setting a standard for the manufacturing and usage of composite materials is “Structural Design of Polymer Composites, Eurocomp design code and handbook”.

6.2.4 Connections

When an FRP element is penetrated its durability, stiffness and resistance to breaking forces are all affected. In FRP bridge decking the connections to steel girders are commonly done by shear connectors or bolts, which have the same effects by penetration as above. Research on adhesive joint systems, which would provide a smoother transition without penetration, is being done. This would decrease stress concentrations in the deck, however when asymmetrical loads impact the decking this could cause uplifting of the deck due to high peeling forces in the connections. This can lead to property loss of the adhesive and debonding of the deck from its supports.

6.2.5 Railings

With usual materials like concrete the railings are normally fixed onto the reinforcement of the concrete. They are cast in here in order for them to be completely fixated. This is a weak point in the construction with FRP. In order to fixated this on the FRP's the drilling of holes would be needed as well as the utilization of grout. This would be time consuming and would decrease the properties of the FRP materials.

6.2.6 Creep & Fatigue

Creep occurring in FRP materials is almost always retained by the elastic properties of the polymer resin. This creep occurs, just like in traditional materials, after sustaining a long-term loading. This effect can be increased due to the temperature and working environment since creep is a function of the resin content. The glass fibres have a minimal contribution to the retainment of creep. Normally the occurrence of creep and its effects can be minimized by keeping the maintaining stress under the appropriate working stress.

6.2.7 Thermal effects

Composite materials are prone to prolonged exposure to elevated temperatures because of the difference in the thermal expansion coefficient of the resin and the reinforcement fibres. These elevated temperatures can have visible microcracking, blistering and air bubbles as a consequence. In turn these phenomena can lead to reduced stiffness and increase the water permeability through the resin/fibre interface. All these effects cause de deterioration of the composite material. In order to fully understand the effects of elevated temperatures on composite materials more research needs to be done.

The freeze-thaw effect can also cause damage to FRP materials by making microcracks. When these cracks intertwine larger cracks can occur in the matrix which would damage the entire structure. These microcracks also create an opening which allows infiltration of water and as a consequence substantially lower the shear strength as well as cause the resin to plasticize in some cases. This has a more critical effect in colder climates.

6.2.8 UV Radiation

Polymer resins are very prone to UV radiation, the thinner sections are even faster affected. Composite materials that have been affected by UV radiation have the hardening of the matrix and colour loss/change as a result. These effects can however relatively easy be reduced or even avoided by applying UV-resistant coating on the element surfaces or with the addition of UV-resistant additives in the manufacturing process.

6.2.9 Fire resistance

As discussed in the polymer properties, the fire resistance of polymers is probably one of the biggest disadvantages. The resin used in composites is a product based on oil and is therefore combustible. The release of toxic gases and the decomposition rate under heat and other properties of the composite materials has been investigated. The results can be found in the following graphs. At 500°C less than 10% of the structure survives. At 300°C rapid decomposing starts to occur.

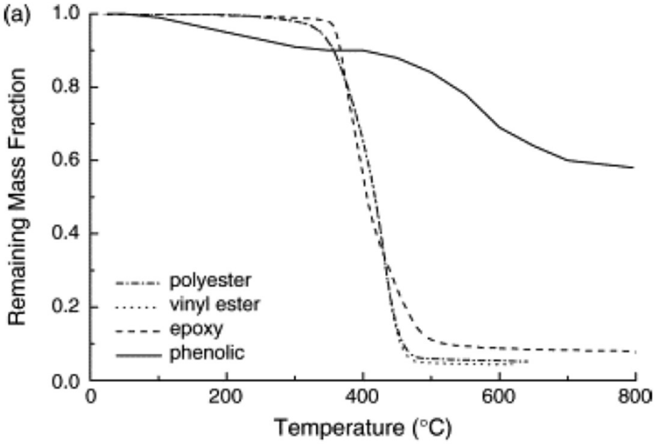


Figure 29 Mass fraction during elevated temperatures

The release of toxic gases is shown in the second graph. The most important one is carbon monoxide since this can be lethal for humans (at a concentration of 1500ppm death occurs within the hour). The relationship between heat and the release of carbon dioxide and monoxide is shown.

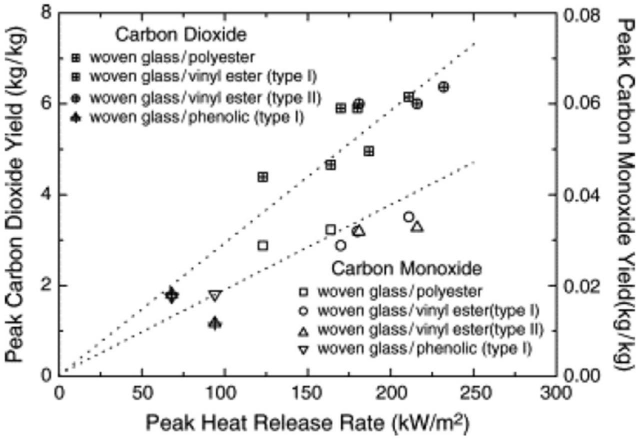


Figure 30 Release toxic gases by elevated temperatures

Chapter 7.

Bridges

7.1 Bridge components

Bridges are a connection between two points separated by an obstacle such as a ravine, a river, a valley or a road with the purpose of passing this obstacle.

A bridge is usually build out of 3 main components: a superstructure, a substructure and foundations. The superstructure is a structural system that carries deck in order to provide the ability of transportation. This consists out of a road/flooring which is supported by the substructure. The substructure is the structural system that supports the superstructure. It consists out of beams, slabs, trusses, cables, arches, etc. The foundation is the deepest part of the bridge, meant to support the abutments and piers. The type of the bridge depends on the design and physical requirements of the bridge.

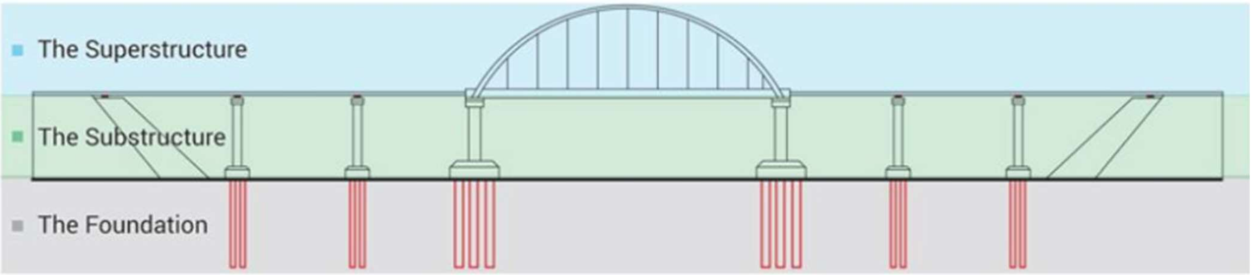


Figure 31 Bridge components

7.1.1 Foundation

Piles: Piles are usually placed deep in the soil underneath the obstacle that needs to be crossed. These piles support the bridge and are part of the initial foundation. They channel the loads, stresses and weight of the bridge evenly through the ground. The materials of these piles depend on the soil type which can be associated with the ground stability and load bearing capacity.

Scouring also affects the piles. This is the removal of the soil around the piers caused by movement of the water. This can affect the stability of the bridge. In order to prevent this the usage of scour prevention mats can be used. These mats can consist out of rows of tyres. Since the shape of tyres entrap sand grains it will gradually form a permanent solution in order to prevent scouring.

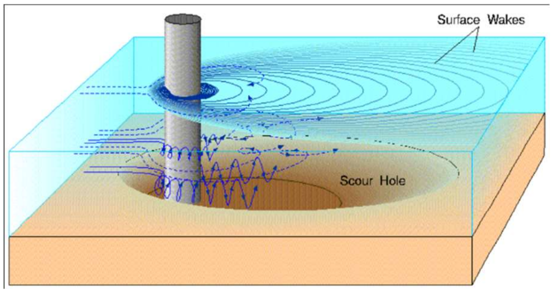


Figure 32 Scouring

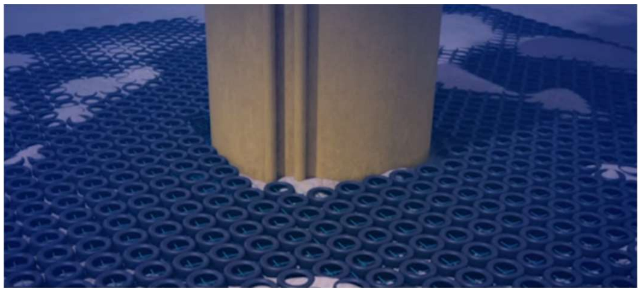


Figure 33 Scour prevention

Caps: caps, also known as pile caps which are placed on top of the pile foundation can provide complementary load transferring capacity to the piles.

Bents: A bent is the combination of piles and a cap. Multiple bents create the foundation for the substructure.

7.1.2 Substructure

Abutments: An abutment is a vertical support that also acts like a retaining wall in order to resist lateral movement of the earth. These abutments are placed at the approaching ends of the bridge.

Piers: Piers are placed on top of the caps and are used to give the different spans of the bridge additional resistance from forces and vibrational effects. These piers are place at the end of the different spans of the bridge.

Pier caps: The pier caps, which are also known as headstock, function as load transferring system for the girders to transfer the loads of the superstructure on top to the bearings.

7.1.3 Superstructure

Girders: Girders, also known as the beams of the bridge, join all the pile caps together by extending themselves across them in order to give support to the deck. This can be a single span, or even multiple spans joining all the bents. These girders are usually designed as trusses in order to improve stress and load resistibility. Because of this pressure will be quickly passed down towards the foundation.

Bearings: Bearings are structural members that transfer loads from the deck to the substructure divided among all the piers. In order to allow movement between parts of the bridge the bearings shift stresses and loads to the piers through the girders. These movements can be torsional or linear. Elastomeric bearings allow lateral shear movement, horizontal rotation and vertical compression.

Trusses: Trusses are triangular shaped components placed in order to divide loads and bending moments through the surface of the bridge

Decks: Decks are the components that get the direct traffic loads. They serve as a functional crossing.

Barriers: Barriers are located on the sides of the deck and are mainly as safety and protection measurements.

Arches: Arches are vertically curved structures that have a lot of strength. These arches aid the load bearing capacities and safety of the bridge. Arches eliminate tensile stresses by converting them into compressive stresses. These arches can be fixed, 2 hinged or 3 hinged. The fixed arches are most often used in short span bridges, the 2 hinged for long span bridges and the 3 hinged for medium span bridges.

7.2 Bridge types

The distribution of the internal forces such as tension, compression, torsion, shear and bending are determined by the core of the structure. All bridges need to withstand these forces, but some types dedicate more of their capacity to the handling of specific types of forces. Some of the bridge types can centralize these forces.

Cable staved bridge: These are bridges that have deck cables connected to one or more vertical towers. These towers are mostly located near the abutments or in the middle of the span. These cables can be connected to the columns through a fan, harp or star design. With these designs the bridge is connected through sloping cables, which is completely different from suspension bridges where the deck is held by vertical suspension cables. These bridges are often used to span medium or long bridges that are between the maximum range of the shorter cantilever bridges and the longer suspension bridges.

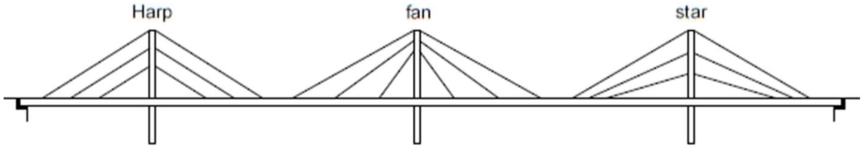


Figure 34 Cable staved bridges

Arch bridge: Arch bridges use arches as their main structural component in order to endure loads and stresses. The location of these arches is always underneath the bridge (never above it). When being supported by different piers multiple arches can be used in order to divide the loads and stresses.

Cantilever bridge: The cantilever bridges have similarities in their appearance to the arch bridges, but they project their loads horizontally into space. The cantilevers are only supported on one side

Suspension bridge: Suspension bridges use main cables or ropes that are attached to the vertical structural elements in order to support the decking which is connected to the main cable with vertical suspension cables.

Beam bridge: This is the oldest type of bridge. The first types of these bridges where the placement of a log over a creek. These bridges can be composed out of one or several horizontal beams that can span the complete length of the bridge or the length between piers.

Truss bridge: This is a bridge build out of beams, but it uses triangularly shaped posts in order to divide the loads over the total length. These bridges are very popular due to their resilience and economical solutions.

7.3 Applied forces

There are various design loads that need to be considered before designing the bridge. These integration of all these loads make sure that the bridge is safe under any circumstances.

The following loads will be discussed: Dead load, live load, impact load, wind load, longitudinal forces, centrifugal forces, buoyancy effect, effect of water current, thermal effects, deformation and horizontal effects, erection stresses and seismic loads.

7.3.1 Dead load

The first design load that should be calculated is the self-weight of the bridge. This generally is the superstructure.

7.3.2 Live load

The life load of a bridge are all the moving loads on the bridge. These are trucks, cars, pedestrians, etc. In order to design this with a practicable safety factor the IRC recommends some imaginary vehicles. These vehicle loads are categorized as class AA, class A and class B.

IRC class AA loading

This class is specified for heavy loading bridges. These can be bridges on highways, industrial areas, cities, etc. The loadings for this class are generally tracked types and wheeled types.

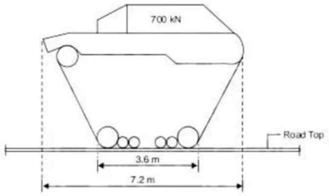


Figure 35 IRC loading class AA 1

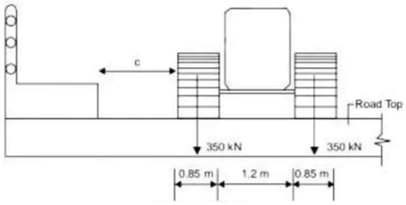


Figure 37 IRC loading class AA 2

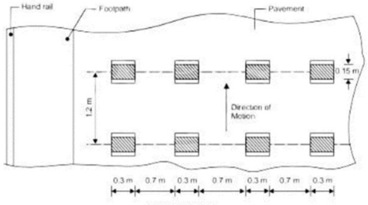


Figure 36 IRC loading class AA 3

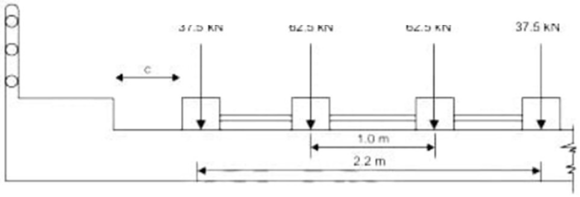


Figure 38 IRC loading class AA 4

IRC class A loading

This class is used in order to design all permanent bridges. This is the standard for live loads of bridges. When another class is used in order to design the bridge, the class A loading needs to be checked as well.

IRC class B loading

This class is used in order to design temporary bridges like bridges made out of timber.

7.3.3 Impact loads

Impact loads are loads that occur suddenly on the bridge. For example, when a vehicle is moving on the bridge it is considered as a live load, yet when the wheel is in movement these loads will periodically change from one wheel to another. This results in an impact load on the bridge. In order to integrate these loads an impact factor is used. This is a multiplying factor which depends on the weight of the vehicle, span of the bridge, velocity of the vehicle, etc. The impact factors are given below.

Span	Vehicle type	Impact factor
Less than 9m	Tracked vehicle	25% up to 5m and linearly reducing to 10% from 5m - 9m

	Wheeled vehicle	25% up to 9m
Greater than 9m	Tracked vehicle (RC bridge)	10% up to 40m
	Wheeled vehicle (RC bridge)	25% up to 12m
	Tracked vehicle (steel bridge)	10% for all spans
	Wheeled vehicle (steel bridge)	25% up to 23m

If the lengths of the bridge exceeds the previous limitations the impact factor should be considered from the graph given by IRC which is shown below.

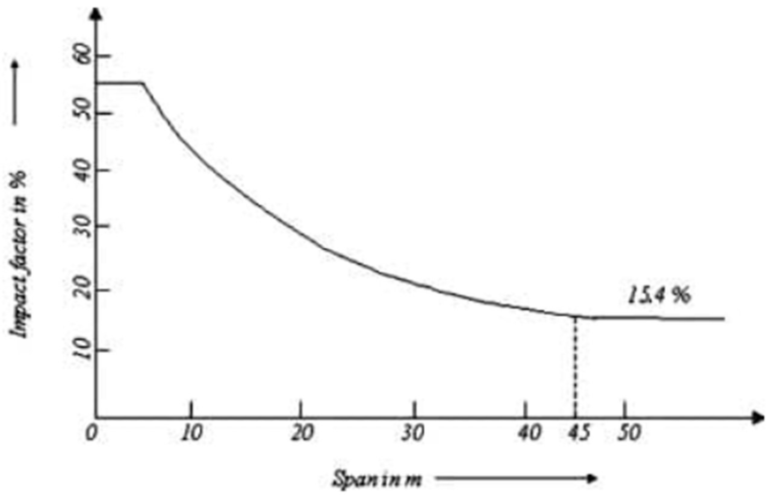


Figure 39 Impact factor bridges >23m

Chapter 8.

Examination existing bridge

8.1 Introduction

In order to compare these elements a bridge that serves a small country lane on the B3 highway in Germany was used. This bridge is located in Friedberg, in the state Hessen. This states highway authority is the owner of this bridge and requested the construction of it. This bridge was made out of abutments that carry the load to the foundations, the frame consists out of 2 steel I-girders and a multi cellular FRP deck (ASSET profile). This was the first steel hybrid/FRP road bridge constructed in Europe. The traffic volume of the B3 highway is very high due to the close distance to Frankfurt and its airport. This is why the Hessen highway authorities opted for a minimum closing time for the road due to construction in order to prevent massive traffic disruptions. The FRP deck provided the perfect solution.

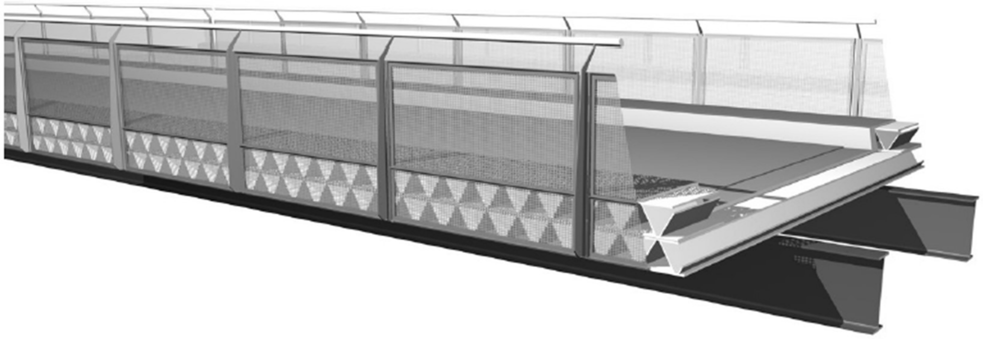


Figure 40 Friedberg bridge

8.2 The bridge

The bridge consists out of foundations of 7m width, the substructure consists out of abutments of 8.3m height and the superstructure consists out of steel I-girders and a pultruded multi cellular FRP deck with a span of 21.5m and is adhesively bonded with the steel girders. By doing this composite action is achieved which results in a reduced vertical displacement of almost 20% compared to steel stringers. The overall span of the bridge is 27m, the width of the upper lane is 3.5m, the emergency pavement (side walk) is 2 times 0.75m. The uniformly distributed load is 9kN/m² for the lane and 2.5kN/m² for the pavement, the loads distributed through the tandem

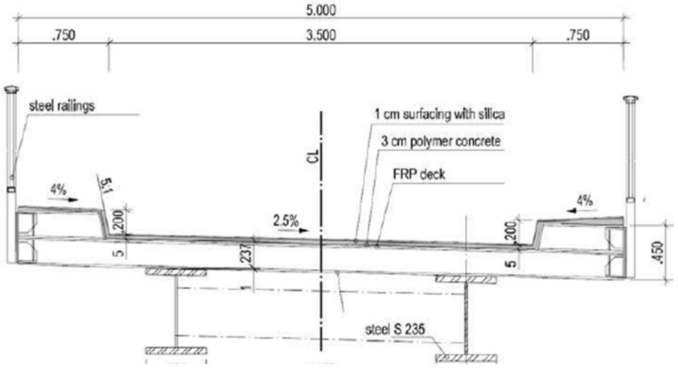


Figure 41 FRP deck Friedberg bridge

system for the lane are 4 times 120kN (this has not been done for the pavement since cars won't use this area.), the concentrated wheel load (punching) is 2 times 81kN (on 0.4m by 0.4m each).

8.3 The deck

The decking used in the Friedberg bridge was manufactured by fiberline's FBD600 ASSET (advanced structural systems for tomorrow) profile. The research and testing of this profile was funded by the European Commission. This resulted in a composite bridge deck profile able to withstand standard bridge traffic loads. The profile consists out of FRP plates which are arranged to create an array of trapezoids in the cross section. The thickness of the different parts differs, this in order to achieve a range of material and structural properties. These properties where optimized in the ASSET research. The sections where pultruded in sections of 1m-1.5m and then adhesively bonded together. The transference of loads from between the flange and the webs can be seen as truss action. In the diagonals tensile and compressive forces occur. This will create force couples along the flanges of the deck, which results in local moments in the top and bottom flanges. These forces affect the area between the flanges and webs. This is there for an accumulation place for stresses in the deck structure.

8.4 Testing

Since the ASSET research was funded by the European Commission extensive testing was done on these elements during the development.

8.4.1 Adhesive testing

In order to test the adhesive joints, tension and shear tests were performed on small FRP test specimens. These tests resulted in the failure of the FRP test specimen, not the adhesive layer or the interlayer.

8.4.2 Compression testing of the composite

A compression test was made lateral to the pultrusion direction in order to see the load bearing behaviour of the deck under compressive loading. A section of 750mm x 600mm of the deck was tested in an upright position under a central loading. The reinforcing layers of the overlapping joints of the individual elements were the first places to succumb. An optimization of these areas will increase the compressive strength perpendicular to the direction of the pultrusion.

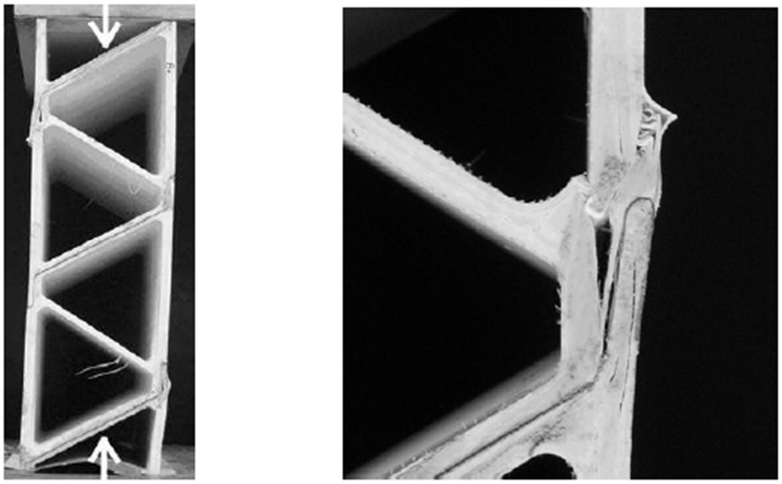


Figure 42 Compressive test/failure in overlapping joints

8.4.3 Composite action testing

To test the composite action between the steel girders and the decking 2 FRP decks are adhesively joined on both sides of a steel girder. Both decks stand on an inwards tilting plate in order to apply the loads. After applying the loads, inter-laminar failure occurs in the with tension loaded nodes as a result of buckling in these points.

8.4.4 Concentrated wheel load testing

The concentrated load is very important for the limited thickness of the FRP decking. However, in order to distribute the loads over a larger area a polymer concrete layer is placed on top of the deck, since the deck is supposed to have composite action with this layer. In every test the FRP decking succumbs before the polymer concrete layer, but in the test where a polymer concrete layer of 30mm was used the load bearing capacities where double than the ones where only the FRP decking was tested.

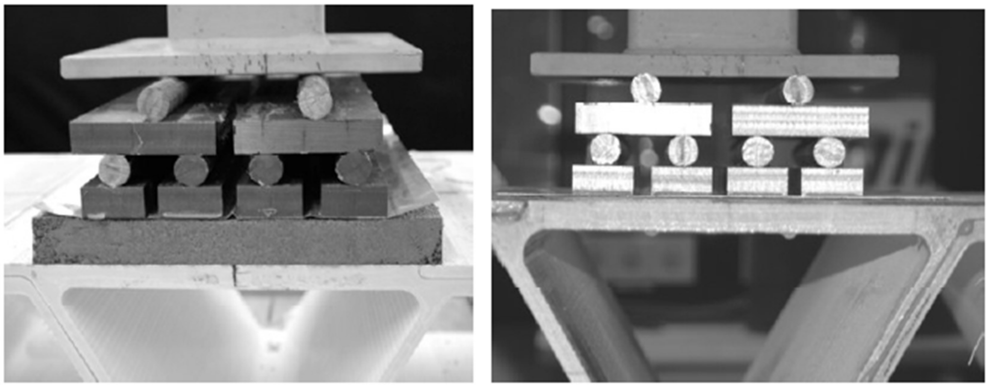


Figure 43 Concentrated wheel loading

8.5 Bridge installation

Elements of 5x1.5m where pultruded in the fiberline company after which they were transported to an assembly warehouse 20km form the final location of the bridge where the protection against weathering and working conditions are guaranteed. Before the assembly of the 20m long deck span the FRP elements where grinded and cleaned in order to create a suitable surface for the adhesive. The FRP decking was then glued to the steel I girders that where welded and coated before arrival in the assembly hall. Next the sidewalk elements where connected through an adhesive on the FRP decking and a layer of the polymer concrete of 45mm was poured in between them. This process was done in 1 week. The construction of the bridge was done by transporting the complete unit to the final location where it was mounted on the abutments with the use of 2 crane lorry's. The placement took about 2 hours, with only the placement of the railing and backfilling of the abutments left to do.

8.6 Comparison Concrete decking and FRP decking

In comparison to the FRP decking an alternative decking system made out of reinforced concrete was designed. The reinforced concrete slabs of the decking are in the range of 200 – 300mm depending on certain criteria, therefore a slab thickness of 225mm was taken. In order to make the two decking designs similar the same 3,5 m lane width and 0,75m sidewalks on either side were chosen. No concrete edge beams are included in this model, but they are included later in the LCC calculations. This is a simplification in order to make compared decks as similar as possible, the concrete decking would, in practice, be used more way more economical.

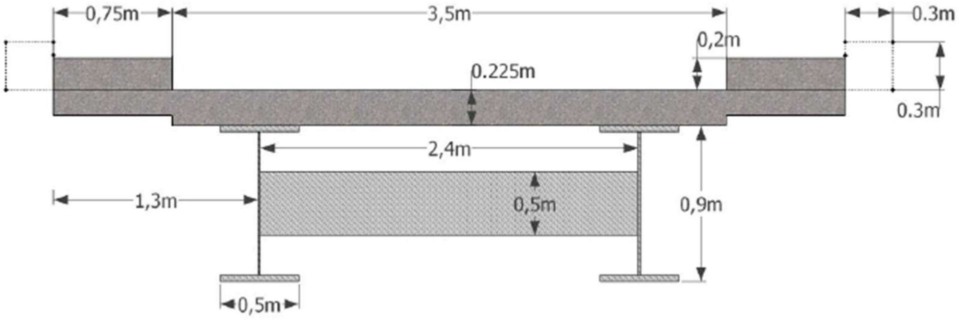


Figure 44 Friedberg bridge redesigned with concrete deck

Both bridge decking systems were then divided into lanes with a sidewalk on either side. The traffic loads or live loads were then applied to the deck, in their respective positions.
Note that for all permanent and variable loads a safety coefficient of 1.35 was used for ULS calculations and 1.0 for SLS. The results derive directly from the “Feasibility Analysis of a Fiber Reinforced Polymer Bridge” by Neil Murphy. The calculation where made by hand and through the London University Stress Analysis Software (LUSAS, this is an engineering software commonly used in order to design bridges).

In the LUSAS software the results of the models were verified for the end reactions of each bridge design. The received values where compared to the handmade calculations. These values were compared in two load cases, self-weight only acting on the structures and the self-weight combined with a worst case traffic loading case.

	Concrete			**FRP**		
Reaction	**LUSAS**	**Hand**	**% difference**	**LUSAS**	**Hand**	**% difference**
R1 (KN)	202	201.5	0.25	70.65	70.14	0.72
R2 (KN)	202	201.5	0.25	70.65	70.14	0.72
R3 (KN)	202	201.5	0.25	70.65	70.14	0.72
R4 (KN)	202	201.5	0.25	70.65	70.14	0.72

Table 2 End reactions

	Concrete			**FRP**		
Reaction	**LUSAS**	**Hand**	**% difference**	**LUSAS**	**Hand**	**% difference**
R1 (KN)	793	785	1.01	617	608	1.46
R2 (KN)	647	648	0.15	468	471	0.64
R3 (KN)	638	648	1.57	458	471	2.84
R4 (KN)	789	785	0.51	602	608	1.00

Table 1 End reaction

8.6.1 End reactions

A comparison between the end reactions were made.

Loadcase	Concrete	FRP	Difference	%
Self –weight (KN)	202	70	132	65
SW & Live Loading (KN)	717	536	180.5	25

Table 3 Comparison end reactions

The reactions of the FRP decking were reduced by 65% in self-weight due to the low density compared to concrete and by 25% in the critical load case scenario.

8.6.2 Deflection

The maximum deflection was found to occur at midspan (by the LUSAS contour plots), this happens, for both models, off centre due to the moving vehicle loading. This analysis was designed at SLS, therefore all the loading was inputted with a safety coefficient. Due the very low material self-weight of the FRP, 60% of the maximum deflection values can be saved compared to the concrete model.

Loadcase	Concrete	FRP	% Reduction
Self-Weight (mm)	5.07	1.98	60.9
Self-Weight & Live Loading (mm)	18	17.38	3.4

Table 4 Comparison deflection

8.6.3 Girder stresses

The maximum tensile stresses at the top and bottom of the flanges located at the points of maximum bending tension were checked on LUSAS. Therefore the bottom flange in midspan experiences the maximum sagging moments and at the top flange the maximum hogging moments. These values of the chosen steel grade were all above the tensile yield strength.

	At Support		At Midspan	
	Self-Weight	SW & Live Loading	Self-Weight	SW & Live Loading
Concrete (MPa)	62	270	17	101
FRP (MPa)	21	210	6	88
% reduction	66	22	65	13

Table 5 Comparison girder stress

8.6.4 FRP deck plate stresses

The maximum stresses occurring in the FRP decking flanges and webs were checked against their limiting values. The occurring stress values in the plates were substantially lower than their limiting values.

Property	Flange Plates	Web Plates
Max Stress x direction (MPa)	64	17
Tensile Strength (MPa)	300	213
Safety factor	5	13
Max Stress y direction (MPa)	78	7
Tensile Strength (MPa)	220	255
Safety factor	3	36

Table 6 FRP plate stresses

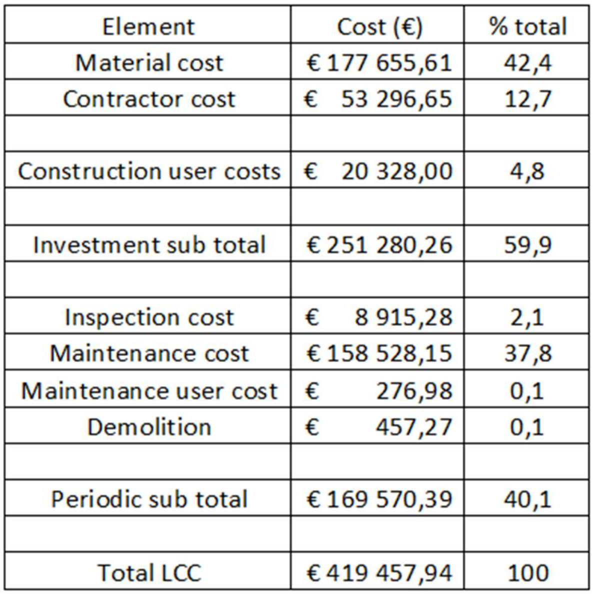
8.7 Life cycle costs

These results derive directly from “Feasibility Analysis of a Fiber Reinforced Polymer Bridge” by Neil Murphy. The price in this document is noted in Swedish Krones, this has been converted to euro with the rate of exchange of the year the document was published (0.11 Krones for 1 euro). 3 cost analysis’s have been made, a low cost, an intermediate cost and a high cost.

8.7.1 Concrete decking

The lowest cost has been calculated for the concrete bridge where the beam has been replaced every 50 years (once in the bridges lifetime).

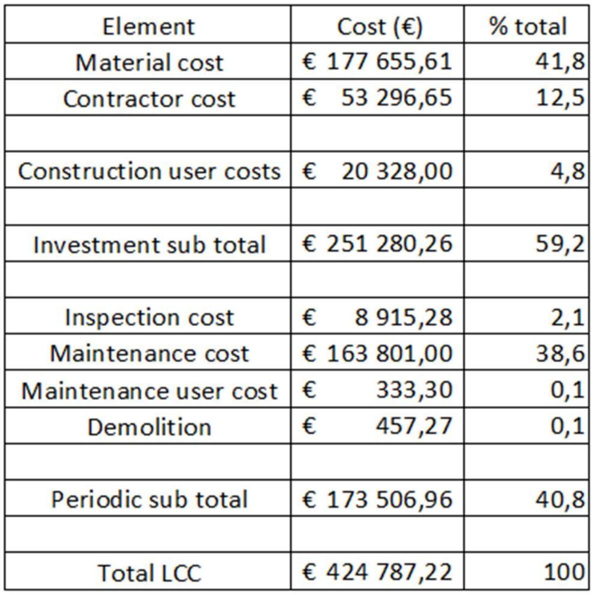
The construction user costs are almost 5% of the total costs. This is because the road and the passing underneath where closed for 2 weeks in which traffic had to be detoured. The maintenance cost of the bridge are almost 38%, this is one of the largest contributors of the total costs.



Element	Cost (€)	% total
Material cost	€ 177 655,61	42,4
Contractor cost	€ 53 296,65	12,7
Construction user costs	€ 20 328,00	4,8
Investment sub total	€ 251 280,26	59,9
Inspection cost	€ 8 915,28	2,1
Maintenance cost	€ 158 528,15	37,8
Maintenance user cost	€ 276,98	0,1
Demolition	€ 457,27	0,1
Periodic sub total	€ 169 570,39	40,1
Total LCC	€ 419 457,94	100

Table 7 Concrete decking lowest cost

The intermediate costs are calculated for the replacement of the edge beam every 40 years. (twice in the bridges lifespan)

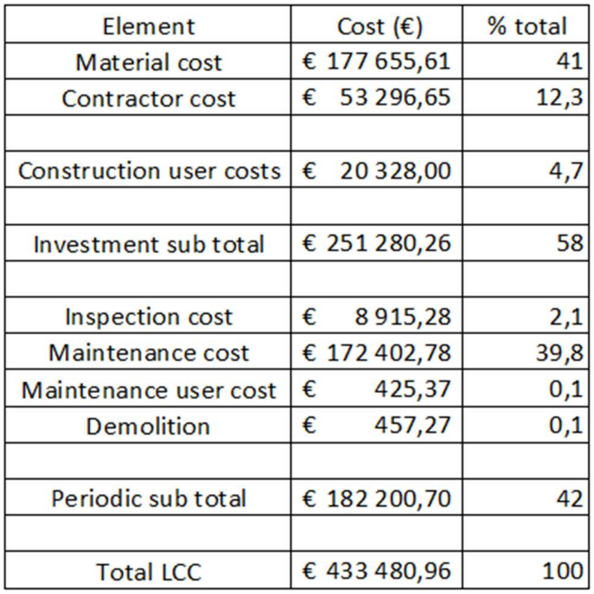


Element	Cost (€)	% total
Material cost	€ 177 655,61	41,8
Contractor cost	€ 53 296,65	12,5
Construction user costs	€ 20 328,00	4,8
Investment sub total	€ 251 280,26	59,2
Inspection cost	€ 8 915,28	2,1
Maintenance cost	€ 163 801,00	38,6
Maintenance user cost	€ 333,30	0,1
Demolition	€ 457,27	0,1
Periodic sub total	€ 173 506,96	40,8
Total LCC	€ 424 787,22	100

Table 8 Concrete decking intermediate cost

Due to the extra maintenance costs the total price increases with around 1%.

The highest costs are calculated for the replacement of the edge beam every 30 years (3 times in the total lifespan). This is a high number of replacements which is normally only applicable in hard environmental conditions.



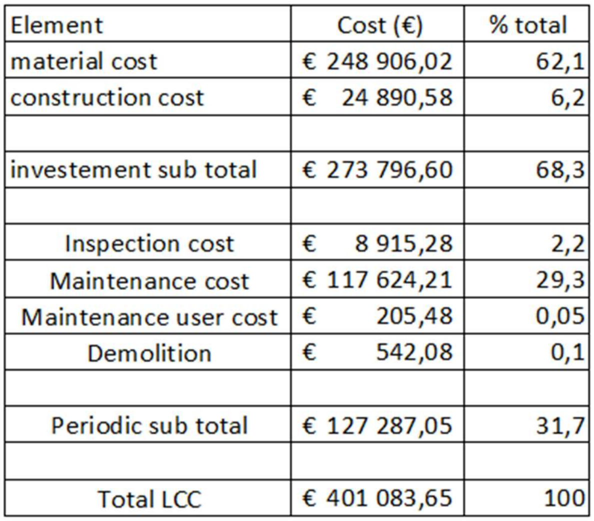
Element	Cost (€)	% total
Material cost	€ 177 655,61	41
Contractor cost	€ 53 296,65	12,3
Construction user costs	€ 20 328,00	4,7
Investment sub total	€ 251 280,26	58
Inspection cost	€ 8 915,28	2,1
Maintenance cost	€ 172 402,78	39,8
Maintenance user cost	€ 425,37	0,1
Demolition	€ 457,27	0,1
Periodic sub total	€ 182 200,70	42
Total LCC	€ 433 480,96	100

Table 9 Concrete decking highest cost

Due to the extra maintenance the total costs has increased with about 2% in comparison with the intermediate costs. In all 3 cost cases the costs are split around 60% for the construction and 40% for maintenance.

8.7.2 FRP decking

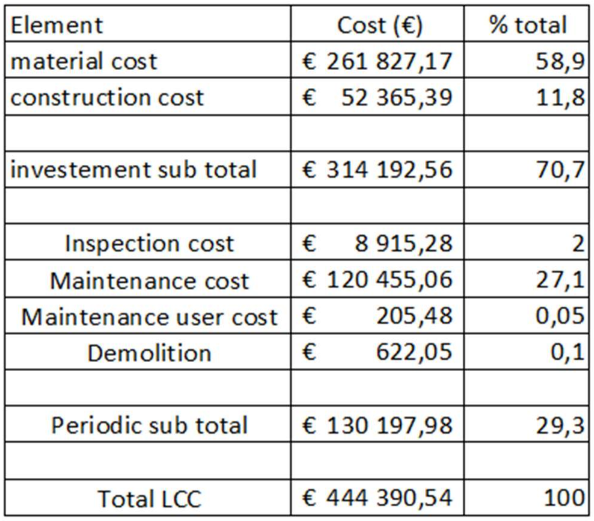
The lowest cost has been calculated for the FRP bridge, this would be the most favourable scenario for the FRP bridge. In contrast to the concrete bridge the construction user cost is not applicable to the FRP bridge since all the elements are prefabricated and can be constructed with in a minimal construction time.



Element	Cost (€)	% total
material cost	€ 248 906,02	62,1
construction cost	€ 24 890,58	6,2
investement sub total	€ 273 796,60	68,3
Inspection cost	€ 8 915,28	2,2
Maintenance cost	€ 117 624,21	29,3
Maintenance user cost	€ 205,48	0,05
Demolition	€ 542,08	0,1
Periodic sub total	€ 127 287,05	31,7
Total LCC	€ 401 083,65	100

Table 10 FRP decking lowest cost

The intermediate costs are the most realistic cost calculation.

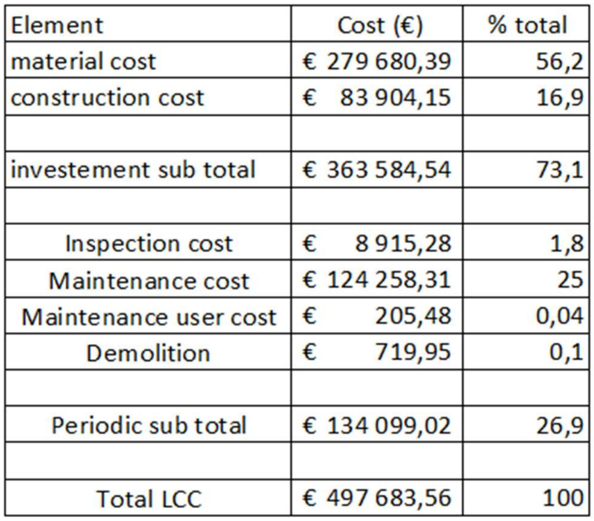


Element	Cost (€)	% total
material cost	€ 261 827,17	58,9
construction cost	€ 52 365,39	11,8
investement sub total	€ 314 192,56	70,7
Inspection cost	€ 8 915,28	2
Maintenance cost	€ 120 455,06	27,1
Maintenance user cost	€ 205,48	0,05
Demolition	€ 622,05	0,1
Periodic sub total	€ 130 197,98	29,3
Total LCC	€ 444 390,54	100

Table 11 FRP decking intermediate cost

The difference in cost with the lowest costs case is around 11%. This is substantially more in comparison with the increased costs of the concrete bridge which were 1%.

The highest cost are made with the highest margins for the FRP bridge.



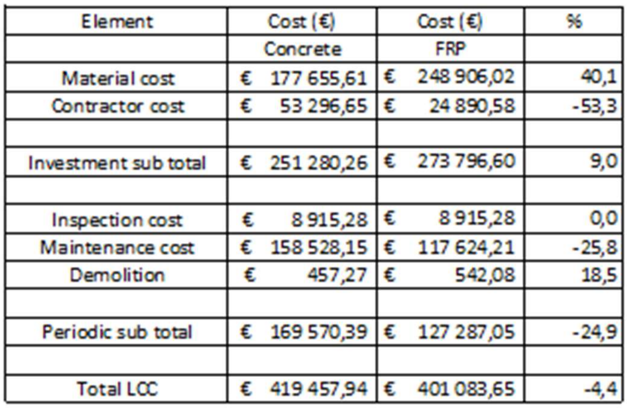
Element	Cost (€)	% total
material cost	€ 279 680,39	56,2
construction cost	€ 83 904,15	16,9
investement sub total	€ 363 584,54	73,1
Inspection cost	€ 8 915,28	1,8
Maintenance cost	€ 124 258,31	25
Maintenance user cost	€ 205,48	0,04
Demolition	€ 719,95	0,1
Periodic sub total	€ 134 099,02	26,9
Total LCC	€ 497 683,56	100

Table 12 FRP decking highest cost

In comparison with the intermediate costs the price has increased with 12%. These high percentage increases show the high cost of FRP maintenance. This is due to multiple factors like the increasement of construction costs of FRP bridge deck, reduction on abutments & foundation, reduction on the steel girder area, accidents on the bridge → parapet replacements, deck joint repairs. For concrete deck only the replacement of the edge beam was a factor. The costs of the FRP decking is divided in 70% initial costs and 30% maintenance costs.

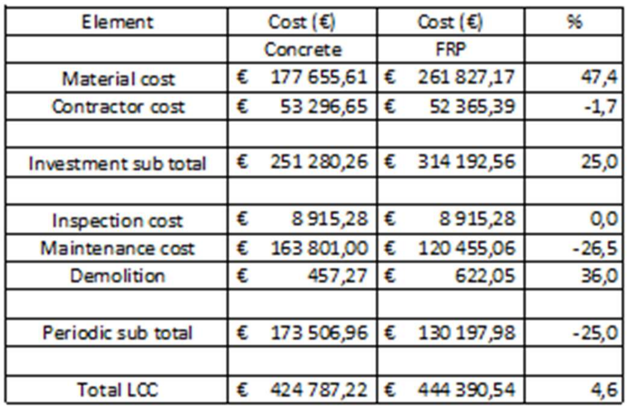
8.7.3 Comparison

The following tables show the comparison of the concrete and FRP decking's. The FRP has a lower total cost than the concrete decking in the in the lowest cost case (-4.4%). In the intermediate and highest cost cases the price of the FRP deck is higher (4.6% & 14.8%). This is partially due to the high initial costs of FRP decking. When this FRP materials will become generally and widely spread used, the price of these materials will go down which will make the FRP more affordable.



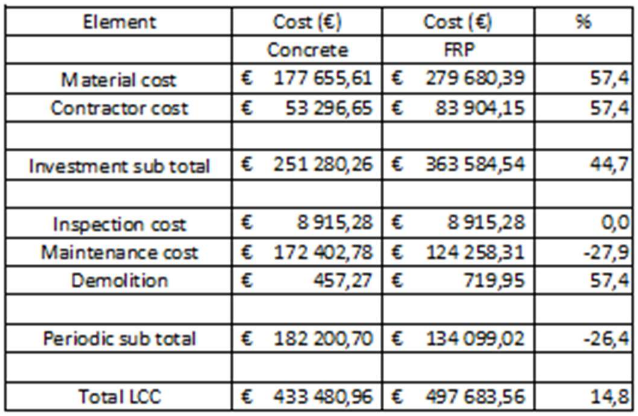
Element	Cost (€)	Cost (€)	%
	Concrete	FRP	
Material cost	€ 177 655,61	€ 248 906,02	40,1
Contractor cost	€ 53 296,65	€ 24 890,58	-53,3
Investment sub total	€ 251 280,26	€ 273 796,60	9,0
Inspection cost	€ 8 915,28	€ 8 915,28	0,0
Maintenance cost	€ 158 528,15	€ 117 624,21	-25,8
Demolition	€ 457,27	€ 542,08	18,5
Periodic sub total	€ 169 570,39	€ 127 287,05	-24,9
Total LCC	€ 419 457,94	€ 401 083,65	-4,4

Table 15 Comparison FRP and concrete decking lowest cost



Element	Cost (€)	Cost (€)	%
	Concrete	FRP	
Material cost	€ 177 655,61	€ 261 827,17	47,4
Contractor cost	€ 53 296,65	€ 52 365,39	-1,7
Investment sub total	€ 251 280,26	€ 314 192,56	25,0
Inspection cost	€ 8 915,28	€ 8 915,28	0,0
Maintenance cost	€ 163 801,00	€ 120 455,06	-26,5
Demolition	€ 457,27	€ 622,05	36,0
Periodic sub total	€ 173 506,96	€ 130 197,98	-25,0
Total LCC	€ 424 787,22	€ 444 390,54	4,6

Table 14 Comparison FRP and concrete decking intermediate cost



Element	Cost (€)	Cost (€)	%
	Concrete	FRP	
Material cost	€ 177 655,61	€ 279 680,39	57,4
Contractor cost	€ 53 296,65	€ 83 904,15	57,4
Investment sub total	€ 251 280,26	€ 363 584,54	44,7
Inspection cost	€ 8 915,28	€ 8 915,28	0,0
Maintenance cost	€ 172 402,78	€ 124 258,31	-27,9
Demolition	€ 457,27	€ 719,95	57,4
Periodic sub total	€ 182 200,70	€ 134 099,02	-26,4
Total LCC	€ 433 480,96	€ 497 683,56	14,8

Table 13 Comparison FRP and concrete decking highest cost

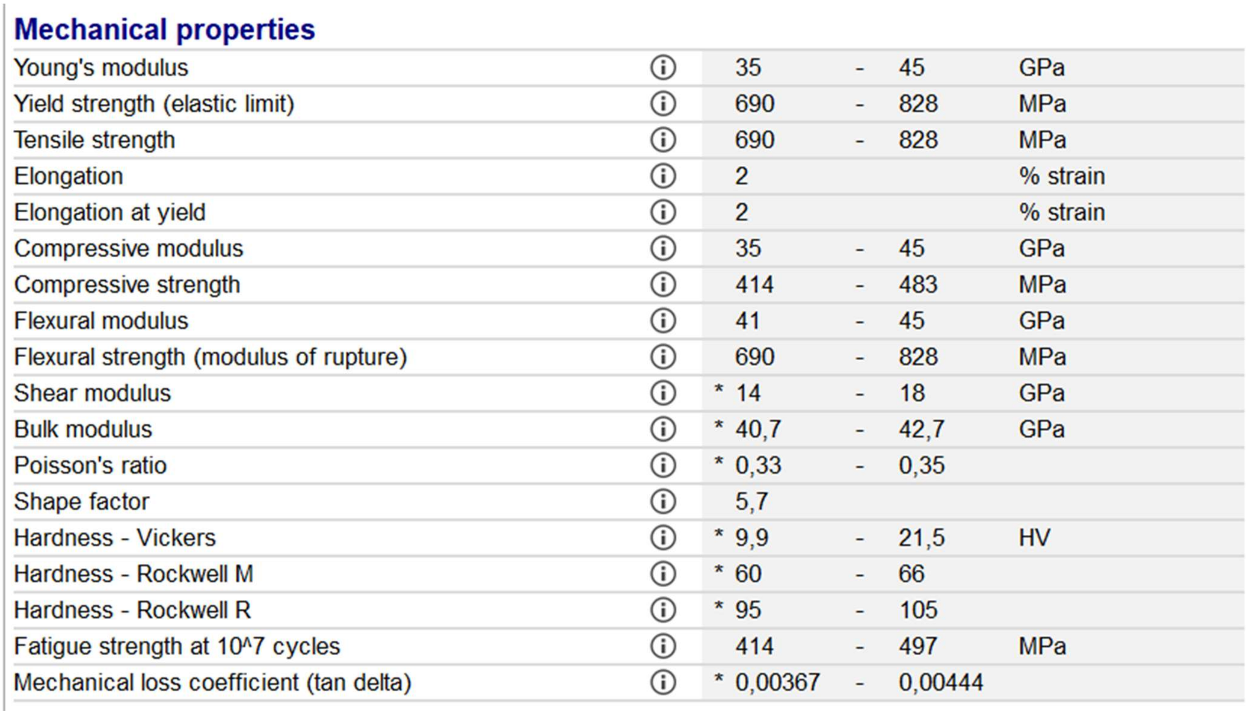
Chapter 9.

Element design

9.1 Tension member

Structural elements which are subject to direct axial stress without significant bending are called tension members. These can be trusses, cables, braces, etc. These tension members have to be designed to have an adequate resistance to the applied loads, taking stress concentrations due to imperfection into account. Axial strain on FRP components can be significant since they have a low young's modulus. This is why an adequate safety coefficient needs to be taken into account in order to prevent the resin from cracking in the event that there is a limiting allowable strain.

In order to calculate a tension member following properties where used:



Mechanical properties

Young's modulus	ⓘ	35	-	45	GPa
Yield strength (elastic limit)	ⓘ	690	-	828	MPa
Tensile strength	ⓘ	690	-	828	MPa
Elongation	ⓘ	2			% strain
Elongation at yield	ⓘ	2			% strain
Compressive modulus	ⓘ	35	-	45	GPa
Compressive strength	ⓘ	414	-	483	MPa
Flexural modulus	ⓘ	41	-	45	GPa
Flexural strength (modulus of rupture)	ⓘ	690	-	828	MPa
Shear modulus	ⓘ	* 14	-	18	GPa
Bulk modulus	ⓘ	* 40,7	-	42,7	GPa
Poisson's ratio	ⓘ	* 0,33	-	0,35	
Shape factor	ⓘ	5,7			
Hardness - Vickers	ⓘ	* 9,9	-	21,5	HV
Hardness - Rockwell M	ⓘ	* 60	-	66	
Hardness - Rockwell R	ⓘ	* 95	-	105	
Fatigue strength at 10^7 cycles	ⓘ	414	-	497	MPa
Mechanical loss coefficient (tan delta)	ⓘ	* 0,00367	-	0,00444	

Table 16 Mechanical properties unidirectional E-glass fibres and a polyester resin

The element is manufactured through the pultrusion process with unidirectional E-glass fibres and a polyester resin. (Polyester/E-glass fibre, pultruded rod). The ultimate limit state and serviceable limit state will be calculated. The following safety coefficients are used:

$\gamma_{m1} = 2.25$, $\gamma m_2 = 1.1$,$\gamma_{m3} = 1.2$, γ_m strength = 3.0, γ_m stiffness = 1.0, $\gamma_{f\,(ULS)}=1.5$, $\gamma_{f\,(SLS)}=1.0$

9.1.1 Tensile failure:

Design material strength:

$$\begin{aligned} f_{x,t,d} &= f_{x,t,k}/\gamma_m \\ &= 690/3.0 \\ &= 230\ \text{N/mm}^2 \end{aligned}$$

Design load (ULS):

$$\begin{aligned} N_{sd} &= \gamma_f N_k \\ &= 1.5\times 50 \\ &= 75\text{KN} \end{aligned}$$

The required cross-sectional area of the rod is given by:

$$\begin{aligned} A &\geq 75000/230 \\ &\geq 326\ \text{mm}^2 \\ D &= 20.4\text{mm} \end{aligned}$$

9.1.2 Deflection

Design tensile modulus (SLS):

$$\begin{aligned} E_{x,t,d} &= E_{x,t,k}/1.0 \\ &= 41 \end{aligned}$$

Design load (SLS):

$$\begin{aligned} N_{sd} &= \gamma_f N_k \\ &= 50\text{kN} \end{aligned}$$

Deflection, d:

$$\begin{aligned} &= N_{sd} l/(E_{x,t,d} A) \\ &= 50000\times 5000/\ (41000\times 326) \\ &= 18.7\ \text{mm} \end{aligned}$$

The SLS for deflection, 20 mm, has not been exceeded. Therefore required rod diameter to meet deflection SLS is 22.6 mm.

Conclusion: To achieve the load ULS and the SLS, a rod diameter of 20.4 mm is required.

9.2 Beam design

Buckling is an effect that dominates the design of elements that have to endure compression. This is particularly so when designing FRP elements submitted to compression. The relatively low young's modulus of FRP needs to be fully taken into consideration for all possible modes of buckling, this buckling can occur globally or locally. Global buckling of an element is considered with the assumption that the element is isotropic and that the relevant young's modulus strains the weak axis. Local buckling of an individual section of the element requires knowledge of both the longitudinal and the transverse bending stiffness of the element.

In the following graph the compressive strength (MPa) and the young's modulus (GPa) of composites with an epoxy resin and carbon fibre reinforcement and composites with an polyester resin and E-Glass fibre reinforcement are examined in order to select a material appropriate for the construction of FRP elements. The carbon fibre elements have the best properties, but their high costs make them a choice that's difficult to justify in constructions. Therefor the polyester/E-Glass fibre, pultruded profile, UD fibre & CSM was used in the following calculation. This is a composite profile manufactured by pultrusion with a polyester resin and unidirectional E-glass fibres and chopped stand mat used for the manufacturing of a composite beam. These calculations are in order to determine the maximum axial compressive load that can be safely applied. This column is assumed to be pin-ended.

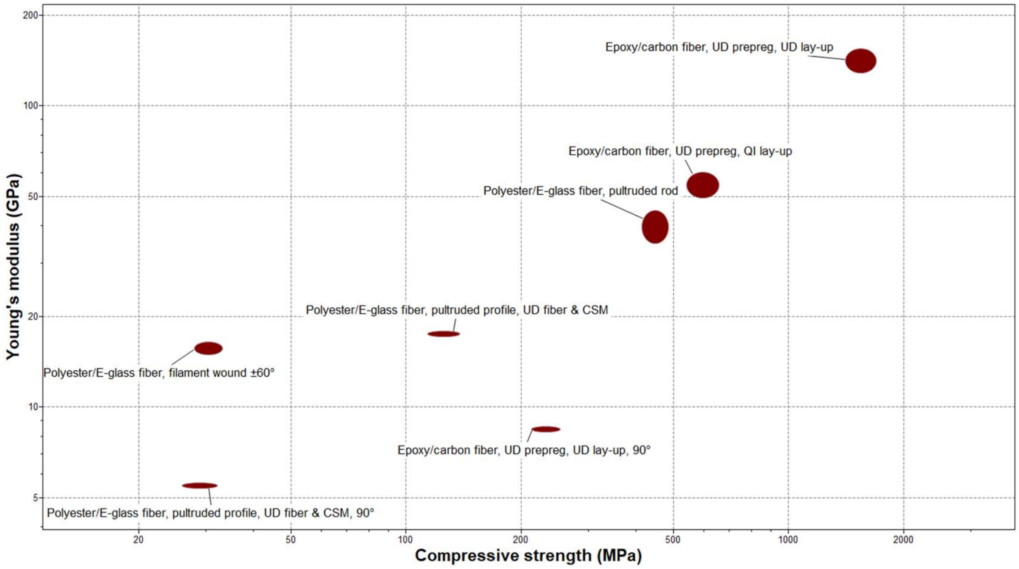


Table 17 Compressive strength/young's modulus

The following Ultimate Limit States will be considered: Compressive failure, Local buckling (short column failure mode), Lateral bending (long column failure mode).

These are the characteristic material properties:

Property	*Units*	*Symbol*	*Characteristic value*
Tensile strength (long.)	N/mm^2	$\sigma_{x,t,k}$	207
Tensile strength (trans.)	N/mm^2	$\sigma_{y,t,k}$	48
Tensile modulus (long.)	kN/mm^2	$E_{x,t,k}$	17.2
Tensile modulus (trans.)	kN/mm^2	$E_{y,t,k}$	5.5
Compressive strength (long.)	N/mm^2	$\sigma_{x,c,k}$	207
Compressive strength (trans.)	N/mm^2	$\sigma_{y,c,k}$	103
Compressive modulus (long.)	kN/mm^2	$E_{x,c,k}$	17.2
Compressive modulus (trans.)	kN/mm^2	$E_{y,c,k}$	6.9
Shear strength (in-plane)	N/mm^2	$\tau_{xy,k}$	31
Shear modulus (in-plane)	kN/mm^2	$G_{xy,k}$	2.9
Flexural strength (long.)	N/mm^2	$\sigma_{x,b,k}$	207
Flexural strength (trans.)	N/mm^2	$\sigma_{y,b,k}$	69
Flexural modulus (long)	kN/mm^2	$E_{x,b,k}$	13.8
Flexural modulus (trans.)	kN/mm^2	$E_{y,b,k}$	5.5
Failure strain (long.)	%		
Failure strain (trans.)	%		
Poisson's ratio (long.)	–		0.33
Poisson's ratio (trans.)	–		0.11

Table 18 Mechanical properties polyester/E-Glass fibre, pultruded profile, UD fibre & CSM

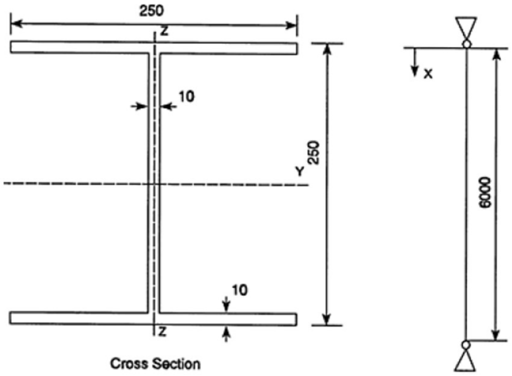


Figure 45 Designed beam

The safety coefficients can be assumed as the following:

$\gamma_{m1} = 1.5$, $\gamma m_2 = 1.1$,$\gamma_{m3} = 1.2$, γ_m strength = 2, γ_m stiffness = 1, γ_f =2.5

9.2.1 Compressive failure:

Design compressive strength:

$$
\begin{aligned}
f_{x,c,d} &= f_{x,c,k}/\gamma_m \\
&= 207/2.0 \\
&= 103.5\text{N/mm}^2
\end{aligned}
$$

9.2.2 Local buckling (beam web):

The local buckling stress for a long plate with “pinned” longitudinal edges is:

$$\mathbf{D_x = E_x t^3/12(1 - \upsilon_{xy}\upsilon_{yx})}$$

maximum inside width of the plate element, b=230 mm ; web thickness, t =10 mm

The longitudinal modulus is:
$$
\begin{aligned}
E_{x,d} &= E_{x,k}/\gamma_m \\
&= 17.2/1.0 \\
&= 17.2/\text{kN/mm}^2
\end{aligned}
$$

Out of this follows:

$$
\begin{aligned}
D_x &= 17.2\times10^3\times10^3/12(1-(0.33\times0.11)) \\
&= 1490\ \text{Nm}
\end{aligned}
$$

The transverse modulus is:
$$
\begin{aligned}
E_{y,d} &= E_{y,k}/\gamma_m \\
&= 5.5/1.0 \\
&= 5.5\ \text{kN/mm}^2
\end{aligned}
$$

Therefore:

$$
\begin{aligned}
D_x &= 5.5\times10^3/12(1-(0.33\times0.11)) \\
&= 476 \\
D_0 &= D_{xy}+2D'
\end{aligned}
$$

where:

$$
\begin{aligned}
D_{xy} &= \upsilon_{yx}E_{x,d}t^3/12(1-\upsilon_{xy}\upsilon_{yx}) \\
&= 0.11\times17.2\times10^3\times10^3/12(1-(0.33\times0.11)) \\
&= 163\ \text{Nm}
\end{aligned}
$$

The stiffness constant is:

$$D'_{xy}= G_{xy,d}t^3/\gamma_m$$

Design shear modulus,
$$
\begin{aligned}
G_{xy,d} &= G_{xy,k}/\gamma_m \\
&= 2.9/1.0 \\
&= 2.9\ \text{kN/mm}^2
\end{aligned}
$$

Therefore:

$$
\begin{aligned}
D'_{xy} &= 2.9\times10^3\times10^3/12 \\
&= 241\text{Nm}
\end{aligned}
$$

and

$$
\begin{aligned}
H_0 &= 148.4\times10^3+(2\times216.7\times10^3) \\
&= 645\ \text{Nm}
\end{aligned}
$$

Finally

$$
\begin{aligned}
\sigma_{x,cr,b} &= 2\pi^2\{(1490\times475)^{1/2}+645\}/(10\times230^2)\times1000 \\
&= 55.4\ \text{N/mm}^2
\end{aligned}
$$

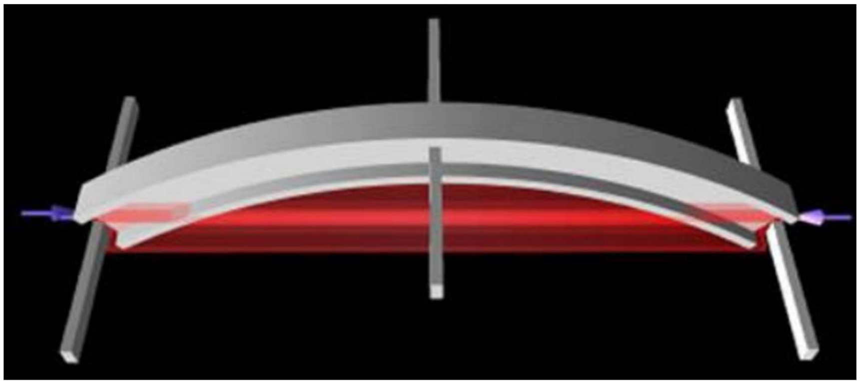


Figure 46 Buckling web

9.2.3 Local buckling (beam flange):

The local buckling stress for a long plate with one “free” and one “pinned” longitudinal edge is:

$$\sigma_{x,cr,b} = \pi^2\{(D_x(b/a)^2)+(12D'_{xy}/\pi^2)\}/tb^2$$

a=half wave length of the buckle=the length of the plate=6000 mm ; b=width of outstanding flange=120 mm ; t = thickness of flange = 10 mm

$$\sigma_{x,cr,b}=\pi^2\{(1490(120/6000)^2)+(12\times241/\pi^2)\}/10\times120^2\times1000$$
$$= 20.1\ \text{N/mm}^2$$

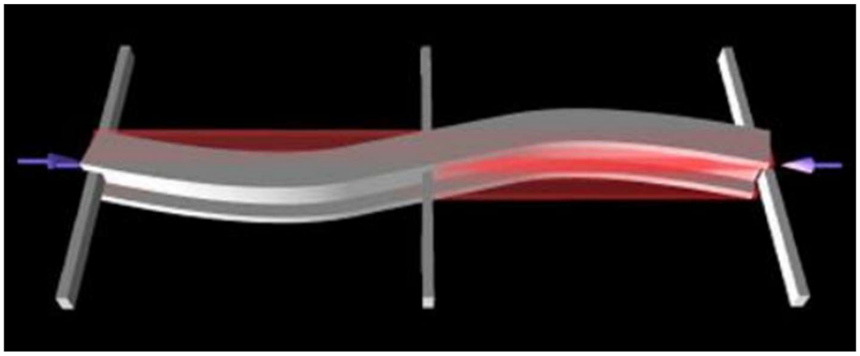


Figure 47 Buckling flange

9.2.4 Lateral bending:

$$\sigma_{x.cr.b}=N_{c.Rd}$$

Where:

$N_{c.Rd}=k\pi^2E_{x,d}\,I/L^2$ The column has pinned ends, therefore k=1.0

$$N_{c.Rd}=\pi^2\times17.2\times10^3\times2.61\times10^7/6000^2=123000\ \text{N}$$
$$\sigma_{x,crb}=123000/7300$$
$$=16.86\ \text{N/mm}^2$$

The lowest value of stress from (1), (2) and (3) gives the critical failure stress. This makes the beam design load:

$N_{sd}=\sigma_{x,cr,b}A$
$=16.86\times 7300$
$=123\ \text{kN}$

Yet with the safety coefficient included:

$=N_{sd}/\gamma_f$
$=123.6/2.5=49.2\ \text{kN}$

9.2.5 Flexural rigidity

This is the resistance offered by a structure that is undergoing a couple moment which causes it to bend. In order to measure the deflection of a beam the function =(span/depth)^3 is used. Therefore there is a significant benefit to be gained from an increase in the depth of a FRP beam (or other materials) that have a relatively low modulus. By increasing the depth the FRP's can be used without significant penalties.

For example: If the modulus of steel and glass FRP are taken as 200 N/mm^2 and 20 N/mm^2, then the increased depth required of a glass FRP beam in order to achieve the same bending deflection as a steel beam is:

$(E_{steel}/E_{GFRP})^{1/3}=(200/20)^{1/3}=2.1$

This means that the glass FRP beam would need to be 2.1 times the depth of the steel beam in order to achieve the same flexural rigidity.

This is a great benefit when materials with a low modulus are used, but in order to be able to utilize these benefits the application needs to allow for an increased beam depth. However, a low span/depth ratio has deflection due to shear as a result. This can be in the same order of magnitude as deflection due to bending. This is usually the case with GFRP composites because of their typically greater depth and also because their relatively low shear modulus. A general rule in order to achieve a feasible depth is that when glass FRP beams with a span/depth ratio greater than 25 the shear deflection is negligible in comparison to bending deflection. yet for the ones with a smaller span/depth ratio, the determination of the deflection due to shear should be made.

9.3Failure types in beams

An example of the main failures types that can occur in beams is given in the following section.

Excessive deflection

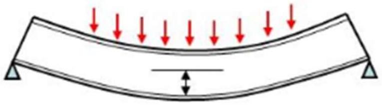


Figure 48 Excessive deflection

Bending failure

Here the loads cause the beam to sag gradually. After a time the sagging becomes to great which makes the usefulness of the beam as a supporting member is obsolete.

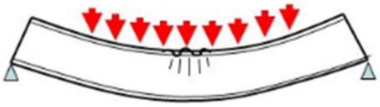


Figure 49 Bending failure

lateral torsional buckling

Lateral torsional bucking is a condition where the steel columns undergoes lateral displacement combined with twisting from its plane.

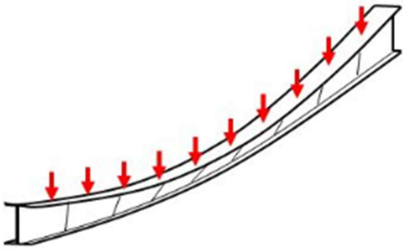


Figure 50 lateral torsional buckling

Shear failure

When the shear capacity of a beam is exceeded, the failure occurs on near the friction points of the adjacent parts.

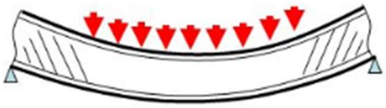


Figure 51 Shear failure

Bearing failure

This is failure occurring, as the name suggests, at the bearings of the beam. Here the web undergoes local buckling.

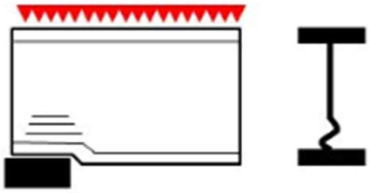


Figure 52 Bearing failure

Chapter 10.

Conclusion

The goal of this thesis was in order to examine the benefits of the integration of composite materials in bridges. These composite materials where especially aimed at fibre reinforced polymers since they have a low self-weight, a good durability and can have high mechanical properties. The different production processes also make sure that a wide variety of materials and shapes is easy to manufacture. The use of fibre glass is the most applicable since the costs of aramid or Kevlar fibres are very high. Glass fibres are easy to manufacture which makes them more affordable. Where these FRP could be applicable in the different parts of bridges needed to be examined. In the foundations and substructure of the bridge it is not recommended to use FRP since these parts can distribute loads easier when they have a bigger mass. For the superstructure of the bridge it is beneficial to use FRP since this has multiple advantages. The low self-weight and the ability to prefabricate all the elements result in a very short built-up time. This on his turn has the result that traffic detours can be minimalised. Instead of closing a road for 2 weeks this time can be abbreviated to 2 hours. Since these materials are very light, the lifting methods can be customized to the weight which results in smaller or even mobile cranes. All these advantages have a decrease of the costs as a result.

The durability of these material is also a big advantage. They are resistant to corrosive substances such as de-icing salt which causes corrosion to steel structures and reinforcement. This makes regular maintenance a necessity for concrete or steel structures which increases the costs made during the life cycle. The maintenance of FRP's can be minimized to applying a coating every few years and thus FRP have a low life cycle cost.

One of the biggest disadvantages of FRP is the high initial cost. This is partly because the materials aren't used that often yet. When the demand for FRP elements increases the costs will decrease. Engineers are nevertheless not jumpy on using FRP since there hasn't been set any design standards yet. There are a few design books that are written with the intention on being able to be used as a standard design code, but nothing has been standardized yet. When a general design code is set engineers might be more willing to use these materials. Another disadvantage is the fire resistance of these materials, at elevated temperatures these materials quickly lose their mechanical properties and they might start to release toxic gases.

So, the modern day heavy traffic gives raise to the demand for new technologies in order to reduce traffic interference. This can be done through faster assembly and less maintenance need. However, only a few bridges that meet these demands have been build to date. Before the material will become wide spread a lot of aspects need to be examined further. For example: a generally accepted structural analysis has not been established yet. The use of these materials are promising, but they are not yet on point to be fully integrated in bridge structures.

Chapter 11.

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Chapter 12.

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