Feasibility study on a composite quay wall

Ramon van der Valk

In this report the literature study belonging to the feasibility study on a composite quay wall is presented. The main focus of this literature study is fibre reinforced polymers. The fields of application, the types of fibre reinforced polymers and their manufacturing processes as well as how to determine the properties of a fibre reinforced polymer will be treated. Besides the fibre reinforced polymer, properties of concrete and steel will also be discussed. This literature study is concluded with a chapter dedicated to quay walls. The function of quay walls, the development and the types of quay walls will be elaborated into more detail.

Gemeente Rotterdam

Delft University of Technology

MSc Hydraulic Engineering

5/25/2016

TABLE OF CONTENTS

1. Introduction ... 1

2. Fields of application ... 2

2.1 Aerospace industry ... 2

2.2 Maritime industry ... 3

2.3 Construction industry ... 4

2.4 Water retaining structures ... 5

2.5 Master thesis studies ... 7

3. FRP materials ... 10

3.1 Reinforcements ... 10

3.2 Resins ... 16

3.3 Cores ... 18

3.4 Gel coats ... 19

4. Manufacturing of FRP ... 20

4.1 Open mould processes ... 20

4.2 Closed mould processes ... 22

4.3 Continuous processes ... 26

4.4 Finishing methods ... 27

4.5 Overview of the processes ... 28

5. Failure mechanisms ... 29

5.1 Mechanical ... 29

5.2 Other mechanisms ... 31

6. Joints ... 32

6.1 Types of joints ... 32

6.2 Bolted joints ... 33

6.3 Bonded joint ... 34

6.4 Bolted-bonded joints ... 34

7. Determination of properties of FRP ... 35
7.1 Rule of mixture ... 35
7.2 Stiffness of unidirectional material ... 37
7.3 The laminate theory ... 44
8. Costs of FRP ... 51
8.1 Costs of the fibres ... 51
8.2 Costs of the resins ... 52
8.3 Costs of a FRP construction ... 52
9. Codes and Guidelines ... 53
9.1 Eurocomp – design and handbook ... 53
9.2 CUR 96 – Fibre reinforced plastics in civil load bearing structures ... 53
9.3 JRC science for policy report ... 54
10. Concrete ... 55
10.1 Materials ... 55
10.2 Manufacturing of concrete ... 57
10.3 Failure mechanisms ... 57
10.4 Properties of concrete ... 58
10.5 Cost estimation ... 58
11. Steel ... 60
11.1 Materials ... 60
11.2 Manufacturing of steel ... 60
11.3 Failure mechanisms ... 61
11.4 Properties of steel ... 61
11.5 Cost estimation ... 62
12. Quay walls ... 63
12.1 Functions of quay walls ... 63
12.2 Development of quay walls over time ... 64
12.3 Types of quay wall ... 65
References ... 70

1. INTRODUCTION

This literature study will discuss the topics of composite, steel and concrete. Where steel and concrete have been used for many decades now for the construction of quay walls. Composite is a relative new material and has not been used as major building material for quay walls.. The main focus of the literature study will therefore be the composite material. Steel and concrete will also be present in this literature study but not with as much background information as will be provided for composite. The topics on the materials concrete and steel will be presented after the composite material topic.

The composite topic will start off with the fields of application of composite. Hereafter, the composite will be taken apart so that all the individual ingredients can be treated. When the fields of application and the ingredients of composite have been discussed the manufacturing process of composite will be presented. The chapter of the manufacturing processes will be followed by the topics failure mechanisms and joints. After the chapter dedicated to joints, the material properties of composite and how to determine will be presented. The codes and guidelines will be discussed before the topic is concluded with estimations on the costs of composite.

The topic of the classic materials steel and concrete will start off by discussing the materials that are needed to construct steel and concrete. The manufacturing process of the materials will be discussed hereafter. The concrete and steel chapters are concluded with a cost estimation but before this paragraph the properties of the materials will be presented.

This literature study ends with a chapter related to quay walls. The functions of a quay wall are discussed as well as the development of the quay wall. The chapter is concluded with a paragraph that shows the possible types of quay walls.

2. FIELDS OF APPLICATION

Composite is a material consisting of at least two microscopic, still to be distinguished, materials that work together to achieve a better result [Nijssen, 2013]. So the term composite is more a collection term. This literature study will focus on the fibre-reinforced plastics or polymers, also known as FRP. More information about FRP's will be given in the following paragraphs. This paragraph will focus on the fields of application of FRP's. When the term composite is mentioned in this literature study it is meant as fibre-reinforced polymer/plastic.

Composite materials are being used since the early 1900s. It started with the invention of celluloid by John Wesley Hyatt. Multiple developments took place over the years but the exponential growth of the use of composites started in 1940. This was caused by the application of composite as protection of radar antennas in military aircrafts. Nowadays composite materials are being used in all kind of sectors [Vereniging kunststof composieten Nederland].

Composite is known for its weight reduction and durability. These advantages are very useful for the transport sector. For instance, the wings of aircrafts, car bumper or bulletproof panels. The ability to construct a bulletproof panel is not only used in the transport sector but obviously also in the military sector as well.

Composite is used in the maritime sector to assure smooth sailing of a yacht and large container vessels.

The favourable material characteristics of composite such as high stiffness combined with high tensile stresses causes that composite are more and more applied in the construction sector.

These are just a few examples of the fields of application of composite. In the following paragraphs more examples for the above mentioned sectors will be treated into more detail.

2.1 AEROSPACE INDUSTRY

The appliance of fibre-reinforced polymers in the aerospace industry is mainly due to its excellent strength to weight ratio. This quality of FRP's causes that the airplanes will weigh less and will therefore have a lower fuel consumption compared to an aircraft constructed mainly out of metal. After the introduction of composites in the aerospace industry, the application of composite was limited to small parts due to the high initial costs of composite. The helicopter industry was among the first to recognize the potential of composite and to use them on a primary structure. The main and tail rotor blades were one of the major structural parts designed and built with composites towards the end of the 1960s [Kassapoglou, 2013].

With the rising fuel prices the use of FRP's in the aerospace industry will grow. This can be derived from the evolution of the share of composites compared to the total weight of a plane in commercial and military aircrafts. The trend of the share of composite in an airplane is given in Figure 1.

The Boeing 787 is an example of an airplane that consists for approximately 50 percent of composite materials. This causes the airplane to weigh less and be more fuel efficient. Besides that the amount of maintenance and operation costs will decrease. The Boeing 787 has among other things a composite fuselage and composite wings.

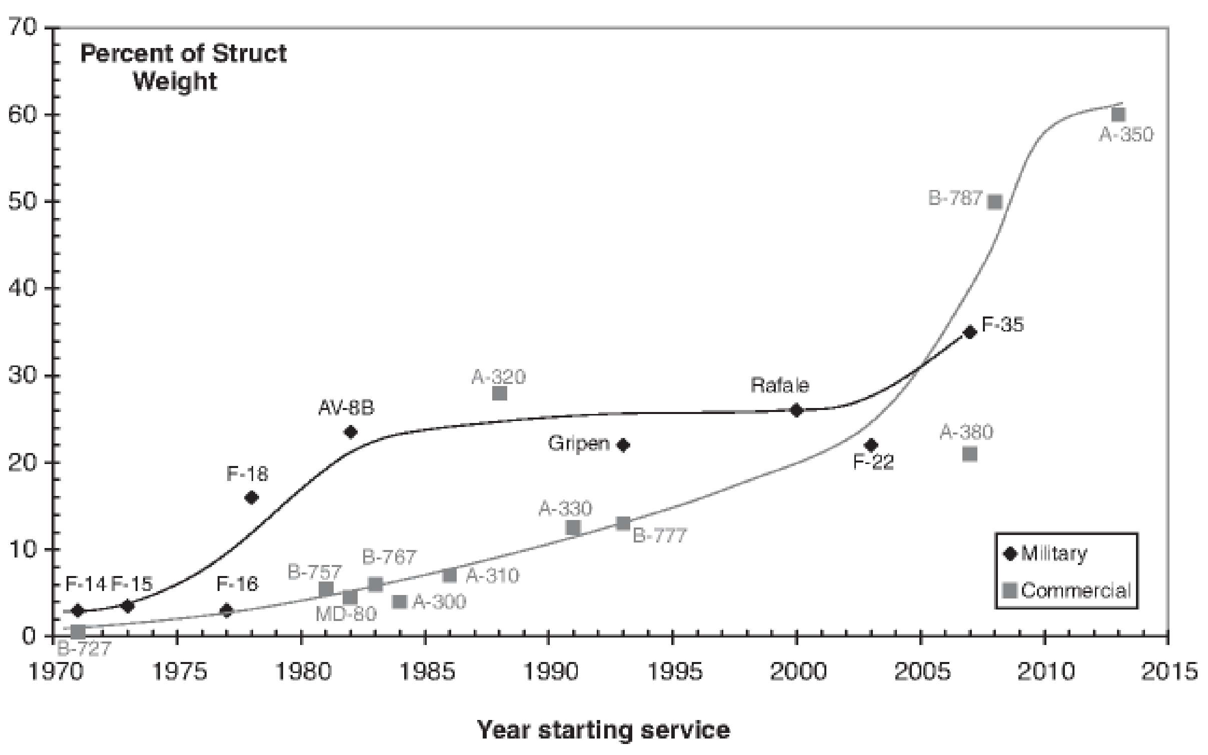


Figure 1: Applications of composites in military and civilian aircraft structures [Kassapoglou, 2013]

2.2 MARITIME INDUSTRY

Composites have been used in the maritime industry for the construction of boats shortly after the Second World War. Before the Second World War boats were mainly constructed out of timber. Wooden boats are very sensitive for seawater and marine organisms which will cause degradation of the boat. After the Second World War wood became very scarce and expensive so boat builders were more or less forced to look for alternatives.

The application of FRP composites to maritime crafts was initially driven by a need for lightweight, strong, corrosion resistant and durable naval boats. Most of these early applications were driven by the need to overcome corrosion problems experienced with steel or aluminium alloys or environmental degradation suffered by wood [Selvaraju, 2011]. Another reason for using composite was to reduce weight, which is very important for the racing industry. Racing sail and power events force a builder not only to maximize structural performance through weight reduction, but also subject vessels to higher loads and greater cycles than would normally be seen by vessels not operated competitively [Greene, 1999]. Figure 2 gives an example of composite racing boats.

Figure 2: Competitive composite sailing vessels [Source: volvooceanrace.com]

2.3 CONSTRUCTION INDUSTRY

Composite combines;

- High specific strength,
- Relative low volumetric weight,
- Large design freedom,
- Shock absorbing,
- Durability,
- UV-resistant,
- Low maintenance,
- Not sensitive to corrosion,
- Long service life.

These are all characteristics that contribute to the preference for applying composite more and more in the construction industry [Vereniging kunststof composieten Nederland]. Composite bridges as well as composite buildings have been constructed. An example of a composite building is the bus station Zuidtangent in Hoofddorp. The building has a length of 50 meters, a width of 6 meters and a height of 5 meters. Passengers for the bus line can wait under the canopy and there is an enclosed room where the bus drivers can wait. Figure 3 gives an impression of the bus station

Figure 3: Impression of the bus station in Hoofddorp

Fibre-reinforced polymers serve for a great variety of applications despite the fact that the material is relatively new in civil engineering. The most important structural applications are [Kolstein, 2008];

- Cables and tendons,
- Trusses,
- Bridge deck systems,
- Beams and girders,
- Laminates and wraps,
- Columns and poles,
- Gratings and handrails,
- All-composite FRP bridge deck structures,
- Hybrid new bridge structures.

An example of a hybrid bridge structure is the overpass Nieuwe Houtenseweg. The overpass crosses the A27 between junction Rijnsweerd and junction Lunetten. The bridge has a length of 141 meters and a width of 6.2 meters. The bridge deck is made out of composite and together with the steel framework the bridge weighs approximately 33% of a similar concrete bridge [Heijmans, 2012]. An impression of the hybrid overpass is shown in Figure 4.

Figure 4: The hybrid overpass Nieuwe Houtenseweg at the A27

2.4 WATER RETAINING STRUCTURES

Until recently there were only two cases where composite structures have been used as a water retaining structure. In both cases it concerns lock doors made out of composite. The sluices are the Kreekraklock and the Spieringlock. Since the beginning of 2016 there is a third case, the lock gates in the Wilhelminakanaal. Each case will be treated into more detail.

2.4.1 KREEKRAKLOCK

The Kreekraklock is located in the Schelde-Rijnkanaal and until 1997 there was a sweet-salt separation system consisting out of 256 steel gates. The steel gates, with a format of circa 1.80 x 0.80 meters, showed substantial corrosion with a relative high corrosion speed of 1 millimeter per year. As a pilot project, one of the steel gates was replaced by a gate of FRP. This gate has functioned for more or less 4 years before the separation of salt- and freshwater was declared no longer necessary. The gate has resisted about 20.000 load cycles and has a total slideway of approximately 20 kilometers without showing major signs of damage.

The maximum head difference was 3.2 meters and the applied material is glass fiber reinforced vinylester. The gate had conductors of PETP and slides of UHMPE. The slides were manufactured by means of over-pressure injection. The water retaining gate was equipped with stiffeners on all four edges. The first FRP gate of the Kreekraklock is shown in Figure 5 [Vereniging kunststof composieten Nederland].

Figure 5: The first FRP gate of the Kreekraklock

2.4.2 SPIERINGLOCK

The Spieringlock is located in the Biesbosch and is mainly used by small recreational vessels. The lock chamber has a length of 40 meters and a width of 6 meters. The water is retained by miter gates, which have to be able to withstand a maximum head difference of 1.3 meters. Rijkswaterstaat decided in 2000 to replace the wooden lock gates by FRP gates. The argumentation behind this decision is based on the expected lower maintenance costs for FRP gates and the relatively low mass of the gates, 14.000 kg of the wooden gates compared to 5.100 kg for the FRP gates. The lower mass will lead to smaller forces on the hinges and operation mechanism.

Figure 6: The FRP miter gates of the Spieringlock [Source: www.bhic.nl]

A single gate has dimensions of 3.6 x 6.4 meters and weighs approximately 2550 kg. The gate is constructed out of E-glassfibres in combination with a polyester resin. This decision is based on the low costs of the materials compared to other types of FRP. The fibres are for a large part oriented in one direction. 55% of the fibres are oriented in the highest loaded direction while the other directions, -45°/+45°/+90°, are equipped with 15% of the total amount of fibres [Bouwdienst Rijkswaterstaat, 2001].

2.4.3 WILHELMINAKANAAL

The Wilhelminakanaal is located in the province Noord-Brabant. The part of the Wilhelminakanaal at Tilburg is currently being widened and deepened. Part of this project is the replacement of the locks as well. In October 2015 the first composite lock gates have been installed. The gates are 6.2 meters wide and 5 meters high. In January 2016 the larger lock gates have been installed in the new lock in the Wilhelminakanaal. These locks are also completely constructed out of composite and are the largest composite lock gates in the world [Rijkswaterstaat, 2016].

The gates are 6.2 meters wide and 12.9 meters high. The mitre gates will withstand a maximum head difference of 7.90 meter. The gates have been manufactured with the worldwide patented InfraCore®Inside technology. InfraCore®Inside is a safe and strong construction material. Due to the appliance of the technology the gates are lightweight, durable and easy to install. The glass fibres, the reinforcement, are constructed with the InfraCore®Inside technology. With this technology it is possible to construct fibre-reinforced plastic sandwich constructions, where the upper and lower skin is inextricably linked with each other that can withstand a high load. The gates are provided with a yellow protective layer and require little-maintenance [FiberCore Europe, 2016].

The lock gates have a two to three times longer lifetime than conventional gates constructed out of steel or wood because FRP does not decay. In addition, there is much less wear on the hinges of the gates, because the doors have the same volumetric weight as water [FiberCore Europe, 2016].

Figure 7: Installation of the composite lock gates [Photo courtesy of FiberCore Europe]

2.5 MASTER THESIS STUDIES

There have already been a couple of (feasibility) studies on the appliance of FRP in civil engineering. Most of the studies are related to bridges and lock made out of FRP entirely of partially. Not every thesis about with FRP as topic will be treated in detail. For all the theses see the repository of the TU Delft. A couple of master theses will be discussed which are related to hydraulic engineering.

2.5.1 KADEMUUR VAN DE TOEKOMST

M. P. van Breugel made a MSC thesis for a quay wall of the future in 2003. He studied the feasibility of a quay wall that could adapt to the changing design and loading conditions. He designed a quay wall constructed out of FRP blocks that could be filled with ballast. These blocks can be reused when the quay wall is no longer in service

To determine the dimensions of the blocks and the material that had to be applied as ballast the construction has been tested against four criteria. The criteria are; sliding of the foundation layer, internal shifting of the block layers, tilting of the entire structure due to failure of the foundation and tilting of the block layers relative to each other.

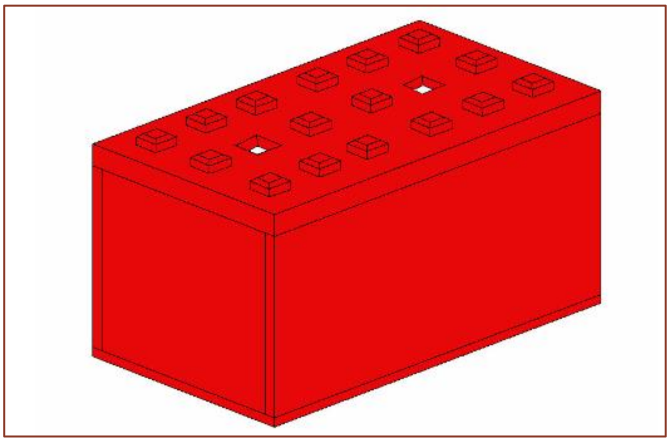


Figure 8: Layout of the FRP block [Picture courtesy of M. P. van Breugel]

The outcome is that as ballast sand will be used and the block has a height of 3 meters, a width of 2.75 meters and a length of 5.5 meters. Although the quay wall seemed technical feasible at that time, the costs of the quay wall were so much higher than the costs of an ordinary quay wall that the idea was declared economical unfeasible. An illustration of the FRP block is given in Figure 8. [Breugel, 2003]

2.5.2 FEASIBILITY STUDY FOR FRP IN LARGE HYDRAULIC STRUCTURES

The MSC thesis of L. Kok is a feasibility study for the application of FRP in large hydraulic structures. He made a design for the small gate of the Hartel Canal Barrier constructed out of FRP. The barrier has a span of 49,3m, height of 9,3m and is subjected to a maximum head difference of 5,5m. With performing a multi-criteria analysis he came to the conclusion to design the gate in the global lens shape. An impression of the design of the gate is given in Figure 9.

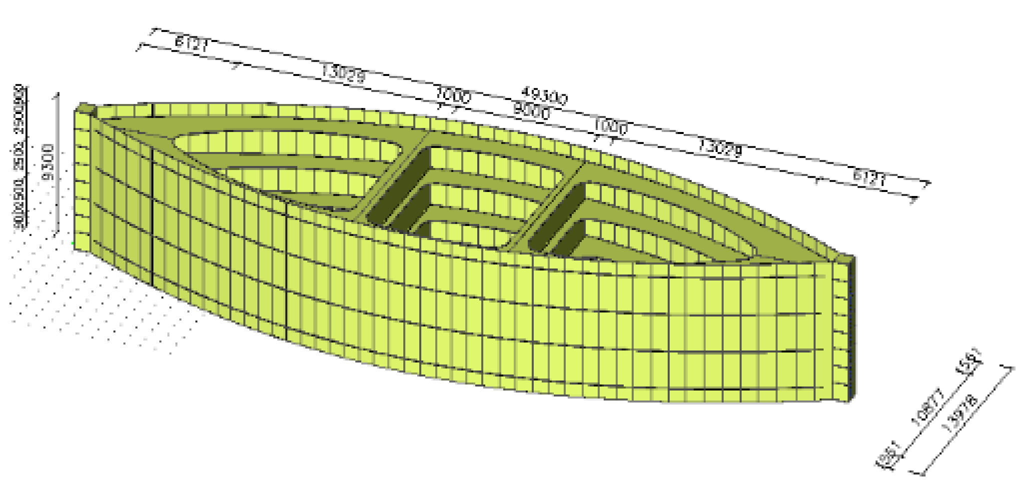


Figure 9: Illustration of the design of the lens shaped lock gate [Picture courtesy of L. Kok]

It was concluded that the weight reduction would be 22% if the gate was constructed from FRP instead of steel. The FRP gate has a weight 210 tons instead of the 270 tons of the steel gate. L. Kok concluded that the life-cycle costs of the gate made of FRP are comparable to those of the current steel gate. [Kok, 2013] Despite that the study is performed with great care there are some things that are not included in the analysis;

- The life cycle costs contain a lot of uncertainties,
- Detailing of the composite design is kept out of the scope of the project,
- The dynamic behaviour of the gate is excluded from the research, which is especially for storm surge barriers important due to the low weight in combination with high flow velocities underneath the gate when partially opened,
- Effects of a ship collision are based on indicative static forces where an energy approach would have given much more reliable results.

2.5.3 FEASIBILITY STUDY ON FIBRE REINFORCED POLYMER SLIDES IN THE EASTERN SCHELDT STORM SURGE BARRIER

The MSc thesis of van Straten is based on a feasibility study for FRP gates of the Eastern Scheldt Storm Surge Barrier. The governing gate has a height of 22 meters and spans a length of 41.5 meters. A maximum positive head difference of 6.2 meters is accounted for while also a negative head difference of 3.4 meters is taken into account. The design of the gate is a straight box girder consisting out of 2 plates which are connected to each other by 8 horizontal plates.

The vertical plates are constructed as sandwich elements. Each plate consists of two skins with a thickness of 34 millimetres and a core of 50 millimetres in between. The total thickness of a plate is therefore 118 millimetres. The total gate thickness is equal to 4 meters. An impression of the gate is given in Figure 10.

The laminates are stacked according to the 55% / 15% / 15% / 15% configuration. This means that 55 % of the fibres are placed in the horizontal direction. The horizontal plates which are placed to connect the vertical plates are equipped with holes so that material can be saved. The total mass of a single gate is approximately 180 tons. The gate needs to be filled with water in order to be closed. The mass of the displaced water is higher than the self-weight of the gate.

Van Straten has showed that the combination of E-glass and polyester is the most attractive material combination for application in lock gates. It was also concluded that vacuum assisted resin injection would be the most suitable production technique for the application of FRP in this way. [Straten, 2013]

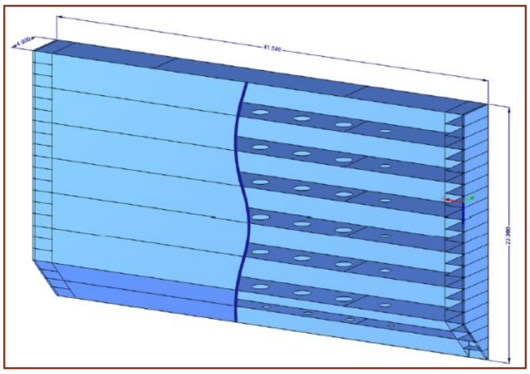


Figure 10: Impression of the FRP gate of the Eastern Scheldt Storm Surge Barrier [Picture courtesy of R. W. van Straten]

More information about manufacturing of FRP is given in chapter 4 of this literature study.

2.5.4 FEASIBILITY STUDY ON THE APPLICATION OF FIBER-REINFORCED POLYMERS IN LARGE LOCK GATES

In the Feasibility study of A. Zorgdrager a design for a lock gate constructed out of FRP has been made. The design of the lock gates of the third Beatrixlock with a span length of 25 meters, served as a case study to investigate the feasibility of FRP in large lock gates. Based on the material knowledge he gathered during his literature study, lifting gates appeared to be the most suitable gate type for application of FRP. The underlying argumentation is that lifting gates offer a good possibility for inspection and a large advantage for the supporting structure and driving equipment will be obtained due to the lower weight of FRP gates.

The gate has a length of 25 meters, a height of 12.8 meters and the distance between the curved plates right in the middle equals 4 meters. The gate will be constructed from a combination of E-glassfibres and polyester, around a core of foam. The fibres are placed in multiple layers of unidirectional plies, where 55% of the fibres are placed in the main direction of loading. The total fibre volume fraction equals 50% of the total skin volume. An impression of the design of the gate is given in Figure 11.

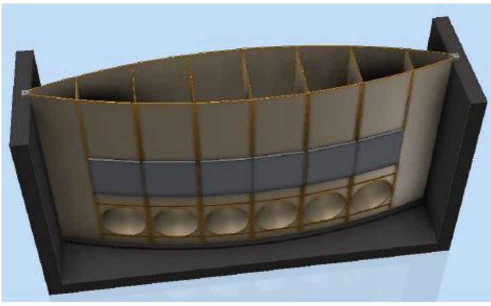


Figure 11: Impression of the design of the FRP gate for the third Beatrixlock [Picture courtesy of A. Zorgdrager]

During the structural design, the curved plates turned out to have a total thickness of 88 millimetres, consisting of two 22 millimetre skin plates with a 44 millimetre core in the middle. The webs are formed by a 24 millimetre core surrounded by two skin plates of 12 millimetres each. The design of the gate, including valves, tubes and sliding strips, has a mass of nearly 100 tons.

The conclusion of the study is that the study has proved the potential of FRP for application in large lock gates, although the absence of ductility in the material, the relatively low material stiffness, low interlaminar shear strength and the lack of (publicly available) knowledge on the detailing and long term performance of FRP structures seem to be large challenges which have to be conquered first before application is possible in projects where the consequences of failure are large. [Zorgdrager, 2014]

3. FRP MATERIALS

A composite consists of two or more materials. The properties of the composite material are not equal to the properties of the different components. FRP composites consist of load-bearing fibres and a matrix in which they are embedded. The fibres are the reinforcement and the matrix is a resin. The matrix should hold the fibres in their position and prevent them from buckling. The matrix should also protect the fibres against humidity and transfer the loads to the fibres.

The mechanical properties are influenced by the material design. Not only the type of reinforcement and resin that will be used but also the amount of fibres, the angle of the reinforcement with the loading direction and the adhesion between the fibres and the matrix will be of influence on the mechanical properties of FRP [Kolstein, 2008].

In the following paragraphs the base materials of the FRP will be treated into more detail.

3.1 REINFORCEMENTS

The reinforcement in a composite consists of fibres. They are used within resin systems to improve the mechanical properties of cured resin and provide usable components. The fibre that has been applied the most with epoxy resins is the glass fibre. Glass fibre is supplied in a variety of forms, e.g. continuous rovings, woven rovings, cloths and random chopped fibre mats. Other fibres are high strength carbon fibres and polyaramid fibres. The high strength and stiffness-t-weight ratio of carbon and polyaramid fibres make them particularly attractive for the manufacture of lightweight structural components.

3.1.1 GLASS FIBRE REINFORCEMENT

There are different types of glass fibre reinforcements with each having its own specific material characteristics. Each type of glass fibre reinforcement is indicated with a letter. The different classes are: A, C, E, R and S. The class of glass fibre reinforcement is determined by the chemical composition of the fibre. 'A' stands for alkali glass and was at one time the common base material for glass fibre production. The 'C' type fibre is a special chemical resistant glass used for surface tissue manufacture. 'E' or electrical grade glass is a very low alkali content borosilicate glass that provides good electrical, mechanical and chemical resistance properties that is currently the common base material for glass fibre production. The 'R' and 'S' classes are high strength glasses supplied in fibre form mostly for the aerospace industry [Kolstein, 2008].

It is the ease with which glass strand can be converted into various fabrics that has caused the growth of its use in many other fabrication processes. The most useful forms of glass fibre for the reinforced plastic industry that are used will be treated in the following paragraphs.

ROVINGS

Continuous filament rovings are directly made from the melt spinning of glass. Rovings are usually made by collecting individual fibres, they can form a strand of fibres by winding them together. The spool size and the number of strands that are used depend on how the rovings will be used. Continuous filament rovings are used in the pultrusion, filament winding and weaving processes [Nijssen, 2013].

MAT

Mats are the cheapest solution for planar reinforcement, but for unidirectional rovings mats are more expensive. Two types of mats will be treated, the chopped strand mat (CSM) and the continuous filament mat (CFM).

Chopped strand mat (CSM)

In chopped strand mat rovings are chopped and dispersed uniformly on a mat forming stage. The loose fibres will be bonded with a binder. These binders are built up of two forms, emulsion and powder. The emulsion is based on a polyvinyl acetate emulsion and the powder is based on a bisphenol polyester powder. The weight of CSM ranges between the 225 g/m^2 and-900 g/m^2 and contains 3 to 6 percent binder by weight [Kolstein, 2008].

Continuous filament mat (CFM)

Continuous filament mat is produced on the same way as CSM and consists of multiple layers of continuous glass fibres deposited randomly in a swirl-like pattern [Kolstein, 2008]. How the mats are produced is being discussed in chapter 4.

FABRICS[1]

Woven glass fabrics can be divided in the class that has been prepared from rovings and the class that has been prepared from yarn. Woven roving is made from 'E' glass rovings by wearing the untwisted rovings into fabric. Yarn-based fabrics are woven from continuous filament glass fibres, which have been twisted before winding on to a bobbin. Woven fabrics, whether made from rovings or yarn, are available in different weaves. The different types of weaves are;

Plain weave

Each warp, along the roll, and weft, across the roll, thread passes over one thread and under the next. This formation provides good distortion resistance and reproducible laminate thickness. The same amount of fibres is used in both directions. This is the oldest and most common weave technique in the textile industry. An impression of a plain weave is given in Figure 12.

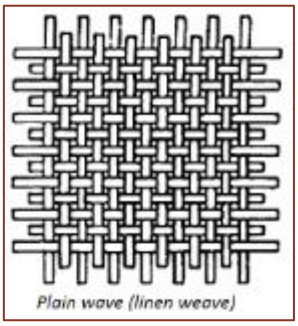


Figure 12: Plain weave

Twill weave

The way the warp and weft pass over each other can be varied. For example a 3 x 1 twill means that the weft pass over one and under two warps Twill weave fabrics have a good drapability which says something about the ease with which a fabric adopts an imposed form. An impression of a 3 x 1 twill weave is given in Figure 13.

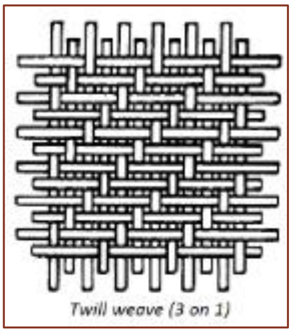


Figure 13: Twill weave

[1] [Kolstein, 2008]

Satin weave

For the satin weave one warp is woven over several yarns and then under one yarn. Hence, one side of the fabric consists mostly of warp threads and the other side of weft treads. When a configuration is passing four yarns and over one yarn is called a five-harness satin weave. The higher the satin number is, the higher the warp and weft threads. Satin weaves are less open than other weaves, which causes higher strength in both directions. Satin weave has an excellent drapability. An impression of a satin weave is given in Figure 14.

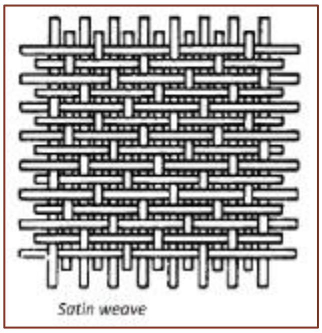


Figure 14: Satin weave

Unidirectional weave

With the unidirectional weave fine weft threads hold warp threads together such that the fabric is mostly unidirectional in structure. Maximum tensile properties are obtained in the warp direction with these fabrics. An impression of an unidirectional weave is given in Figure 15.

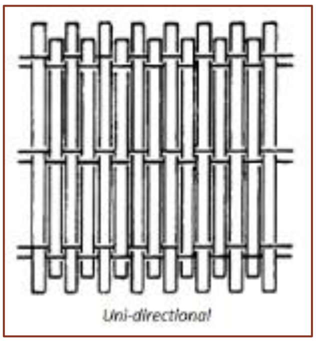


Figure 15: Unidirectional weave

3.1.2 POLYARAMID FIBRE REINFORCEMENT

Polyaramid fibre is one of the most important man-made organic fibres ever developed and, because of its unique combination of properties it is used in a wide variety of applications. The main feature of polyaramid fibre is high tensile strength with low density.

Polyaramid fibres are over five times stronger than steel on a weight for weight basis. Polyaramid fibres also have excellent thermal and dimensional stability, excellent wear resistance and good heat resistance. Polyaramid fibres fracture in a ductile manner and fracture involves fibrillation of the fibres where carbon and glass fibres fracture without reduction in cross-sectional area because they are almost completely brittle.

Polyaramid fibres are more susceptible to fibre breaking in bending by a compressive mode due to their low compressive strength, this in contrast to carbon and glass fibres. Bending the fibres produces high surface compressive stresses as well as tensile stresses. Long before the bending curvature is sufficient to cause tensile fracture, the compressive region of the fibre undergoes yielding by development of deformation bands.

The many advantages of this type of fibre can be used whilst guarding against the disadvantage of low compressive strength. Combination with other fibres in the form of hybrid fabrics often provides an acceptable compromise to take advantage of the unique properties of polyaramid fibres. [Kolstein, 2008]

3.1.3 CARBON FIBRE REINFORCEMENT

Carbon fibre is mostly used in industries where the cost is of a secondary importance such as the aerospace industry. The combination of excellent performance characteristics coupled with light weight make it an indispensable reinforcement.

The strength of carbon fibres is higher than glass fibres and also the stiffness and fatigue resistance is higher. So the properties of carbon fibres are ideal for structural purposes. The main disadvantage of carbon fibres are the relative high costs and the energy requirements for the production of the fibres.

Carbon fibres are generally surface-treated to improve bonding between fibre and matrix. Carbon fibres are supplied in a number of different forms, from continuous filament tows to chopped fibre mats. The highest strength and modulus are obtained by using unidirectional reinforcement. [Kolstein, 2008]

3.1.4 OTHER REINFORCEMENTS

The most common used reinforcements to manufacture a FRP are the above mentioned glass, polyaramid and carbon fibre reinforcements. However, there are other fibres available and they have been applied over the years. Some examples are [Kolstein, 2008];

- Polyester fibres, they are used in the manufacturing of surfacing tissues and when they are used for structural reinforcement they produce laminates with very high impact resistance. They also have excellent chemical and abrasion resistance.
- Jute fibres, they are cheap, readily available and naturally occurring fibres which are used in woven fabrics.
- Sisal fibres, they are naturally occurring and inexpensive fibres used in phenolic based DMC's, but rarely with polyester or epoxy resins.
- Nylon, they are mostly used in combination with glass reinforcement. When high impact, abrasion resistant and chemical resistant laminates are required, nylon is used to reinforce an epoxy resin.
- Boron fibres are very expansive and therefore their applicability is limited. Boron fibres are used to reinforce epoxy resins for specialized aerospace applications.

3.1.5 OVERVIEW OF THE REINFORCEMENT PROPERTIES

The stress-strain curves of reinforced fibres are presented in Figure 16 where it can be seen that glass fibres have higher elongation to failure than carbon and polyaramid fibres, but lower strengths and moduli. An overview of different reinforcement properties will be given in Table 1. It should be noted that the values are approximate values. The abbreviations 'HM' stands for high modulus where 'HT' stands for high tenacity and the abbreviation 'SM' stands for standard modulus. [Kolstein, 2008]

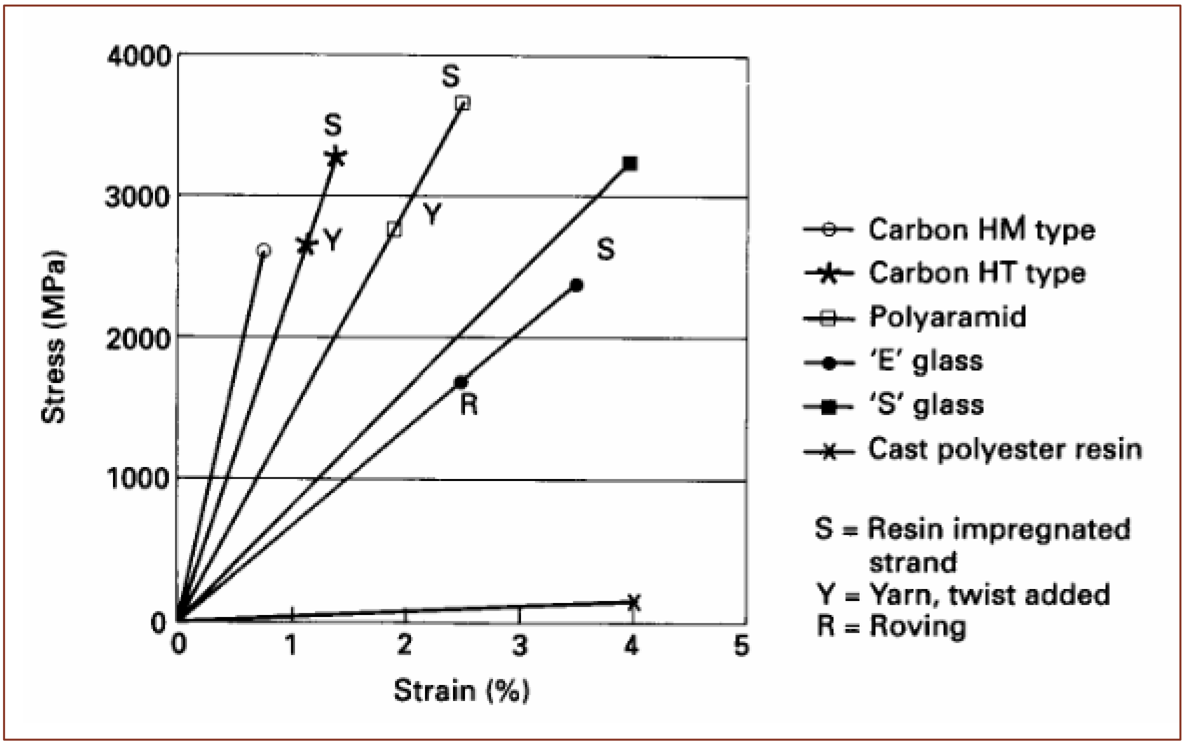


Figure 16: Stress-strain curves of reinforced fibres

Table 1: Approximate properties of fibres [Nijhof, 2004]

Fibre	Density, ρ [kg/m³]	Elastic modulus, E [GN/m²]	Tensile strength, [GN/m²]	Max. elongation, ε [%]
Glass				
E	2540	70	1.7 - 2.7	2.4 – 3.7
S	2490	85	2 – 3	2.3 – 3.5
Polyaramid				
HM	1450	130	3.0 – 3.5	2.3 – 2.6
Carbon				
SM	1800	220 - 240	3.5 – 4.5	1.5 – 1.9
HT	1800	250 - 300	4.4 – 5.0	1.5 – 1.8
HM	1850	360 - 420	2.0 – 3.0	0.5 – 0.7

The stiffness of a composite can differ in different directions due to the fibre orientation. This is represented in a polar stiffness diagram, wherein the stiffness in various directions is referred to as the distance from the origin to the line in that direction. An example of a polar stiffness diagram is given in

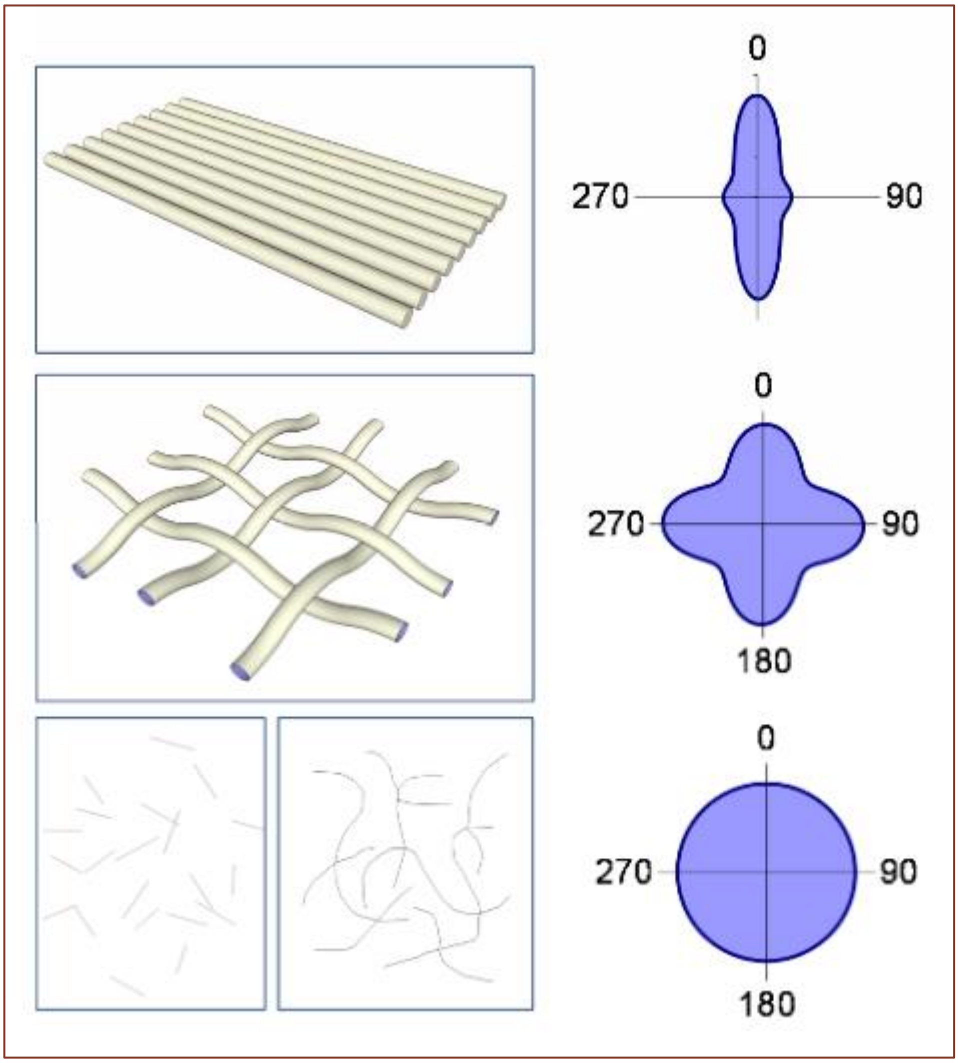


Figure 17: Polar stiffness diagram [Nijssen, 2013]

3.2 RESINS

At first it seems illogical to partially offset the high strength and stiffness of the fibres by mixing it with another material. Bundles of parallel fibres are of little use in a load-bearing structure. Bundles of parallel fibres have structural integrity in tension but their structural potential cannot be harnessed unless the bundles can be joined. This is the same when it comes to shear and compression. Without a means of distributing load across a series of fibre bundles, the material is of no use for structural applications. The only way the fibres can be used then is as a rope, which works in cable tension. To construct a material that can be used for structural applications a resin has to be added to the fibres. The main functions of the resin are [Nijssen, 2013]:

- Binding the fibres and wrap the fibres with the resin so that it can withstand a higher compression,
- Distributing the load to the fibres by means of shear stresses,
- Adding buckling capacity to the material,
- Protecting the fibres from external influences such as ultraviolet light.

The types of resins will be divided into two categories, namely thermosetting and thermoplastic resins. When heated, thermoplastics will become soft and workable. When the thermoplastic is cooled it returns to a solid form. The advantage of this characteristic of a thermoplastic is that it can be formed into almost any shape. It is however also a disadvantage when structural purposes are taken into account. Thermosets are produced with a polymerization reaction or hardening. A thermosets does not become soft when heated but will burn eventually. The most important resins are polyester, vinyl ester and epoxy which are thermosetting resins These will be discussed into detail along with other thermosetting and thermoplastic resins but not as detailed as the most important resins. [Kolstein, 2008]

3.2.1 POLYESTER

A polyester resin is the most applied resin mainly because the low cost. With polyester the most important ingredients, the unsaturated polyester, monomers and styrene, are already mixed. The hardening is started when a catalyst is added to the mixture. When a catalyst and accelerator are added to the mixture, the mixture can react in a cold state without pressure to form the final structure. Polyester is sensitive to water but this sensitivity does not apply to all the polyesters. It is even possible to construct moveable bottoms of a swimming pool out of polyester. [Nijssen, 2013]

3.2.2 VINYLESTER

Vinylester are mainly applied where a higher chemical resistance is required than a polyester can offer. Vinylester is also less sensitive to moist and can be used as a protection layer for a polyester construction that will be exposed a lot to water. The vinylester also has better elongation properties so it has a higher resistance against impact loads and fatigue. The vinylester can be seen as an extension of a polyester. Vinylester have the disadvantage that they turn yellow. This has to do with the type of connections a vinylester is made of, the aromatic ester connections. [Nijssen, 2013]

3.2.3 EPOXY

Epoxy resins are more expensive than polyester and vinylester resins. Epoxy resins are applied in fields where the fatigue of the material is of great importance such as the construction of the blades for a wind turbine. Epoxy resins offer the best mechanical properties for FRP for a number or reasons:

- They are well known as adhesives,
- Adhere well to a wide range of resins for particular processing rules,
- Can be cured with a variety of curing agents to give a broad range of properties after cure.

An overview of some characteristics of the resins polyester, vinyl ester and epoxy are given in Table 2. The advantages and disadvantages of the resins are given in Table 3.

Table 2: Characteristics of the resins [Nijssen, 2013]

	Stiffness [GPa]	Tensile strength [MPa]	Elongation [%]	Density [kg/m^3]	Cure shrinkage [%]
Polyester	2.4 -4.6	40 – 85	1.2 – 4.5	1150 – 1250	6 – 8
Vinylester	3 – 3.5	50 – 80	5	1150 – 1250	5 – 7
Epoxy	3.5	60 – 80	3 – 5	1150 – 1200	<2

Table 3: Advantages and disadvantages of the most applied resins [Cripps, 2016]

	Advantage	Disadvantage
Polyester	Easy to use	Only moderate mechanical properties
	Lowest cost of available resins	High styrene emissions in open moulds
		High cure shrinkage
		limited range of working times
Vinylester	Very high chemical/environmental resistance	Post curing generally required for high properties
	Higher mechanical properties than polyesters	High styrene content
		Higher cost than polyesters
		High cure shrinkage
Epoxy	High mechanical and thermal properties	More expensive than vinyl ester
	High water resistance	Critical mixing
	Long working times available	Corrosive handling
	Temperature resistance can be up to 140 °C wet / 220 °C dry	
	Low cure shrinkage	

3.2.4 OTHER THERMOSETS

The three resins that are treated in the sections above are the most common applied resins. There are of course also other thermosetting resins available. The resins will only be identified and will not be treated into further detail in this literature study. The other thermosetting resins are [Kolstein, 2008]:

- Phenolics,
- Furane,
- Polymide,
- Silicone,
- Melamine,
- Urea-formaldehyde

3.2.5 THERMOPLASTICS

Besides the thermosetting resins there are also thermoplastic resins as mentioned in the beginning of this paragraph. Thermoplastics are tough, elastic and corrosion resistant. The disadvantages of the thermoplastics compared to the thermosetting resins are they will become soft when the temperature is above their melting point, they are viscous under moisten conditions and in the finished state they have a lower heat resistance than thermosetting resins. Due to these disadvantages thermoplastic resins are currently not being applied for a structural purpose.

3.3 CORES

The purpose of a core is to increase the laminate's stiffness by effectively thickening it with a low-density core material. The flexural stiffness of a panel is after all proportional to the third power of its thickness. With the application of a core a sandwich construction will be created. The FRP materials will form the outer skins and the core will form the connection between the outer skins. When the sandwich is than subjected to a bending load, the outer skins will be put in compression and tension while the core is put into shear, as can be seen in Figure 18 [Cripps, 2016]. Materials that can be used as core material are available in three forms:

1. Basically lightweight,
2. Lightweight due to foamed,
3. Lightweight due to honeycomb.

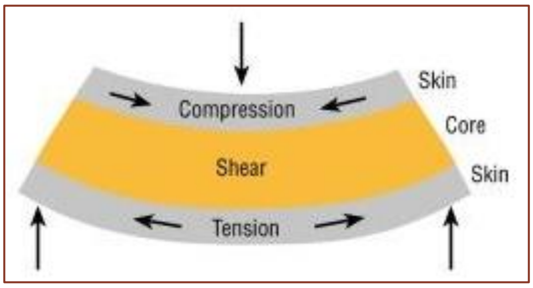


Figure 18: Sandwich construction in bending

3.3.1 FOAM

Foams have been extensively used in the manufacturing of FRP structures. Foams can be used as non-structural support formers in producing a desired shape. Foams can also be applied in high density forms with thinner skins and sandwich constructions. Low density foams can also be used for a sandwich construction unless the method of construction of the FRP requires significant pressure. Foams may be made from many plastic materials in various densities. [Kolstein, 2008]

3.3.2 Honeycombs

The first structural honeycomb was made by the Chinese approximately 2000 years ago and it was made out of paper. The aerospace industry is the industry where honeycombs are being applied the most because honeycombs are relatively expensive. Honeycombs are formed from virtually any thin sheet material connected together in a manner that resembles the honeycomb made by bees, as can been seen in Figure 19 [Nijssen, 2013].

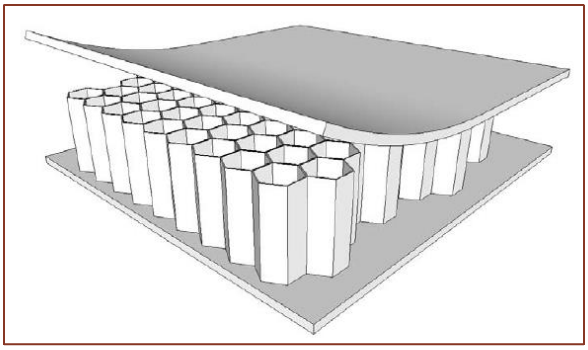


Figure 19: Sandwich construction with a honeycomb

The structural performance is particularly high in direct compression and shear owing to the directionality of the shaped form. Honeycomb products are manufactured from impregnated resin sheet material or metal foil by bonding a staggered intervals and then expanding into the required shape, most commonly a hexagon. [Kolstein, 2008]

3.3.3 Solids

For a solid sandwich construction wood is the most appropriate material. Wood has been used extensively for many applications such as doors. For lightweight constructions balsa is still being used, although synthetic materials are superseding the balsa. Syntactic foams consisting of bonded micro spheres of inorganic materials, glass and ceramics are also useful core materials. [Kolstein, 2008]

3.4 GEL COATS

With the development of the FRP industry the demand for protective coatings and barrier layers increased. The first materials marketed as protective coatings for composites were pre-formulated, compounded products called gel coats. Gel coats improve the durability of components, protect the laminate from the environment, reduce the fibre pattern, provide a smooth aesthetic finish and eliminate the need for painting. The application of a gel coat has therefore structural and aesthetic benefits and it reduces the required maintenance [Norwood, 2016]. Pigments are used to confer colour and to modify the effects of absorbed radiations. Adding a pigment influences the viscosity, the dispersion behaviour and sometimes the cure characteristics of the final gel coat. To enhance the handling properties of the gel coat there is a wide range of additives available. The choice of an additive is related to the applied pigment. [Kolstein, 2008]

4. MANUFACTURING OF FRP

This chapter describes the methods how fibre-reinforced composites can be made. The content of this chapter will be restricted to thermosetting resins reinforced with glass, carbon or aramid fibres.

Each manufacturing process has its own advantage and disadvantage. The manufacturing process also influences the material properties. Which manufacturing process should be chosen depends on the form, the complexity, repetition, costs and the required properties of the final product. In the following paragraphs the open mould, closed mould and continuous process will be treated into more detail. Each paragraph will have several sub paragraphs where the details of a specific manufacturing process will be treated.

The main problems associated with moulding unreinforced thermosets are;

1. The possibility of air bubbles being trapped in the mould,
2. Design of the mould so that the component can be extracted from it,
3. Shrinkage.

The steps that are involved to create a FRP composite are;

1. Mixing resin and activator,
2. Dispensing resin into the mould,
3. Curing.

When reinforcement is required it complicates the process by adding the following two operations;

4. Positioning reinforcement,
5. Impregnating reinforcement with resin.

All fibre reinforced polymer composite manufacturing processes contain these five elements. Methods of executing the individual elements can be thought of as techniques. Many of the described processes on the following paragraphs and sub paragraphs differ in only one or two of the five elements.

4.1 OPEN MOULD PROCESSES

In this paragraph the open mould processes will be discussed.

4.1.1 Hand laminating

Hand laminating is still widely used despite that it is labour-intensive and difficult to control the quality. An advantage of hand laminating is its inherent flexibility and the low outlay in moulds and equipment. First, apply gel coat with a brush or a soft roller to the mould. Allow the gel coat to gel. Second, apply the laminating resin with a brush or a soft roller. Third, cut and fit reinforcement layer and then finally consolidate with a ribbed roller, see Figure 20. This process can be repeated until the required thickness is reached. [Kolstein, 2008]

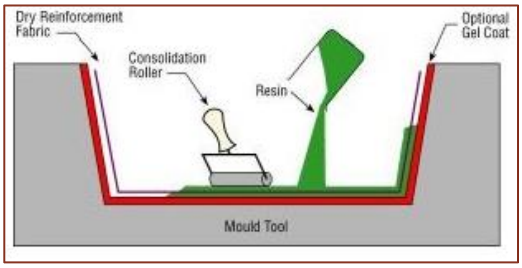


Figure 20: Hand laminating method [Cripps, 2016]

4.1.2 Saturation

Saturation is the first stage in the mechanization of open mould lay-up. The resin is mechanically mixed and sprayed on to the model. Most modern spray guns use an air drive pump. The pump delivers resin and catalyst to a hand-held, trigger operated gun. The catalyst and resin are mixed in the gun and then ejected under pressure. This type of spray guns can only operate with low viscosity resins. Saturation offers improved control over resin mixing, but the distribution control is still in the hands of the operator. Fibre volume content and thickness variations are therefore still hard to control. [Kolstein, 2008]

4.1.3 Spray-up

With the spray-up method the resin and fibres are sprayed on to the mould simultaneously. An air-driven chopper unit is mounted on a resin spray gun. The chopper devours strands of continuous reinforcement, cuts them and splits them out in short lengths. The chopped reinforcement is sprayed on to the mould along with the resin. An advantage of this method is that it is a relatively cheap method. However, the distribution of the mixture is still in the hands of the operator. This disadvantage can be ruled out when the spray gun is attached to a robot. [Kolstein, 2008] Figure 21 gives a schematization of the spray-up method.

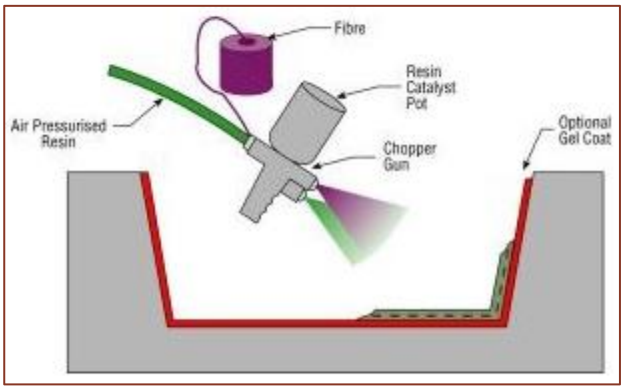


Figure 21: Spray-up method [Cripps, 2016]

4.1.4 Filament winding

Filament winding is particularly suitable for pressure vessels and is employed for the production of simple hollow shapes. The component is moulded on a rotating male former. The fibres are impregnated with resin and are wounded around a rotating male former. Figure 22 gives an impression of the filament winding process. The winding angle can be controlled by adjusting the rotation speed and the winding angle itself. Advantage of this method is that the quality control is easy to carry out during the process. A disadvantage is that the range of shapes that can be produced is limited.

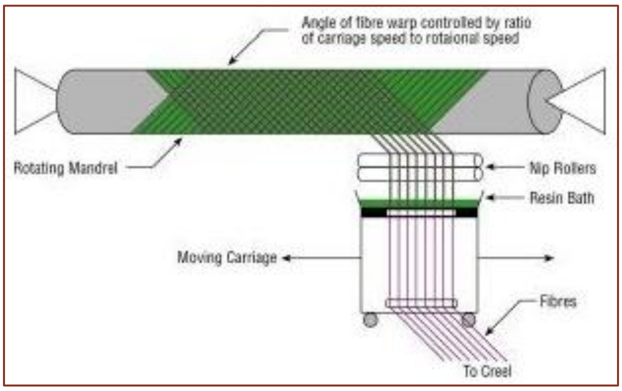


Figure 22: Filament winding method [Cripps, 2016]

The filament winding can also be combined with the auto spray-up technique. Layers of random chopped fibre are interleaved with wound-on continuous fibre strands to build up thickness on a rotating former. The resin is applied by the spray gun along with the chopped fibres as discussed in the sub paragraph about spray-up. It is more cost-effective for low-pressure applications than a totally filament-wound laminate. [Kolstein, 2008]

4.1.5 Centrifugal casting

With centrifugal casting hollow shapes are created just as with the filament winding method. The difference between the methods is that with centrifugal casting the mould surface is on the outside. The resin and reinforcement are placed inside a cylindrical mould which rotates at high speed. See Figure 23 for an impression of this method. Air is expelled and the laminate is consolidated due to the centrifugal forces. The reinforcement has a higher density than the resin which leads to a resin-rich inner surface and the reinforcement moved to the outer surface. With the centrifugal casting the quality control is again easy to carry out but this method also leads to a non-moulded inner surface. [Kolstein, 2008]

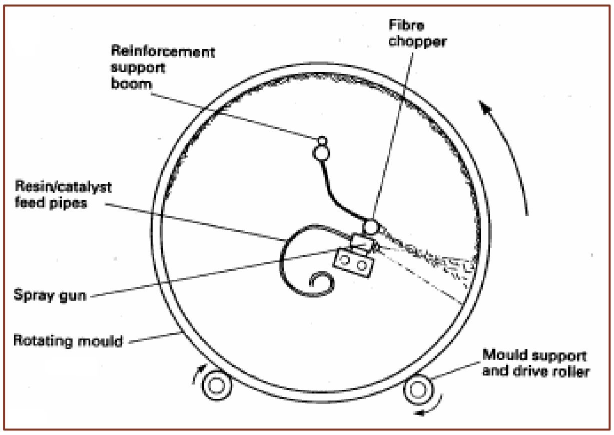


Figure 23: Centrifugal casting method [Kolstein, 2008]

4.2 CLOSED MOULD PROCESSES

The closed mould processes will be discussed in this paragraph.

4.2.1 Vacuum bag

The simplest form of the closed mould process is the vacuum bag moulding. The reinforcement and resin are applied by hand laminating to an open mould. A release film is laid over the laminate followed by a rubber bag that will be clamped to the edge of the mould. The space between the bag and the mould is then evacuated so that the atmospheric pressure is applied to the laminate. Figure 24 gives a representation of this method. It might be necessary to apply additional rolling on the outside of the bag to achieve complete consolidation. Vacuum bag is a very effective method for bonding sandwich laminates together. The production rate however is quite low. [Kolstein, 2008]

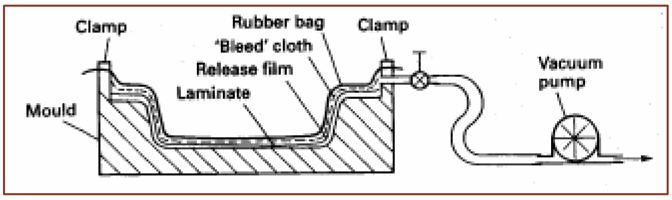


Figure 24: Vacuum bag method [Kolstein, 2008]

4.2.2 Pressure bag

The pressure bag method is similar to the vacuum bag method. The pressure bag method allows the use of higher pressures than the atmospheric pressure. This leads to better consolidation and higher fibre content. Better curing can also be achieved when heated air or steam is used in the bag. The mould needs to be much more robust than for the vacuum bag method as it has to withstand the loads generated by the applied pressure.

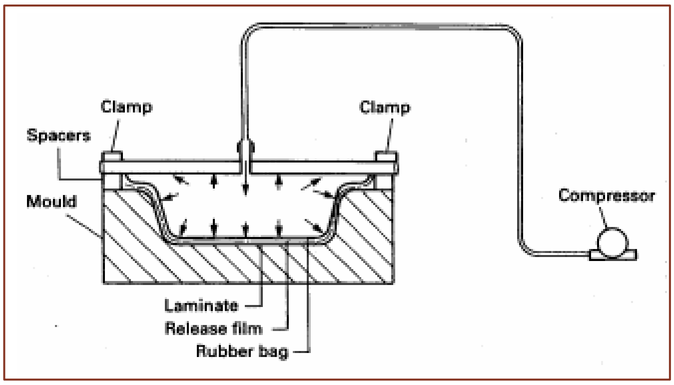


Figure 25: Pressure bag method [Kolstein, 2008]

The use of a bag press makes this process reasonably productive. The pressure bag process is used for the production of high quality components made with preimpregnated reinforcement, also known as prepreg. The resin is in partially cured state in a prepreg. Under the action of heat and pressure the prepreg forms to the shape of the mould and then sets and cures. [Kolstein, 2008] See Figure 25 for an impression of this method.

4.2.3 Autoclave

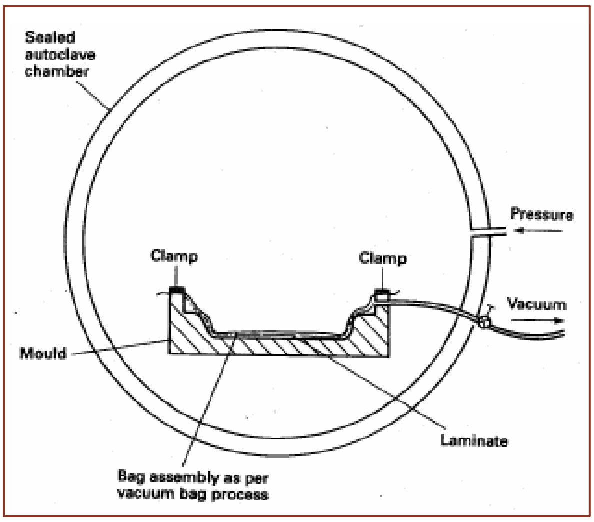


Figure 26: Autoclave method [Kolstein, 2008]

A combination of vacuum and pressure bag moulding is called autoclaving. Autoclaving produces the highest quality components and it is nowadays used almost exclusively with prepreg materials. The process uses a vacuum bag assembly inside a heated and pressurized vessel. The layers of prepreg material are laid on the mould to make up the full thickness. The mould is sealed with bleed cloth, release film and the vacuum bag that are placed over the prepreg material. The mould is then loaded into the autoclave where the laminate is subjected to vacuum, pressure and heat simultaneously. This ensures that all air is extracted from the laminate and full consolidation and cure are achieved. Figure 26 gives a representation of this method.

The advantage of the autoclave process is that moulds are not subjected to large forces and can therefore be lightweight constructions. A disadvantage from this process is that the dimensions of the mould are limited by the inner dimensions of the autoclave. [Kolstein, 2008]

4.2.4 Leaky mould

The leaky mould process is a process where a male and female mould is used. When the male and female moulds are clamped together, they form a cavity of the exact shape of the finished component. The reinforcement and resin are laid in the hollow mould, the female mould, by hand laminating. The male mould is placed over the female mould and pressed into the female mould. When the curing is complete the clamps will be removed. The moulds are separated and the component is extracted. This process produces components with accurate dimensions and a good quality finish on both sides. [Kolstein, 2008]

4.2.5 Cold press

The cold press process can be compared with the leaky mould process. There are also male and female moulds being used for this process. The moulds are rigid and mounted in a hydraulic press. The hydraulic press is capable of exerting pressure of at least 2 bar. The resin is distributed due to the compression operation and the reinforcement is impregnated with it and purging air from the mould at the same time. The reinforcement is placed as a dry pack on the mould. The resin is mixed and the required quantity is poured on to the reinforcement. Now the mould is closed and the pressure is applied. After hardening the mould can be opened and the composite can be removed. The cold press method gives accurate components with a good surface on both sides. A disadvantage is the limited press size, low fibre content and the high investment cost. [Kolstein, 2008]

4.2.6 Hot press

Hot press process is an evolution of the cold press process. With the heat press process the rate of production can be increased substantially by applying heat to the mould surface to accelerate the cure process. Due to the higher temperatures, up to 140 °C, metal moulds must be used. A liquid resin can be used, but mostly prepregs or sheet and dough moulding components are used. This method gives a very high production rate with close tolerances. Disadvantages are the limited press size and the high costs of the required equipment. [Kolstein, 2008]

4.2.7 Resin injection

The reinforcement pack is made up and loaded into the mould with the resin injection just as with the cold press process. With the resin injection process the mould is closed onto the dry pack before the resin is introduced in contrast to the cold press process. The resin is mixed and pumped into the mould by an air-driven dispensing machine through one or more injection points. The fill time depends on the size of the component and the fibre content. See Figure 27 for a representation of this method.

Resin injection is limited to random reinforcement and low fibre content, but it is capable of making more complex shapes than the cold press moulding process at a similar production rate. [Kolstein, 2008]

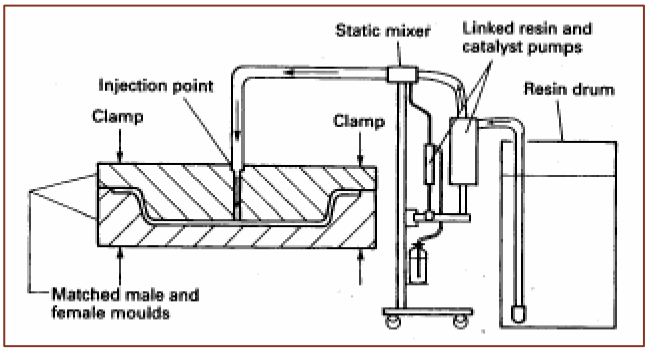


Figure 27: Resin injection method [Kolstein, 2008]

4.2.8 Vacuum-assisted resin injection

To overcome the limitations of resin injection vacuum-assisted resin injection is developed. The benefits of vacuum-assisted resin injection are the ability to produce large mouldings and higher fibre content, and the freedom to use high strength reinforcements. The detriment of this technique is that production development is usually needed on each mould.

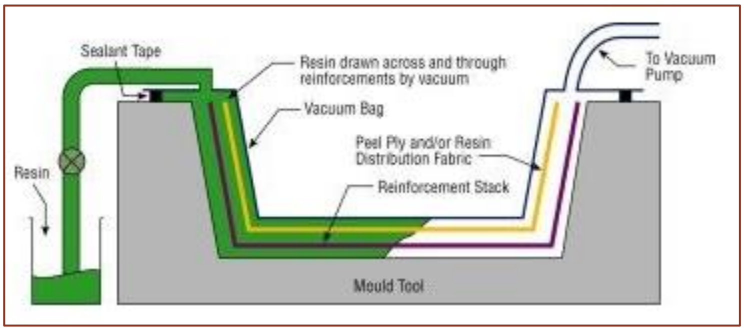


Figure 28: Vacuum-assisted resin injection method [Kolstein, 2008]

The reinforcement pack is loaded on to the mould and the mould is closed. A seal is formed around the edge of the mould and a partial vacuum introduced within the mould cavity. The partial vacuum leads to consolidation of the pack and it removes air. A pump or gravity feed injects the resin. An important feature of the process is the use of a flexible upper mould. The upper mould can then deform under injection pressure and allows the resin to pass. The resin is then reformed to its proper shape by vacuum when injection is complete. This ensures a high fibre content and good impregnation. [Kolstein, 2008] The vacuum-assisted resin injection method is represented in Figure 28.

4.2.9 Injection moulding

The injection moulding technique is used to manufacture most thermoplastic components. When this technique is applied for making composite parts, a dough must be mixed first. The dough contains all the ingredients including the reinforcement. The dough is loaded into the moulding machine hopper and processed in the same way as unreinforced materials. The dough is forced into the mould by a screw or piston and this causes degradation of the fibres. Figure 29 gives a representation of this method. Only short, random fibres can be used and their orientation is determined by the low during filling. So the properties of parts tend to be variable.

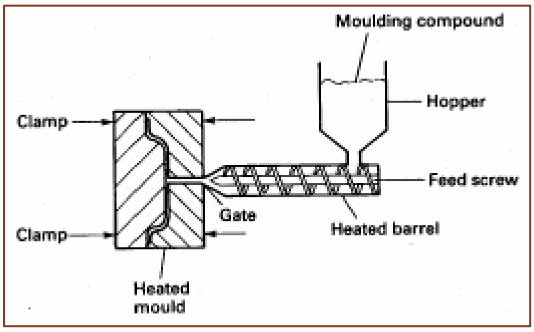


Figure 29: Injection moulding method [Kolstein, 2008]

Advantages of this moulding technique are the high production rate, the close tolerances and the ability to manufacture complex shapes. The disadvantages are the high costs for the required equipment, the mechanical properties are limited and variable and the size is limited. [Kolstein, 2008]

4.3 CONTINUOUS PROCESSES

In this paragraph the continuous processes will be treated. A continuous process is a process that makes a large number of elements in a relatively fast way.

4.3.1 Continuous laminating

The reinforcement and resins are combined and contained between two layers of release film in the continuous laminating process. The release film acts as carriers transporting the laminate on a conveyer through a curing oven. The release film is peeled of when the laminate emerges from the oven. The cured laminate is then cut to the required length. A representation of this method is given in Figure 30.

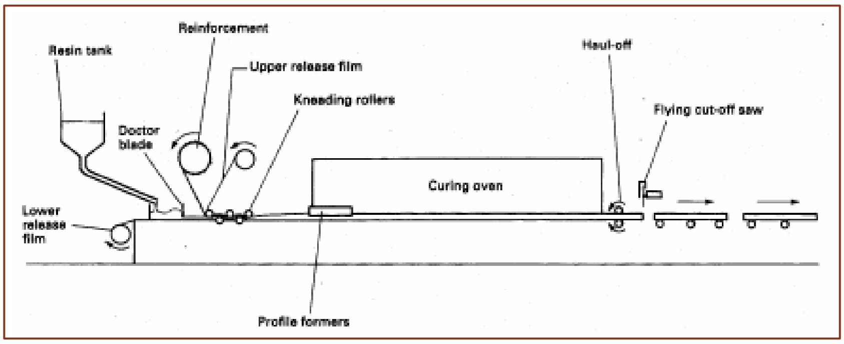


Figure 30: Continuous laminating method [Kolstein, 2008]

This process can only manufacture flat sheets or, by passing the material over formers prior to curing, a corrugated profile. The reinforcement is impregnated with the resin by either passing the reinforcement through a bath before the release films are attached or by applying a layer of resin to each release film. In both cases the laminate and its carriers will pass through nip rollers to complete the consolidation and control the thickness. The method is capital intensive but has also a high production rate. [Kolstein, 2008]

4.3.2 Pultrusion

Pultrusion is a continuous process for the production of constant section profiles in composite materials. The fibre reinforcement is first impregnated with resin mix. It is pulled through a heated steel die which causes the resin to react and cure [Clark, 2005]. The impregnation of the reinforcement with the resin can be done by submerging the reinforcement in a bath before it enters the die or by injection directly into the die. The pultrusion method is schematically represented in Figure 31.

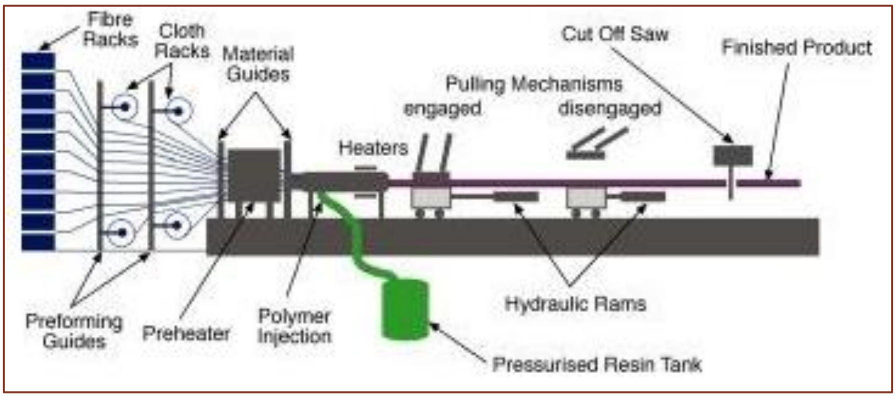


Figure 31: Pultrusion method [Cripps, 2016]

Pultrusion is, in essence, an apparently simple process. However, the production of complex and consistently high quality profiles requires a high degree of technical resource and experience. The shape of the die determines the profile shape. But the quantities of reinforcement and resin mix are critical to ensure that the die is filled properly. Resin systems must be highly reactive to cure in the available time. Die temperature, machine speed and resin reactivity are parameters which interact and must be balanced [Clark, 2005]. The Pultrusion technique enables very high fibre contents to be achieved. The high fibre contents can be achieved by using continuous yarn, woven cloth or mat reinforcement. Very high and consistent mechanical properties are attained by the tension applied to the fibres. The tension applied to the fibres also ensures good alignment. The shapes that can be constructed are limited. [Kolstein, 2008]

4.3.3 Continuous filament winding

With the continuous filament winding technique filament wound pipe will be produced continuously. A winding head containing several 'cheeses' of continuous yam reinforcement rotates around the spindle, wrapping on yam as it goes. The pipe emerges at a constant rate from a curing oven. More than one winding head can be used to create additional fibre angles. This technique is only suitable for circular tubes. [Kolstein, 2008]

4.4 FINISHING METHODS

Mouldings produced by many of the processes require some kind of finishing method. Most composite components emerge from the mould with excess material attached which needs to be removed in order to bring the part to its finished size. The amount of rest material varies with the applied moulding technique. When the hot press or injection method has been applied the amount of rest material is less than when hand lamination has been applied.

To eliminate the rest material several techniques can be applied. These techniques are:

- Cutting-trimming / deflashing,
- Sawing,
- Routing,
- Drilling,
- Planing,
- Turning,
- Buffing,
- Etching,
- Painting.

Where buffing, etching and painting are surface finishing techniques. Surface finishing techniques might not be applicable when a pigment is added to the resin or when a gel coat is applied.

Two important matters have to be taken into account for the finishing of composites;

1. Excessive wear of the equipment due to the presence of, for example, glass fibre in many composites,
2. The released products from the finishing and machining of the mouldings. The harmfulness of plastic, glass and carbon particles is not yet known, but many plastics and very small particles are irritating and / or toxic / carcinogenic.

4.5 OVERVIEW OF THE PROCESSES

An overview of the above treated manufacturing processes is given in Table 4. For each manufacturing process the following data will be displayed.

- The fibre volume fraction,
- The size range,
- The processing pressure,
- The processing temperature,
- If there is core material present yes or no,
- What the tolerance of the overall dimensions is,
- What the relative production cost is,
- What the relative equipment cost is.

Table 4: Overview of the manufacturing processes [Kolstein, 2008]

Type	Fibre volume [%]	Size range [m²]	Processing pressure [bar]	Processing temperature [°C]	Core material [-]	Tolerance [mm]	Relative production cost [-]	Relative equipment cost [-]
Open mould processes								
Hand laminating	13 – 50	0.25 – 2000	Ambient	Ambient	Yes	1.0 – 5.0	High	Very low
Saturation	13 – 50	0.25 – 2000	Ambient	Ambient	Yes	1.0 – 5.0	Moderate to high	Very low
Spray-up	13 – 21	2.0 – 100	Ambient	Ambient	Yes	1.0 – 3.0	Low	Moderate
Filament winding	55 – 70	0.1 – 100	Ambient	Ambient	Yes	1.0 – 2.0	Low	Moderate to high
Centrifugal casting	20 – 60	0.5 – 100	Ambient	40 – 60	No	1.0 – 3.0	Low	Moderate to high
Closed mould processes								
Vacuum bag	16 – 60	0.5 – 20	1	Ambient	Yes	1.0 – 3.0	High	Low
Pressure bag	20 – 70	0.5 – 20	up to 3.5	Ambient	Yes	1.0 – 3.0	High	Low
Autoclave	35 – 70	0.25 – 5.0	up to 10	140	Yes	0.5 – 1.0	High	High
Cold press	15 – 25	0.25 – 5.0	2 – 5	20 – 50	No	0.25 – 1.0	Low	Moderate
Hot press	12 – 40	0.1 – 2.5	50 – 150	130 – 150	No	0.2 – 1.0	Very low	Very high
Resin injection	10 – 15	0.25 – 5.0	up to 2	20 – 50	Yes	1.0 -2.0	Moderate	Moderate
Vacuum-assisted resin injection	15 – 35	1.0 – 30	up to 2	15 – 30	Yes	2.0 – 5.0	Moderate	Low
Injection moulding	5 – 10	0.01 – 10	750 - 1500	140	No	0.1 – 0.5	Very low	Very high
Continuous processes								
Continuous laminating	10 - 25	Up to 2.0 m wide	Low	100 – 150	No	1.0	Very low	high
Pultrusion	30 – 65	Up to 1.0 m wide	Varies	130 – 150	No	0.2 – 0.5	Low	High
Continuous filament winding	55 – 70	Up to 2.0 m diameter	Ambient	Ambient	No	1.0 – 2.0	Low	High

5. FAILURE MECHANISMS

Just like other materials composite can fail. An important difference with an isotropic material is that, depending on the structure of the laminate and the load, there is a plurality of basic failure mechanisms. The most important mechanisms will be treated in this chapter. The fail mechanisms are divided into two groups, namely mechanical and other failure mechanisms. It is important to understand the failure mechanisms so that a proper design of the laminate structure can be made.

5.1 MECHANICAL

This paragraph will treat the mechanical failure mechanisms splitting, delamination, buckling, fatigue, impact damage and creep.

5.1.1 Splitting

The failure mechanism splitting causes cracks in the composite, parallel to the fibres, and through the entire thickness of one or more lamellae. Splitting can occur when a lot of fibres are running in the same direction and the adhesion transversely to the fibres is not sufficient. Splitting can be caused by, for example, bending stress in the transverse direction. This failure mechanism can be countered by constructing the structure of the laminate in such a way that the orientation of the fibres are not all in the same direction. [Nijssen, 2013]

5.1.2 Delamination

Delamination resembles the splitting failure mechanism, but with delamination the crack occurs in the plane of the laminate between two lamellae. This failure mechanism can easily occur due to the fact that the shear tress between lamellae can be high and there is no reinforcement between the lamellae. Delamination can start everywhere in a composite but the edges of a laminate or lamellae are the most sensitive for this failure mechanism. Lamellae are also more sensitive to delamination when the stiffness of two laminates differ. This is inherently the case with sandwich constructions. The core material differs in many characteristics with respect to the skin material.

Delamination can be prevented by preventing high shear stresses between lamellae. This can be achieved by adding extra layers of laminate to the structure or by reducing the extreme loads. A good finish of the edges of the lamellae also contributes to preventing high shear stresses. [Nijssen, 2013]

5.1.3 Buckling

Buckling can occur in any long, slender pressure element. On the material level you need to take into account the damage caused by buckling for composite materials. Under the influence of a pressure load the fibres, fibre bundles and lamellae tend to buckle. This will lead to delamination.

The resistance against buckling can be increased by using a stiffer material in the construction or by reducing the so called buckling length. [Nijssen, 2013]

5.1.4 Fatigue

Fatigue is a physical phenomenon that causes damage to and eventually failure of the structure. Fatigue is however not a single load that causes damage to the structure but it is a series of loads, load cycles, that will cause the structure to fail. Fatigue life is usually measured as the number of cycles to failure for a given applied load level. The composites may experience microcracking, delamination, fibre fracture fibre and or matrix decoupling and microbuckling under fatigue loading.

The fatigue performance of composite materials is affected by many factors. These factors are; properties of the fibres and matrix, the interphase region, the manufacturing progress, loading parameters and in-service environmental conditions. The properties of the fibres play the most important role in fatigue performance. In general, composites made from fibres with higher modulus have a higher fatigue resistance.

Besides the transverse and shear properties, the matrix also affects axial loaded unidirectional fatigue properties. The effect of the matrix is reflected in the failure mode for unidirectional laminates. If the ductility of the matrix is higher than the fibre, the fibres will fracture multiple times over its length. The overload goes through shear over the matrix to the adjacent fibres. If the ductility of the matrix is lower than the fibres, the matrix cracks cause bridging by the fibre, eventually leading to fibre fracture or delamination along the fibre–matrix interface.

Damage due to fatigue can be reduced by adjusting the materials and fibre orientations to the loading, adjusting the construction such that the loading is more favourable or reducing the tension in the construction by adding layers of material. [Karbhari, 2007]

5.1.5 Creep

Creep is the time-dependent and permanent deformation of materials when they are subjected to an externally applied load over an extended period of time. Normally, creep is undesired because it negatively affects the lifetime of a material. Another time-dependent response of a material is relaxation. Stress relaxation is the inverse of creep where a material is subject to a constant strain and a reduction in stress occurs over time.

Creep behaviour of FRP composites depends on fibre orientation, fibre volume fraction and structure of the material. However, creep of FRP composites is predominantly a result of creep in the polymer matrix. Unlike the conventional materials like steel and concrete, FRP's are more vulnerable to creep during the manufacturing, due to the applied resin and adhesive.

Creep in polymers is recoverable at low strains when the applied load is removed, unlike creep in metals.. The period for which the load is removed and the strain approaches zero is known as the recovery period. Figure 32 shows the strain versus time response of a viscoelastic material for a given load history. The recovery period is shown in the figure as the time when the applied load is removed and the strain in the material dissipates and returns to its initial state.

[Karbhari, 2007]

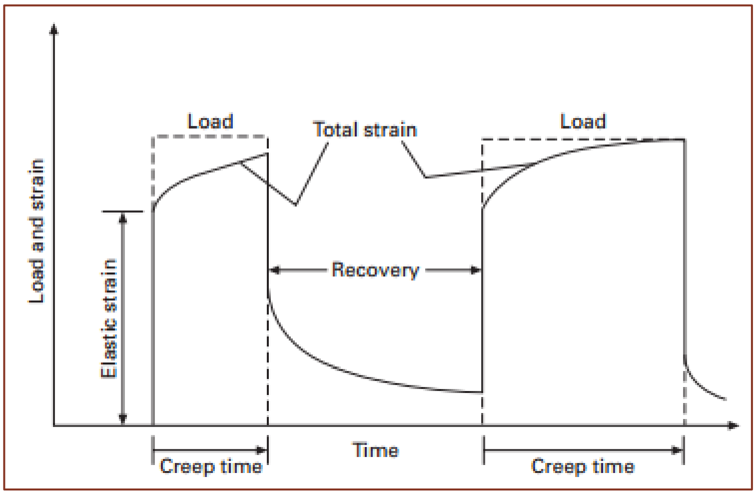


Figure 32: Creep response of a viscoelastic material for a given load history

5.1.6 Impact damage

Due to the elastically behaviour of composite materials, damage due to impact is hard to detect. The severity of the damage is not always possible to detect from the state of the impacted surface. When a metal material has been subjected to an impact load it can be detected by a dent in the material. However, a composite material will rebound for a large part. This means for the design that the planning for inspection, maintenance and possible repairs, the accessibility of both sides of the construction should be implemented. [Nijssen, 2013]

5.2 OTHER MECHANISMS

This paragraph will treat other failure mechanisms than the mechanical failure mechanisms. The treated mechanisms are osmosis, UV, erosion and damage due to temperature or fire.

5.2.1 Osmosis

Osmosis is a general term for the transport of water and solutes by a medium as a result of difference in concentration. For a composite, osmosis refers mostly to water absorption by the resin. Water absorption by the resin can lead to damage. When a resin is continuous exposed to moisture it will absorb water. The water absorption is reversible, when a composite dries, the water will leave the resin. The damage however, is not always reversible. Polyester is the most sensitive to damage caused by osmosis. Damage to a composite by osmosis can be detected when the material starts to blister. The water can also cause damage indirectly, when it freezes the water will expand leading to damage.

The use of resins which are little to not sensitive for osmosis are recommended to prevent damage. When a polyester resin has been applied in the construction a gel coat can be applied to the construction to prevent damage by osmosis. [Nijssen, 2013]

5.2.2 UV

Damage by ultra-violet light does not directly affect the strength and stiffness characteristics of the material because potential damage to the construction is limited to the first millimetre of the construction. UV damage leads to visual damage. After time, the construction will decolour. [Nijssen, 2013]

5.2.3 Erosion

In applications where an abrasive medium sands along any surface, erosion can occur. At a sufficient velocity, water can be an abrasive medium. In general, the damage is initially confined to the surface, but when underlying lamellae are damaged, the constructive characteristics can be affected. Testing can provide insights into the susceptibility to erosion, but there are many different test methods, which leads to a complicated comparison of results. [Nijssen, 2013]

5.2.4 Damage due to fire

For the most of the composites it holds that the matrix is the most sensitive to raised temperatures and fire. With temperatures above the glass transition temperature the matrix becomes rubberlike. At higher temperatures the matrix will melt and if the temperature rises even further the matrix material will burn. This goes for the thermoplastics as well as the thermosets. This results in the loss of the connection between the fibres and will eventually lead to failure.

With a fire proof layer the time to failure of the structure can be delayed. [Nijssen, 2013]

6. JOINTS

The FRP elements will be of a finite length. To form a watertight quay wall the elements will have to be connected to one another. This chapter will therefore treat the subject of joints in FRP structures. Joints are needed due to the limitations in material size or for convenience in manufacturing or transportation. The purpose of a joint is to transfer load between the two items being joined. This chapter will treat the types of joints followed by a more detailed description of bonded, bolted and a combination of bonded and bolted joints. This chapter is concluded with a short comparison between the three treated types of joints.

6.1 TYPES OF JOINTS

The configuration of a joint is predominantly determined by the loads acting on the joint. A moment resisting joint is more complex than a simple joint. The simpler the design of the joint will be, the less it will cost. A moment resisting joint is shown in the left of Figure 33 while a simple joint is presented on the right.

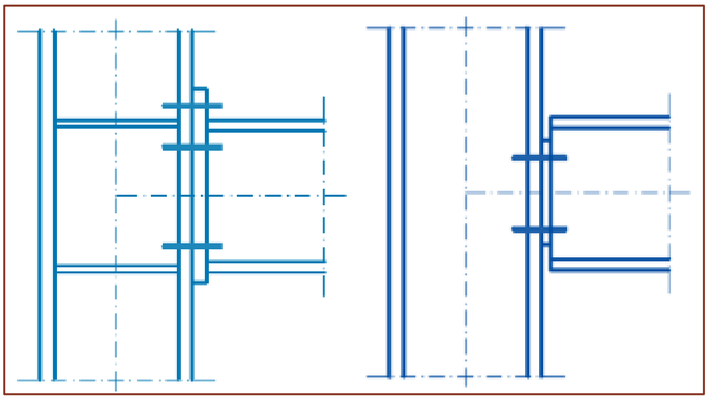


Figure 33: A moment resisting and a simple joint [BRON XXXXXXXXX]

The previous distinction between joint types is made on the basis of the resisting capacity of a joint. There is also another way of distinguishing joints, namely by the type of connection. Materials can be mechanical fastened or chemical bonded. The mechanical fastening revers to a bolted connection while the chemical bonding revers to a bonded or adhesive connection. In special cases it might also be required to create a combined joint.

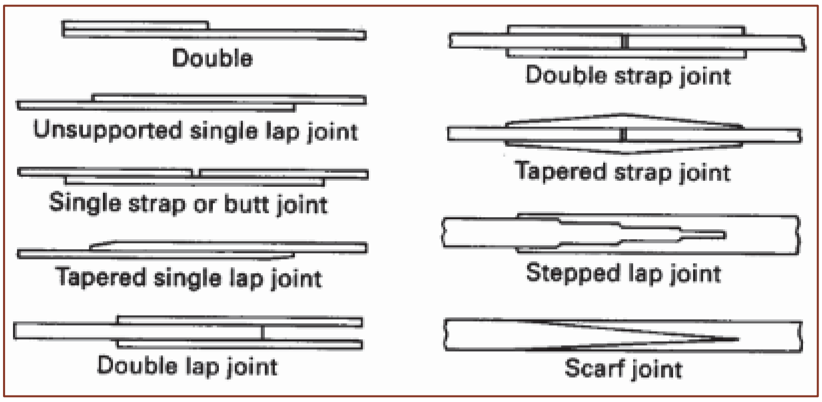


Figure 34: Basic joint types [Kolstein, 2008]

The basic type of joints are presented in Figure 34. These types of joint can be used for mechanical fastening as well as for chemical bonding. The weakest joint is the unsupported single lap joint and the strongest joint is the most complicated one, this is the stepped joint. [Kolstein, 2008]

As mentioned before, the purpose of a joint is to transfer load between two materials or items that are being joined. As a result of the load transfer, the stresses in the components as well as in the joining medium in the joint region will vary. The joint configuration must be properly designed otherwise the joint will fail due to the occurring stresses. Examples of good and bad configurations are given in Figure 35 on the next page.

The mechanical fastening, chemical bonding and the combined bolted-bonded connection will be treated into more detail in the following paragraphs.

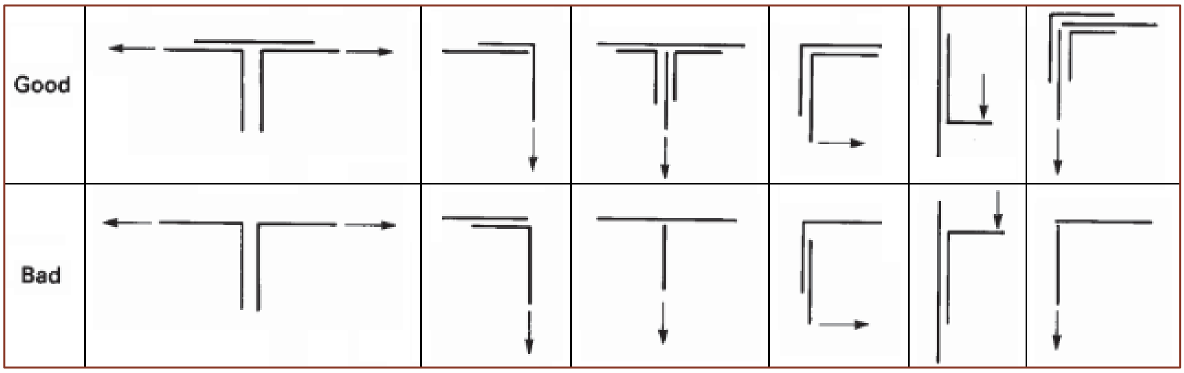


Figure 35: Examples of good and bad joint configurations [Kolstein, 2008]

6.2 BOLTED JOINTS

The design procedure for a bolted joint in FRP is similar to the procedure for steel joints. A bolted connection consists of a steel bolt. Steel is another kind of material than FRP. Where FRP is heterogeneous and anisotropic, steel is a homogeneous and isotropic material.

A bolted joint is easier to prepare compared to bonded joints. The design procedure for a bolted joint is the same as for steel joints as mentioned before. This is an advantage compared to the bonded joints because there is not as much experience with a bonded joint as with a bolted joint. This is reflected by the amount of design codes that are available for both types of joints. Another advantage of a bonded joint is that it is dismountable. The resistance however, is less when compared to bonded joints. The stress concentrations are also higher for a bonded joint. And there is a risk of galvanic corrosion of the metal bolts with a bolted joint.

The failure modes of a bolted joint are presented in Figure 36. Failure mode (a) represents the net-tension failure. This failure mode is caused primarily due to tensile stresses at the entire width of the edge end. This occurs when the ratio of by-pass to bearing load is high or when the ratio of hole diameter against plate width is high. Failure mode (b) shows the pin-bearing failure mode. This failure mode occurs when the ratio diameter of the hole over the plate width is low or when the by-pass load to bearing is low. Shear-out failure is represented by failure mode (c). This mode occurs along the shear-out plane of the whole section from the bolt to the edge. Failure mode (d) shows the bolt-shear failure mode which is caused by high shear stresses in the fastener. [Clarke, 2005] Except failure mode (d), all the other failure modes are brittle.

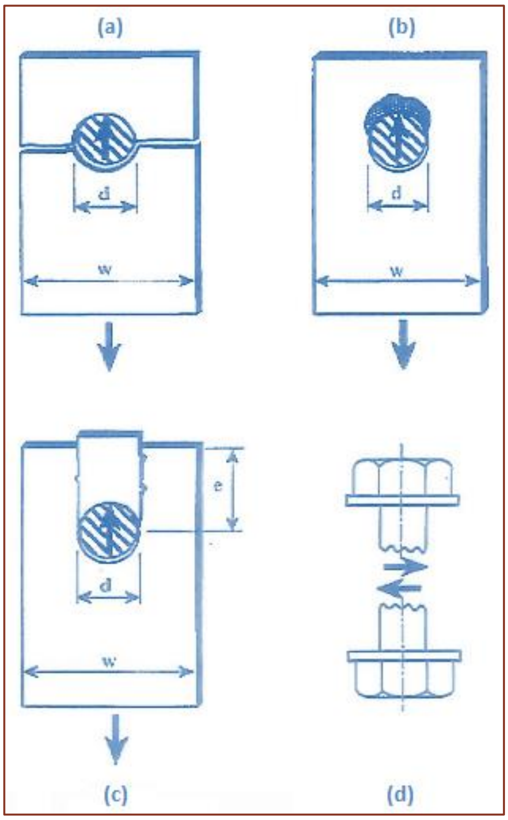


Figure 36: Failure modes of a bolted joint [Bron XX]

6.3 BONDED JOINT

A bonded joint is also known as an adhesive connection. This means that two parts are joined with an adhesive. The most used types of adhesives are epoxy, acrylic and poly-urethane. Each adhesive has its own advantages and disadvantages so the choice for an adhesive depends on which properties are required from the adhesive. Particular attention must be paid to the surface preparation, the level of moisture in the workshop environment, the laminate and the adhesive, and to the selection of the adhesive to achieve a satisfactory joint. [Kolstein, 2008] Figure 37 gives a schematization of a joint and some important parameters for the design of a bonded joint.

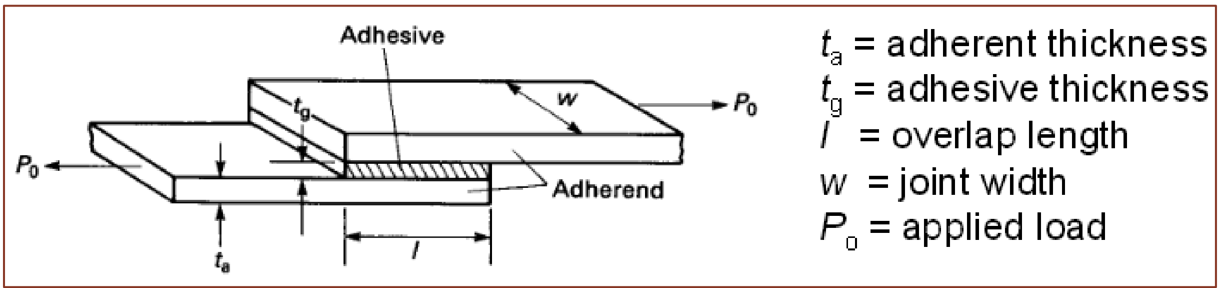


Figure 37: Schematization of a joint and indication of important parameters [BRON XXXXXXXXXXX]

Advantage of a bonded joint is that the joint has a higher tolerance for assembly than a bolted joint. Another advantage is that the bonded joint is less expensive than the bolted joint. However, disadvantages of a bonded joint are that such a joint is more sensitive to environmental conditions, surface preparation is required and the failure of such a joint is brittle. This type of failure does not give warning signs and the failure will occur suddenly.

The maximum shear and peel stresses occur around the ends of the overlap due to stiffness of the adherents and the adhesive. The overlap is, therefore one of the most important parameters that determines the strength of the bonded joint.

The failure modes of a bonded connection are shear failure and peel failure. With a higher in-plane stiffness of the adherent, the variation of the stresses will be less. A lower stiffness of the adhesive will also lead to less variation of stresses. Shear failure is presented by the top figure of Figure 38 while peel failure is presented by the bottom figure of Figure 38. An alternative mode of failure is the inadequate preparation of the joint. This failure mode should be treated as a quality control matter. [Kolstein, 2008]

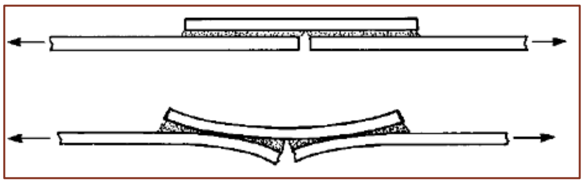


Figure 38: Failure modes for a bonded joint [BRON XX]

6.4 BOLTED-BONDED JOINTS

A bonded-bolted joint combines adhesive bonding and mechanical fastening. This combination will not improve the joint strength compared to that of a well-designed bonded joint. Since a structural adhesive provides a much stiffer load path than fasteners, the adhesive carries the load almost entirely and no load sharing between the adhesive and the bolts occurs [Kolstein, 2008]. The design of a combination joint should therefore be performed according to the procedures used in the design of adhesively bonded joints.

A bolted-bonded joint may be justified in the following cases:

- Bolts can prevent manufacturing defects and service-induced bond line damage from spreading.
- Bolts can provide the required clamping pressure during bonding process.

  In certain cases, bolted-bonded joints may be used in such a way that the bonded joint satisfies the serviceability limit state requirements and the bolted joint satisfies the ultimate limit state requirements or vice versa. [Clarke, 2005]

7. DETERMINATION OF PROPERTIES OF FRP

To be able to make calculations with FRP structures the structural and material properties of the FRP have to be determined. The previous paragraphs have treated the kind of FRP materials which are available and also the ways of manufacturing a FRP have been elaborated. The chosen materials as well as the manufacturing process will have its influence on the properties of the FRP. This paragraph will give an insight in how the properties of a FRP have to be determined and which models can be used to achieve this.

7.1 RULE OF MIXTURE[2]

To establish the composition of fibre reinforced material the rule of mixture can be applied. With this rule the ratio of resin and fibre in the material can be determined. The mass of the components are indicated with 'M' and the volume with 'V'. To distinguish the fibre and matrix properties the indices 'f' and 'm' are used. It is assumed that there are no voids in the material, the following holds;

$$M_c = M_f + M_m; \qquad V_c = V_f + V_m \qquad \text{Eq. 7.1}$$

The mass and volume are related to one another by the density ρ. So the densities are;

$$\rho_f = \frac{M_f}{V_f}; \qquad \rho_m = \frac{M_m}{V_m}; \qquad \rho_c = \frac{M_c}{V_c} \qquad \text{Eq. 7.2}$$

The volume fractions of the components are;

$$\upsilon_f = \frac{V_f}{V_c}; \qquad \upsilon_m = \frac{V_m}{V_c}; \qquad \upsilon_f + \upsilon_m = 1 \qquad \text{Eq. 7.3}$$

By combining equation 7.2 and 7.3 and given that the volume fractions as well as the densities are known, this will lead to the density of the composite;

$$\rho_c = \frac{M_f + M_m}{V_c} = \frac{V_f\rho_f + V_m\rho_m}{V_c} \quad \rightarrow \quad \rho_c = \upsilon_f\rho_f + \upsilon_m\rho_m \qquad \text{Eq. 7.4}$$

This equation is called the rule of mixture.

The masses of the fibre material are in general known in the production of FRP products and the amount of resin is weighed. In other words, the mass fractions of the components are known;

$$m_f = \frac{M_f}{M_c} = \frac{V_f\rho_f}{V_c\rho_c} = \frac{\rho_f}{\rho_c}\upsilon_f; \qquad m_m = \frac{M_m}{M_c} = \frac{V_m\rho_m}{V_c\rho_c} = \frac{\rho_m}{\rho_c}\upsilon_m; \; m_f + m_m = 1 \qquad \text{Eq. 7.5}$$

From this equation the density of the composite material can be calculated with the following formula;

$$\frac{1}{\rho_c} = \frac{\upsilon_f + \upsilon_m}{\rho_c} = \frac{m_f}{\rho_f} + \frac{m_m}{\rho_m} \quad \rightarrow \quad \rho_c = \left(\frac{m_f}{\rho_f} + \frac{m_m}{\rho_m}\right)^{-1} \qquad \text{Eq. 7.6}$$

Substituting this formula into equation 7.5 gives the volume fractions;

$$\upsilon_f = \frac{\rho_m}{m_m\rho_f + m_f\rho_m} m_f; \; \upsilon_m = \frac{\rho_f}{m_m\rho_f + m_f\rho_m} m_m \qquad \text{Eq. 7.7}$$

2 [Nijhof, 2004]

7.2 STIFFNESS OF UNIDIRECTIONAL MATERIAL

The simplest form of a material having a reinforcement of continuous fibres is that in which the filaments are embedded parallel to each other. This type of material is called a unidirectional material. This paragraph will treat different models which can determine the stiffness of unidirectional material. The paragraph will be concluded by a comparison of the models.

7.2.1 Simple models to determine the stiffness[3]

To determine the stiffness of unidirectional FRP in longitudinal direction the parallel model can be used as a first estimation. The longitudinal direction is the direction that corresponds with the direction of the fibres. When the unidirectional material is stressed in longitudinal direction, the matrix and fibres will deform collectively. The parallel model is presented in Figure 39.

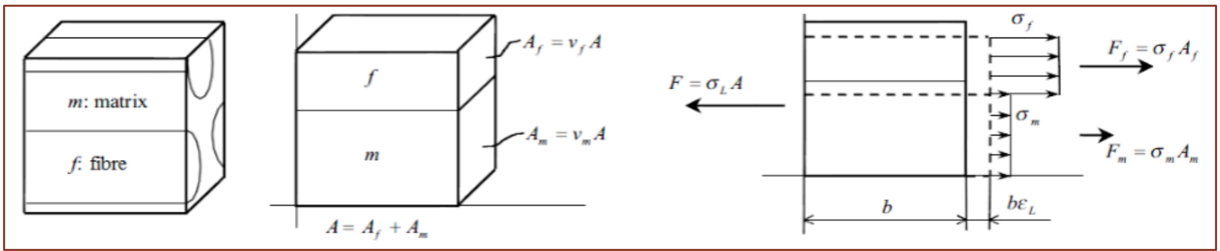


Figure 39: Parallel model for a unidirectional FRP stressed in longitudinal direction [Nijhof, 2004]

The surfaces of the matrix and fibres is constant in the cross-section of the unidirectional FRP. The force F is acting in the longitudinal direction. Dividing this force by the surface of the cross-section will result in the mean longitudinal stress, σ_L, where the index L indicates the longitudinal direction. The total force acting on the cross-section can therefore be written as;

$$F = \sigma_L(A_f + A_m) = F_f + F_m = \sigma_f A_f + \sigma_m A_m \qquad \text{Eq. 7.8}$$

With the rule of mixture this can be rewritten as;

$$\sigma_L = v_f \sigma_f + v_m \sigma_m \qquad \text{Eq. 7.9}$$

It is assumed that the difference in lateral contraction between the fibres and matrix can be neglected. It may therefore be assumed that there is a uniaxial stress in the fibres as well as in the matrix. With Hooke's law, σ=E·ε, the strains in longitudinal direction can be written as;

$$\varepsilon_f = \frac{\sigma_f}{E_f} = \varepsilon_m = \frac{\sigma_m}{E_m} = \varepsilon_L = \frac{\sigma_L}{E_L} \qquad \text{Eq. 7.10}$$

The longitudinal Young's modulus, E_L, can now be written as;

$$E_L = v_f E_f + v_m E_m \qquad \text{Eq. 7.11}$$

[3] [Nijhof, 2004]

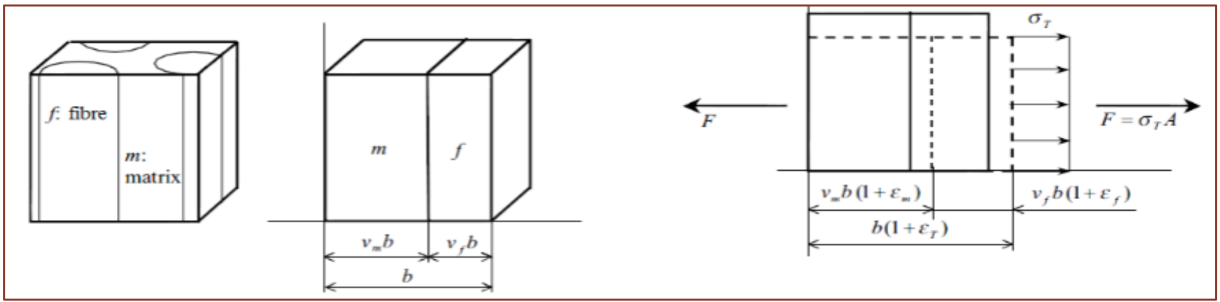


Figure 40: Series model for a unidirectional FRP loaded in transversal direction [Nijhof, 2004]

The simplest approach to estimate the transversal Young's modulus is similar to the approach for the longitudinal Young's modulus. The unidirectional FRP is now loaded in transversal direction as can be seen in Figure 40. The parallel model becomes a series model. The same transverse stress acts in both components. The transversal strain of the composite, ε_T, is equal to the weighed sum of the component strains;

$$\varepsilon_T = \upsilon_f \varepsilon_f + \upsilon_m \varepsilon_m \qquad \text{Eq. 7. 12}$$

The stresses in the components are equal and uniaxial stress is assumed. This leads to;

$$\frac{1}{E_T} = \frac{\varepsilon_T}{\sigma_T} = \frac{\upsilon_f \varepsilon_f + \upsilon_m \varepsilon_m}{\sigma_T} = \frac{\upsilon_f \varepsilon_f}{\sigma_f} + \frac{\upsilon_m \varepsilon_m}{\sigma_m} = \frac{\upsilon_f}{E_f} + \frac{\upsilon_m}{E_m} \qquad \text{Eq. 7.13}$$

The estimation of the transversal Young's modulus with this equation appears to deviate from reality and can therefore not be applied in practice. This deviation is caused by the implication of the series model that the lateral contraction in both components is equal. The model can be improved by taking a combination between the parallel and series model. This combination leads to two estimation formulas for the transversal Young's modulus;

$$E_T = \sqrt{\upsilon_f}\left(\frac{\sqrt{\upsilon_f}}{E_f} + \frac{1-\sqrt{\upsilon_f}}{E_m}\right)^{-1} + (1-\sqrt{\upsilon_f})E_m \qquad \text{Eq. 7.14}$$

$$E_T = \left(\frac{\sqrt{\upsilon_f}}{\sqrt{\upsilon_f}E_f + (1-\sqrt{\upsilon_f})E_m} + \frac{(1-\sqrt{\upsilon_f})}{E_m}\right)^{-1} \qquad \text{Eq. 7.15}$$

The derivation of both formulas can be found on page 10 and 11 of [Nijhof, 2004].

7.2.2 The variation theorem of Hashin and Shtrikman[4]

With the variation theorem of Hashin and Shtrikman the boundaries of the effective constants that describe the stiffness behaviour of the FRP can be determined. The variation theorem of Hashin and Shtrikman gives the narrowest boundaries possible based on volume fractions. For their variation theorem Hashin and Shtrikman compared two different bodies whose geometrical circumstances such as size and volume were equal, just as the conditions. The two bodies are of different material. One is a heterogeneous, anisotropic material while the other body is a homogeneous but possibly anisotropic material. The boundaries are given for the compression modulus k^*, the longitudinal modulus of elasticity E_L^*, the transversal modulus of elasticity E_T^*, the longitudinal-transversal poisson's ratio μ_{LT}^*, the longitudinal-transversal shear modulus G_{LT}^* and the transversal shear modulus G_{TT}^*. The asterisk indices indicates that the value is an effective value. The formulas to determine the boundaries are;

If $k_f > k_m$ and $G_f > G_m$;

$$k_m + \frac{v_f}{\frac{1}{k_f - k_m} + \frac{v_m}{k_m + G_m}} \leq k^* \leq k_f + \frac{v_m}{\frac{1}{k_m - k_f} + \frac{v_f}{k_f + G_f}} \qquad \text{Eq. 7.16}$$

$$\langle E \rangle + \frac{4 v_f v_m (\mu_f - \mu_m)^2}{\frac{v_m}{k_f} + \frac{v_f}{k_m} + \frac{1}{G_m}} \leq E_L^* \leq \langle E \rangle + \frac{4 v_f v_m (\mu_f - \mu_m)^2}{\frac{v_m}{k_f} + \frac{v_f}{k_m} + \frac{1}{G_f}} \qquad \text{Eq. 7.17}$$

$$\langle \mu \rangle - \frac{v_f v_m (\mu_f - \mu_m)\left(\frac{1}{k_f} - \frac{1}{k_m}\right)}{\frac{v_m}{k_f} + \frac{v_f}{k_m} + \frac{1}{G_f}} \leq \mu_{LT}^* \leq \langle \mu \rangle - \frac{v_f v_m (\mu_f - \mu_m)\left(\frac{1}{k_f} - \frac{1}{k_m}\right)}{\frac{v_m}{k_f} + \frac{v_f}{k_m} + \frac{1}{G_m}} \qquad \text{Eq. 7.18}$$

if $\frac{\mu_f - \mu_m}{k_f - k_m} < 0$, otherwise reversed;

$$G_m + \frac{v_f}{\frac{1}{G_f - G_m} + \frac{v_m}{2G_m}} \leq G_{LT}^* \leq G_f + \frac{v_m}{\frac{1}{G_m - G_f} + \frac{v_f}{2G_f}} \qquad \text{Eq. 7.19}$$

$$G_m + \frac{v_f}{\frac{1}{G_f - G_m} + \frac{v_m (k_m + 2G_m)}{2G_m (k_m + G_m)}} \leq G_{TT}^* \leq G_f + \frac{v_m}{\frac{1}{G_m - G_f} + \frac{v_f (k_f + 2G_f)}{2G_f (k_f + G_f)}} \qquad \text{Eq. 7.20}$$

$$\left\{\frac{1}{4G_{TT(-)}} + \frac{1}{4k_{(-)}} + \frac{\mu_{LT(+)}{}^2}{E_{L(-)}}\right\}^{-1} \leq E_T^* \leq \left\{\frac{1}{4G_{TT(+)}} + \frac{1}{4k_{(+)}} + \frac{\mu_{LT(-)}{}^2}{E_{L(+)}}\right\}^{-1} \qquad \text{Eq. 7.21}$$

The plus and the minus indices in equation 7.21 indicate the upper and lower value.

7.2.3 The interpolation formulas by Tsai[5]

From cross-sections of unidirectional FRP Tsai concluded that the filament cross-sections are partly lying in strands against each other. He takes this into account in his model to determine the effective technical constants. In one extreme case, all filaments are isolated from one another in the matrix. The other extreme case is that the filaments are positioned against one another in such a way that the matrix is isolated in cylinders. Both cases give the same model. Reality is somewhere in between these two extreme cases.

[4] [Nijhof, 2004]

[5] [Nijhof, 2004]

Tsai therefore introduced a filament contiguity factor *C*. When this factor is equal to 1 it means that there is a complete closed off fibre network. If the factor is equal to 0 there is total fibre isolation. The interpolation formulas of Tsai can be found in [Nijhof, 2004] on page 91.

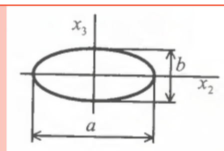
7.2.4 Halpin, Tsai and Hahn[6]

The results of various calculations are used by Halpin and Tsai as a starting point for the derivation of simplified formulas to determine the effective technical constants of unidirectional FRP. They have applied the method of curve fitting to derive the simplified equations. Halpin and Tsai succeeded to derive and form a general formula for the technical constants;

$$\boldsymbol{P = P_m \frac{1+\xi\eta v_f}{1-\eta v_f}} \quad \text{with} \quad \boldsymbol{\eta = \frac{P_f - P_m}{P_f + \xi P_m}} \qquad \text{Eq. 7.22}$$

P indicates the considered characteristic. When indices are applied the characteristic is the considered component. Without indices the characteristic of the composite is considered. Table 5 presents the parameters of the Halpin and Tsai model to determine the technical constants.

Table 5: Parameters of the Halpin and Tsai model [Nijhof, 2004]

P	P_f	P_m	ξ	Remarks
$\boldsymbol{E_L^*}$	$E_{L;f}$	$E_{L;m}$	$\frac{2l}{d}$	l = fibre length d = fibre diameter
$\boldsymbol{\mu_{LT}^*}$	$\mu_{LT;f}$	$\mu_{LT;m}$	∞	
$\boldsymbol{E_T^*}$	$E_{T;f}$	$E_{T;m}$	$\frac{2a}{b}$	
$\boldsymbol{G_{LT}^*}$	$G_{LT;f}$	$G_{LT;m}$	$\left(\frac{a}{b}\right)^{\sqrt{3}}$	
$\boldsymbol{G_{TT}^*}$	$G_{TT;f}$	$G_{TT;m}$	$\frac{k_m}{k_m + 2G_{TT;m}}$	$\xi = \frac{1}{3-4\mu_m}$ for an isotropic matrix (resin)

Components are often assumed to be isotropic and the fibres are assumed to be continuous with a circular cross-section. If these assumptions are implemented in the formulas of Halpin and Tsai this will result in;

$$\boldsymbol{E_L^* = v_f E_f + v_m E_m} \qquad \text{Eq. 7.23}$$

$$\boldsymbol{\mu_{LT}^* = v_f \mu_f + v_m \mu_m} \qquad \text{Eq. 7.24}$$

$$\boldsymbol{E_T^* = E_m \frac{E_f + 2(v_f E_f + v_m E_m)}{v_m E_f + v_f E_m + 2E_m}} \qquad \text{Eq. 7.25}$$

$$\boldsymbol{G_{LT}^* = G_m \frac{G_f + v_f G_f + v_m G_m}{v_m G_f + v_f G_m + G_m}} \qquad \text{Eq. 7.26}$$

$$\boldsymbol{G_{TT}^* = G_m \frac{(3-4\mu_m) G_f + v_f G_f + v_m G_m}{(3-4\mu_m)(v_m G_f + v_f G_m) + G_m}} \qquad \text{Eq. 7.27}$$

[6] [Nijhof, 2004]

Tsai and Hahn have reduced the relations for unidirectional FRP with filaments having a circular cross-section to modified mixture rules. The general formula is;

$$\boldsymbol{P = \frac{v_f}{v_f+\eta v_m} P_f + \frac{\eta v_m}{v_f+\eta v_m} P_m} \quad \text{Eq. 7.28}$$

P is the property to be considered and η is a quantity which depends on the ratio in which the stresses are distributed over the components. It is assumed that the matrix is isotropic and that the fibres are transversely isotropic. These assumptions are appropriately for carbon and aramid fibres. The parameters of equation 7.28 are presented in Table 6.

Table 6: Parameters for the Halpin, Tsai and Hahn model [Nijhof, 2004]

P	Pf	Pm	η	When $G_m \ll G_{LT;f}$
E_L^*	$E_{L;f}$	E_m	1	
μ_{LT}^*	$\mu_{LT;f}$	μ_m	1	
$\frac{1}{G_{LT}^*}$	$\frac{1}{G_{LT;f}}$	$\frac{1}{G_m}$	$\eta_{LT} = \frac{1}{2}\left(1+\frac{G_m}{G_{LT;f}}\right)$	$\eta_{LT} = \frac{1}{2}$
$\frac{1}{k^*}$	$\frac{1}{k_f}$	$\frac{1}{k_m}$	$\eta_k = \frac{1}{2(1-\mu_m)}\left(1+\frac{G_m}{k_f}\right)$	$\eta_k = \frac{1}{2(1-\mu_m)}$
$\frac{1}{G_{TT}^*}$	$\frac{1}{G_{TT;f}}$	$\frac{1}{G_m}$	$\eta_{TT} = \frac{1}{4(1-\mu_m)}\left(3-4\mu_m+\frac{G_m}{G_{TT;f}}\right)$	$\eta_{TT} = \frac{3-4\mu_m}{4(1-\mu_m)}$
And with that; $\frac{1}{E_T^*} = \frac{1}{4G_{TT}^*} + \frac{1}{4k^*} + \frac{(\mu_{LT}^*)^2}{E_L^*}$				

7.2.5 The composite cylindrical model

The composite cylindrical model is drafted by Hashin and Rosen. The composite cylindrical model is a consistent model for unidirectional FRP that leads to unambiguous formulas. All fibres have a circular cross-section but can differ in diameter. Each fibre is concentric embedded within a matric cylinder with a diameter such that in each cylinder the quantities of fibre and resin relate to each other as the fractions in the composite. For such a composite cylinder it is assumed that the technical constants are equal to the technical constants of the composite. This results in the lower limits of the Hashin and Shtrikman model for E_L^*, μ_{LT}^*, G_{LT}^* and k^*[Nijhof, 2004]

Christensen and Lo have derived an equation for the transverse shear modulus based upon the cylindrical model of Hashin and Rosen. They assumed that the elastic energy for the heterogeneous material must be equal to the equivalent of the homogenous material. [Nijhof, 2004]

7.2.6 Empirical formulas of Puck et al for FRP

Puck has, in addition to using the rule of mixture for E_L^* and μ_{LT}^*, applied curve fitting on his experimental obtained values to come up with empirical formulas for G_{LT}^* and E_T^*. Both formulas can be written in the following general form;

$$\boldsymbol{P = P_m \frac{1+\alpha v_f^{\beta}}{\gamma v_f \frac{P_m}{P_f} + v_m^{\delta}}} \quad \text{Eq. 7.29}$$

The parameters of this general form of the empirical formula of Puck et al are presented in Table 7 on the next page.

Table 7: Parameters belonging to the general form of Puck's empiric formula [Nijhof, 2004]

		$P = E_T^*$	$P = G_{LT}^*$
	$P_m =$	$\frac{E_m}{1-{\mu_m}^2}$	G_m
	$P_f =$	E_f	G_f
Glass fibre reinforced polymers by Puck	α β γ δ	0.85 2 1 1.25	0.6 0.5 1 1.25
Glass fibre reinforced polymers by Förster & Knappe	α β γ δ	0 - 1 1.45	0.4 0.5 1 1.45
Glass fibre reinforced polymers by Schneider, Menges & Peulen	α β γ δ	1 3 6 0.75	0.25 0.5 1.25 1.25

7.2.7 Comparison of all models[7]

To compare the outcome of the here before mentioned models, the technical constants can be calculated and plotted. This has been done for a unidirectional E-glass/epoxy with assumed isotropic components with the following stiffness values; $E_f = 70\ GN/m^2$, $\mu_f = 0.22$, $E_m = 3.5\ GN/m^2$ and $\mu_m = 0.35$. The plotted results are shown on the next page in Figure 41.

From this figure it can be seen that the boundaries from Hashin & Shtrikman for the longitudinal elastic modulus are very close to each other. For the other moduli, the boundaries of Hashin & Shtrikman are far from close to each other. It is remarkable that the lower limit of Hill is even lower than the respectively lower limit of Hashin & Shtrikman. This confirms the statement that the series model for a transversal cross-section deviates too much from reality to base approximations on it. The other models are closer to the lower limit of Hashin & Shtrikman.

The equation of Tsai & Hahn for the transverse elastic modulus delivers the same values as the lower limit of Hashin & Shtrikman. For the longitudinal transverse shear modulus the lower limit of Hashin & Shtrikman delivers the same values as the equation of Tsai & Hahn, the equation of Christensen & Lo gives some higher values, especially for higher fibre volume fractions.

The plotted relations are also more or less obtained for other fibre materials.

[7] [Nijhof, 2004]

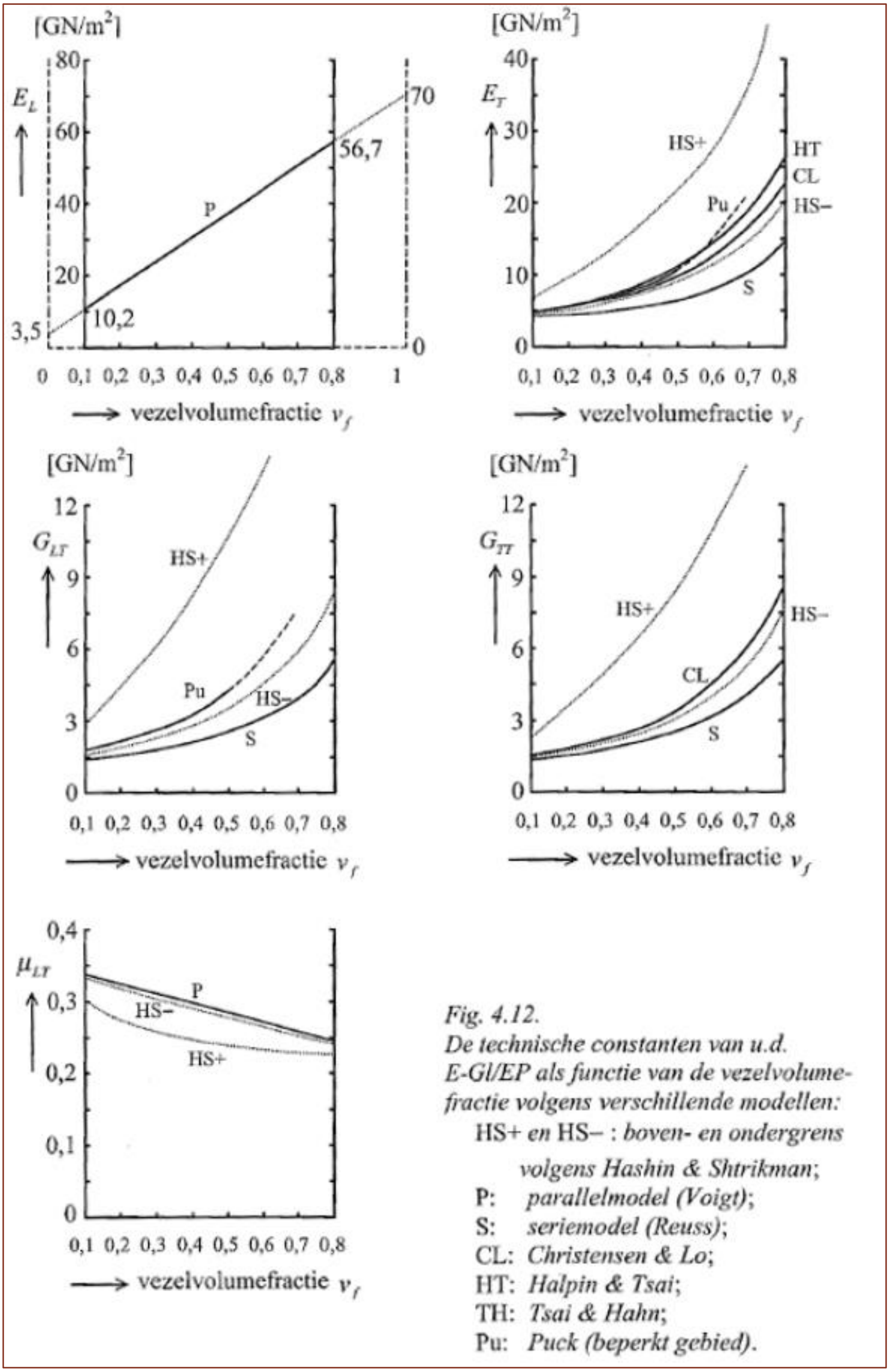


Figure 41: Graphical representation of the technical constants calculated with different models for the same material [Nijhof, 2004]

7.3 THE LAMINATE THEORY

Fibre reinforced polymers are often applied in the form of plates and shells. Such a plate or shell is laminated from several layers of impregnated fibre reinforced material such as filament mats or chopped strand mat (CSM). The description of the structure of a laminate contains the amount of layers, the type of layers, the stacking order and the orientation of the layers. The laminate theory has been developed to calculate the stiffness and strength properties of the laminate on the basis of such a structure description along with the properties of the layers. The laminate theory will be described in this paragraph. The classic plate theory is the foundation of the laminate theory and will therefore be treated briefly before the laminate theory is treated.

7.3.1 The classic plate theory

The classic plate theory starts with thin plates with a constant thickness. The right turning, orthogonal coordinate system is chosen in such a way that the xy-plane coincides with the midplane of the plate. As a result of this choice, the z-axis is therefore perpendicular to the plate. The plate is loaded by forces in the plane as well as with bending moments and twisting moments. The shear force will be neglected in this theory. The displacements in x, y and z direction will be indicated by u, v, and w respectively. Figure 42 gives a representation of the axis on a plate.

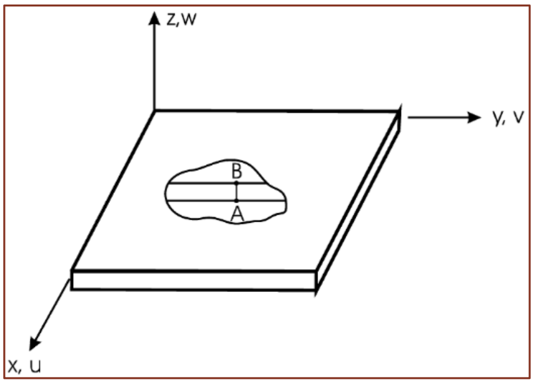


Figure 42: The axis on a plate [Carlsson et al, 2011]

It is assumed that a material line perpendicular to the midplane will remain straight under deformation and perpendicular to the deformed and curved midplane. This assumption is known as the Kirchhoff-Love hypothesis. This hypothesis implies that there will be no rotations between the z-axis and the x-axis or y-axis and as a consequence the induced shear stresses are neglected. The possible normal stress in z direction is not taken into consideration so that a plane stress is assumed in planes parallel to the xy-plane.

The deformation of the plate is now determined by the deformation of the midplane. The position of a random point B at a distance z from the midplane is known when the position of its projection point A on the midplane is known as well as the direction of the perpendicular line on the midplane in point A. Consider the xz-plane and the x-axis after deformation. The elastic line of the x-axis is proposed as $w^0(x)$. The superscript '0' is being used to indicate the variables that are related to the midplane.

The angle of inclination of the elastic line is given by the following formula;

$$\beta = \tan\beta = \frac{\partial w^0}{\partial x}$$ Eq. 7.30

The displacement of point B in the x direction with respect to its projection point A is;

$$u' = -z\sin\beta = -z\tan\beta = -z\frac{\partial w^0}{\partial x}$$ Eq. 7.31

The displacement of point A in x direction is denoted as u^0. The total displacement of point B in x direction is therefore;

$$u = u^0 + u' = u^0 - z\frac{\partial w^0}{\partial x}$$ Eq. 7.32

The curvature of the elastic line is taken positive when the convex side is located in the positive range of the z=axis. The curvature of a flat curve is then given by;

$$\boldsymbol{\kappa_x^0} = \frac{\boldsymbol{1}}{\boldsymbol{R_x}} = -\frac{\frac{\partial^2 w^0}{\partial x^2}}{\left\{1+\left(\frac{\partial w^0}{\partial x}\right)^2\right\}^{\frac{3}{2}}} = -\frac{\partial^2 w^0}{\partial x^2} \qquad \text{Eq. 7.33}$$

In this formula R_x is the radius of curvature of the x-axis at point A. This approach permitted when the deflections are small. With partial differentiation from u to x the strain ε_x in point B can be obtained;

$$\boldsymbol{\varepsilon_x} = \frac{\partial u}{\partial x} = \frac{\partial u^0}{\partial x} - z\frac{\partial^2 w^0}{\partial x^2} = \boldsymbol{\varepsilon_x^0} + z\boldsymbol{\kappa_x^0} \quad \text{with} \quad \boldsymbol{\varepsilon_x^0} = \frac{\partial u^0}{\partial x} \qquad \text{Eq. 7.34}$$

Where ε_x^0 represents the strain in x direction in point A. The curvature and strain in the y-direction can be found in the same way as has been done for the x direction. The shear strain between the x- and y-direction in the point (x, y, z) is given by;

$$\boldsymbol{\gamma_{xy}} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} = \boldsymbol{\gamma_{xy}^0} + z\boldsymbol{\kappa_{xy}^0} \quad \text{with} \quad \boldsymbol{\gamma_{xy}^0} = \frac{\partial u^0}{\partial y} + \frac{\partial v^0}{\partial x}, \qquad \boldsymbol{\kappa_{xy}^0} = -2\frac{\partial^2 w^0}{\partial x \partial y} \qquad \text{Eq. 7.35}$$

Where κ_{xy}^0 is the twisting curvature of the xy-plane.

The deformations of a plane parallel to the midplane can be taken together in a strain state vector {ε} and be expressed in the strain state vector $\{\varepsilon^0\}$ and curvature vector $\{\kappa^0\}$ of the midplane;

$$\{\boldsymbol{\varepsilon}\} = \{\boldsymbol{\varepsilon^0}\} + \{\boldsymbol{\kappa^0}\} \qquad \text{Eq. 7.36}$$

With;

$$\{\boldsymbol{\varepsilon}\} = \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{Bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \end{Bmatrix} \qquad \{\boldsymbol{\kappa^0}\} = \begin{Bmatrix} \kappa_x^0 \\ \kappa_y^0 \\ \kappa_{xy}^0 \end{Bmatrix} = \begin{Bmatrix} -\frac{\partial^2 w^0}{\partial x^2} \\ -\frac{\partial^2 w^0}{\partial y^2} \\ -2\frac{\partial^2 w^0}{\partial x \partial y} \end{Bmatrix}$$

By taking a rectangular part out of the plate with the sides parallel to the coordinate planes, see Figure 43, the forces working on the rectangular part can be obtained. Due to the plane stress only the normal stresses and shear stress is working on the sides of the rectangular plate. By integrating the stresses over the height of the plate, the forces working on the plate can be obtained;

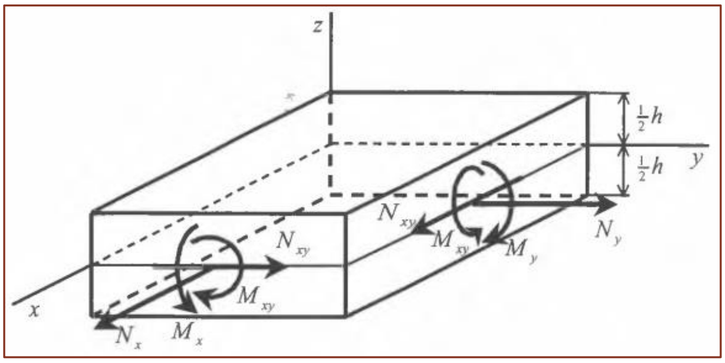


Figure 43: Rectangular part of the plate with the force and moment resultants [Nijhof, 2004]

$$\boldsymbol{N_x} = \int_{-\frac{1}{2}h}^{\frac{1}{2}h} \boldsymbol{\sigma_x dz}; \qquad \boldsymbol{N_y} = \int_{-\frac{1}{2}h}^{\frac{1}{2}h} \boldsymbol{\sigma_y dz}; \qquad \boldsymbol{N_{xy}} = \int_{-\frac{1}{2}h}^{\frac{1}{2}h} \boldsymbol{\tau_{xy} dz} \qquad \text{Eq. 7.37}$$

These forces are positive in the same direction as the positive stresses. When the force resultants act on the midplane, the force resultants will lead to bending moments and a torsion moment. These moments are;

$$M_x = \int_{-\frac{1}{2}h}^{\frac{1}{2}h} \sigma_x z dz; \quad M_y = \int_{-\frac{1}{2}h}^{\frac{1}{2}h} \sigma_y z dz; \quad M_{xy} = \int_{-\frac{1}{2}h}^{\frac{1}{2}h} \tau_{xy} z dz \qquad \text{Eq. 7.38}$$

The forces and moments can be written as the following factors;

$$\{N\} = \begin{Bmatrix} N_x \\ N_y \\ N_{xy} \end{Bmatrix} = \int_{-\frac{1}{2}h}^{\frac{1}{2}h} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} dz = \int_{-\frac{1}{2}h}^{\frac{1}{2}h} \{\sigma\} dz \qquad \text{Eq. 7.39}$$

$$\{M\} = \begin{Bmatrix} M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \int_{-\frac{1}{2}h}^{\frac{1}{2}h} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} z dz = \int_{-\frac{1}{2}h}^{\frac{1}{2}h} \{\sigma\} z dz \qquad \text{Eq. 7.40}$$

When Hooke's law can be applied and the material is isotropic, the relation between the plain stress components and the deformations of the corresponding plane can be written as;

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ & Q_{11} & 0 \\ & & Q_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix}, \text{ in short } \{\sigma\} = [Q]\{\varepsilon\}. \qquad \text{Eq. 7.41}$$

With the plate stiffnesses;

$$Q_{11} = \frac{E}{1-\mu^2}; \quad Q_{12} = \mu Q_{11}; \ Q_{66} = G = \frac{E}{2(1+\mu)}.$$

When this relation is substituted in the formulas for the force resultants the following formulas are obtained;

$$\{N\} = [Q] \int_{-\frac{1}{2}h}^{\frac{1}{2}h} \{\varepsilon\} dz = [Q] \int_{-\frac{1}{2}h}^{\frac{1}{2}h} (\{\varepsilon^0\} + \{\kappa^0\} z) dz = h[Q]\{\varepsilon^0\} \qquad \text{Eq. 7.42}$$

$$\{M\} = [Q] \int_{-\frac{1}{2}h}^{\frac{1}{2}h} \{\varepsilon\} z dz = [Q] \int_{-\frac{1}{2}h}^{\frac{1}{2}h} (\{\varepsilon^0\} z + \{\kappa^0\} z^2) dz = \frac{1}{12} h^3 [Q]\{\kappa^0\} \qquad \text{Eq. 7.43}$$

7.3.2 The laminate theory[8]

Now that the basis for the laminate theory has been presented in the previous part, the laminate theory itself can be discussed. A laminate is consist of a number of layers with a constant thickness. Those layers are called lamellae. It is assumed that the lamellae are under plane stress and that the lamellae are glued together in such a way that there are no shifts of the lamellae with respect to each other. The lamellae therefore satisfy the Kirchhoff-Love hypothesis.

[8] [Nijhof, 2004]

Lamellae of a laminate are numbered in stacking order, so the bottom lamella is lamella 1 and so on. This varying number is indicated with a 'k'. A right turning, orthogonal coordinate system xyz is coupled to the laminate. The xy-plane coincides with the midplane. This is presented in Figure 44.

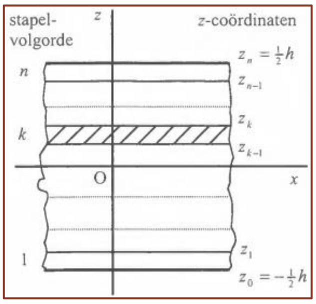


Figure 44: Stacking order of a laminate [Nijhof, 2004]

The k-th lamella has its own right turning, orthogonal coordinate system $(x_1\ x_2\ x_3)_k$ width the $(x_1\ x_2)_k$-plane coinciding with the midplane of the k-th lamella. Hooke's law for each lamella will be;

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_6 \end{Bmatrix}_k = \begin{bmatrix} Q_{11} & Q_{12} & Q_{16} \\ & Q_{22} & Q_{26} \\ & & Q_{66} \end{bmatrix}_k \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_6 \end{Bmatrix}_k \text{ in short; } \{\sigma\}_k = [Q]_k\{\varepsilon\}_k. \qquad \text{Eq. 7.44}$$

Each lamella is coupled to a $(x'_1\ x'_2\ x'_3)_k$ coordinate system which is parallel to the xyz-system. The $(x'_1\ x'_2)_k$ plane coincides with the $(x_1\ x_2)_k$-plane and the axis are rotated over an angle ϑ_k. This angle is the so called orientation angle, which is positive counter clockwise. The orientation angle can be seen in Figure 45 as well as the principal directions of the part of the laminate and the k-th lamella.

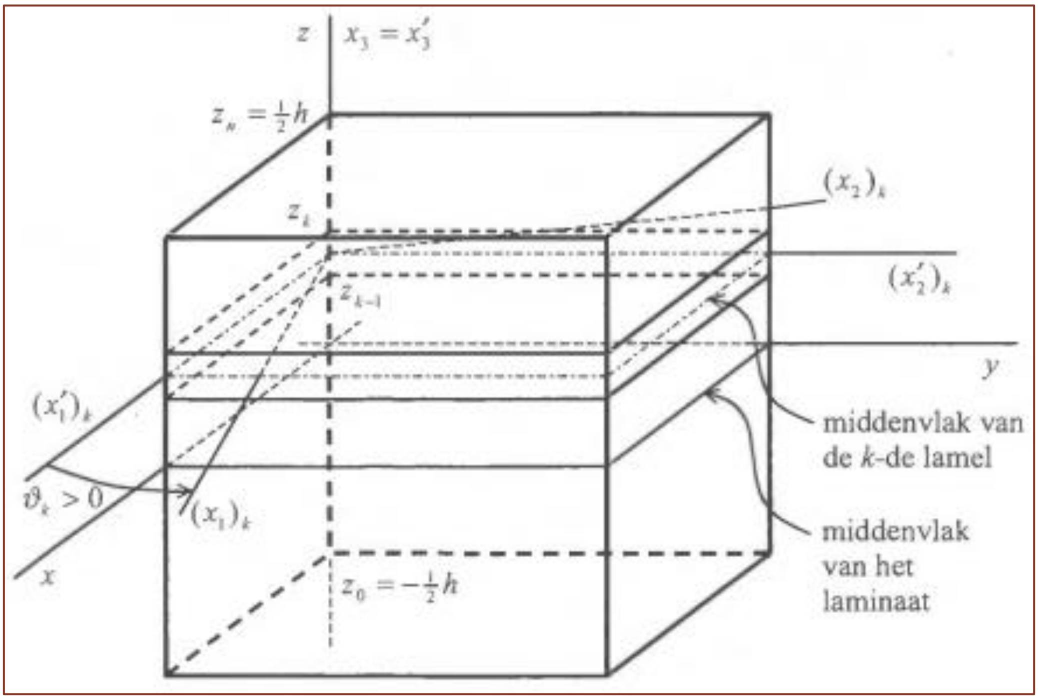


Figure 45: Part of the laminate with the principal directions of the laminate and the k-th lamella [Nijhof, 2004]

There is a system to indicate the laminate lay-up. When the lamellae are identical, the successive orientation angles are used to indicate the laminate lay-up. For example; [0/0/30/-30/-30/30/90/90/30/-30/-30/0/0]. When successive lamellae have the same orientation angle this can be used to shorten the code for the laminate lay-up; $[0_2/30/-30_2/30/90_2/30/-30_2/0_2]$. The code for the laminate lay-up can even be shorter when the laminate is symmetrical. This means that the laminate is mirrored with respect to the midplane. The code then becomes; $[0_2/30/-30_2/30/90]_s$. Hooke's law for the transformed k-th lamella is now;

$$\begin{Bmatrix} \sigma'_1 \\ \sigma'_2 \\ \sigma'_6 \end{Bmatrix}_k = \begin{bmatrix} Q'_{11} & Q'_{12} & Q'_{16} \\ & Q'_{22} & Q'_{26} \\ & & Q'_{66} \end{bmatrix}_k \begin{Bmatrix} \varepsilon'_1 \\ \varepsilon'_2 \\ \varepsilon'_6 \end{Bmatrix}_k \text{ in short; } \{\sigma'\}_k = [Q']_k\{\varepsilon'\}_k. \qquad \text{Eq. 7.45}$$

In order to associate the stiffness properties of the k-th lamella to the laminate directions x and y there has to be a clockwise rotation over a transformation angle φ= -ϑ_k.. The result is the following set of equations;

$$Q'_{11} = Q_{11}\cos^4\vartheta + Q_{22}\sin^4\vartheta + 2(Q_{12} + 2Q_{66})\sin^2\vartheta\cos^2\vartheta + -4Q_{16}\sin\vartheta\cos^3\vartheta - 4Q_{26}\sin^3\vartheta\cos\vartheta$$

$$Q'_{22} = Q_{11}\sin^4\vartheta + Q_{22}\cos^4\vartheta + 2(Q_{12} + 2Q_{66})\sin^2\vartheta\cos^2\vartheta + +4Q_{16}\sin^3\vartheta\cos\vartheta + 4Q_{26}\sin\vartheta\cos^3\vartheta$$

$$Q'_{12} = (Q_{11} + Q_{22} - 4Q_{66})\sin^2\vartheta\cos^2\vartheta + Q_{12}(\sin^4\vartheta + \cos^4\vartheta) + -2(Q_{16} - Q_{26})\sin\vartheta\cos\vartheta(\sin^2\vartheta - \cos^2\vartheta)$$

$$Q'_{66} = (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66})\sin^2\vartheta\cos^2\vartheta + Q_{66}(\sin^4\vartheta + \cos^4\vartheta) + -2(Q_{16} - Q_{26})\sin\vartheta\cos\vartheta(\sin^2\vartheta - \cos^2\vartheta)$$

$$Q'_{16} = (Q_{11} - Q_{12} - 2Q_{66})\sin\vartheta\cos^3\vartheta - (Q_{22} - Q_{12} - 2Q_{66})\sin^3\vartheta\cos\vartheta + Q_{16}\cos^2\vartheta(3\sin^2\vartheta - \cos^2\vartheta) + Q_{26}\sin^2\vartheta(\sin^2\vartheta - 3\cos^2\vartheta)$$

$$Q'_{26} = (Q_{11} - Q_{12} - 2Q_{66})\sin^3\vartheta\cos\vartheta - (Q_{22} - Q_{12} - 2Q_{66})\sin\vartheta\cos^3\vartheta + Q_{16}\sin^2\vartheta(\sin^2\vartheta - 3\cos^2\vartheta) + Q_{26}\cos^2\vartheta(3\sin^2\vartheta - \cos^2\vartheta)$$

Eq. 7.46

Lamellae are often orthotropic. When the axes $(x'_1)_k$ and $(x'_2)_k$ are now chosen along the principal directions of the material of the laminate, equation 7.45 reduces to;

$$\{\sigma\}_k = [Q]_k\{\varepsilon\}_k, \text{ with: } [Q]_k = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ & Q_{22} & 0 \\ & & Q_{66} \end{bmatrix}_k$$

Eq. 7.47

The z-coordinates of the k-th lamella are z_{k-1} and z_k. When the thickness of the laminate is denoted as 'h', the boundaries of the laminate are the lower surface $z_0= -{}^1/_2h$ and the upper surface $z_n= {}^1/_2h$. The deformations of a plane at a distance z from the midplane of the laminate are formulated for the k-th lamella in the following formula;

$$\{\varepsilon'\}_k = \{\varepsilon^0\} + z\{\kappa^0\}; \qquad z_{k-1} \le z \le z_k$$

Eq. 7.48

The corresponding stresses of the k-th lamella are;

$$\{\sigma'\}_k = [Q']_k\{\varepsilon^0\} + z[Q']_k\{\kappa^0\}; \qquad z_{k-1} \le z \le z_k$$

Eq. 7.49

If this is substituted in equation 7.39 and 7.40 and taking into consideration that the stress development in a lamella is linear but that there can be a jump in the stress distribution from one lamella to another, the result is;

$$\{N\} = \begin{Bmatrix} N_x \\ N_y \\ N_{xy} \end{Bmatrix} = \sum_{k=1}^{n}\int_{z_{k-1}}^{z_k}\begin{Bmatrix} \sigma'_1 \\ \sigma'_2 \\ \sigma'_6 \end{Bmatrix} dz = \sum_{k=1}^{n}\int_{z_{k-1}}^{z_k}\{\sigma'\}_k dz$$

Eq. 7.50

$$\{\boldsymbol{M}\} = \begin{Bmatrix} \boldsymbol{M}_x \\ \boldsymbol{M}_y \\ \boldsymbol{M}_{xy} \end{Bmatrix} = \sum_{k=1}^{n} \int_{z_{k-1}}^{z_k} \begin{Bmatrix} \boldsymbol{\sigma'}_1 \\ \boldsymbol{\sigma'}_2 \\ \boldsymbol{\sigma'}_6 \end{Bmatrix} \boldsymbol{z}d\boldsymbol{z} = \sum_{k=1}^{n} \int_{z_{k-1}}^{z_k} \{\boldsymbol{\sigma'}\}_k \boldsymbol{z}d\boldsymbol{z} \qquad \text{Eq. 7.51}$$

$$\{\boldsymbol{N}\} = \left[\sum_{k=1}^{n} [\boldsymbol{Q'}]_k (\boldsymbol{z}_k - \boldsymbol{z}_{k-1})\right]\{\boldsymbol{\varepsilon^0}\} + \left[\frac{1}{2}\sum_{k=1}^{n} [\boldsymbol{Q'}]_k (\boldsymbol{z}_k{}^2 - \boldsymbol{z}_{k-1}{}^2)\right]\{\boldsymbol{\kappa^0}\} \qquad \text{Eq. 7.52}$$

$$\{\boldsymbol{M}\} = \left[\frac{1}{2}\sum_{k=1}^{n} [\boldsymbol{Q'}]_k (\boldsymbol{z}_k{}^2 - \boldsymbol{z}_{k-1}{}^2)\right]\{\boldsymbol{\varepsilon^0}\} + \left[\frac{1}{3}\sum_{k=1}^{n} [\boldsymbol{Q'}]_k (\boldsymbol{z}_k{}^3 - \boldsymbol{z}_{k-1}{}^3)\right]\{\boldsymbol{\kappa^0}\} \qquad \text{Eq. 7.53}$$

The extensional stiffness of the laminate determine the stiffness of the laminate in its plane with respect to tension, compression and shear. The extensional stiffness can now be formulated as;

$$\boldsymbol{A}_{ij} = \sum_{k=1}^{n} \left(\boldsymbol{Q}'_{ij}\right)_k (\boldsymbol{z}_k - \boldsymbol{z}_{k-1})\,;\ \boldsymbol{i},\boldsymbol{j} = \ \mathbf{1},\mathbf{2},\mathbf{6}; \qquad \text{Eq. 7.54}$$

The coupling stiffness gives a coupling between on the one hand between forces in plane {N} and deformations out of plane $\{\kappa^0\}$ and on the other hand between moment resultants {M} and deformations in plane $\{\varepsilon^0\}$. The coupling stiffness is formulated as;

$$\boldsymbol{B}_{ij} = \frac{1}{2}\sum_{k=1}^{n} \left(\boldsymbol{Q}'_{ij}\right)_k (\boldsymbol{z}_k{}^2 - \boldsymbol{z}_{k-1}{}^2)\,;\ \boldsymbol{i},\boldsymbol{j} = \ \mathbf{1},\mathbf{2},\mathbf{6}; \qquad \text{Eq. 7.55}$$

And the bending stiffness is governing for the bending and torsional stiffness of the laminate and is defined as;

$$\boldsymbol{D}_{ij} = \frac{1}{3}\sum_{k=1}^{n} \left(\boldsymbol{Q}'_{ij}\right)_k (\boldsymbol{z}_k{}^3 - \boldsymbol{z}_{k-1}{}^3);\ \boldsymbol{i},\boldsymbol{j} = \ \mathbf{1},\mathbf{2},\mathbf{6}; \qquad \text{Eq. 7.56}$$

The linear relationship between load and deformation of a laminate without a transverse load in matrix form is;

$$\begin{Bmatrix} \{\boldsymbol{N}\} \\ \{\boldsymbol{M}\} \end{Bmatrix} = \begin{bmatrix} [\boldsymbol{A}] & [\boldsymbol{B}] \\ [\boldsymbol{B}] & [\boldsymbol{D}] \end{bmatrix} \begin{Bmatrix} \{\boldsymbol{\varepsilon^0}\} \\ \{\boldsymbol{\kappa^0}\} \end{Bmatrix} \qquad \text{Eq. 7.57}$$

7.3.3 The stiffness analysis of a laminate[9]

If the laminate is composed of known orthotropic lamellae and the lay-up of the lamellae is known, the reduced stiffness $(Q_{ij})_k$ with respect to its own material principal directions are known. With the adjusted to the orthotropic lamellae transformation equation, equation 7.46 with $Q_{16}=Q_{26}=0$, the values of the reduced stiffness $(Q'_{ij})_k$ with respect to its own material principal directions per lamella can be obtained. The stiffness constants of the laminate then follow from these reduced stiffness per lamella, the thickness of the lamellae and the lamellae build-up.

To calculate the deformation of the laminate for a given loading situation, the loading situation must be transformed to loads acting on the midplane of the laminate. So a force resultant parallel to the midplane but at some distance from that plane has to be replaced by an equivalent force acting in the midplane with the addition of a moment resultant that will compensate for the shift of the force.

Equation 7.57 must be inverted to be able to calculate the deformations. The inverted of equation 7.57 is;

$$\begin{Bmatrix} \{\boldsymbol{\varepsilon^0}\} \\ \{\boldsymbol{\kappa^0}\} \end{Bmatrix} = \begin{bmatrix} [\boldsymbol{a}] & [\boldsymbol{b}] \\ [\boldsymbol{b}]^T & [\boldsymbol{d}] \end{bmatrix} \begin{Bmatrix} \{\boldsymbol{N}\} \\ \{\boldsymbol{M}\} \end{Bmatrix} \qquad \text{Eq. 7.58}$$

[9] [Nijhof, 2004]

[a] is the component of in-plane compliance, [b] is the coupling compliance and [d] is the flexural compliance. [a] and [d] are symmetrical and [b] is in general nonsymmetrical. These matrices are given by;

$$[\boldsymbol{a}] = ([\boldsymbol{A}] - [\boldsymbol{B}][\boldsymbol{D}]^{-1}[\boldsymbol{B}])^{-1}$$

$$[\boldsymbol{b}] = ([\boldsymbol{B}] - [\boldsymbol{D}][\boldsymbol{B}]^{-1}[\boldsymbol{A}])^{-1} = -[\boldsymbol{a}][\boldsymbol{B}][\boldsymbol{D}]^{-1} \qquad \text{Eq. 7.59}$$

$$[\boldsymbol{d}] = ([\boldsymbol{D}] - [\boldsymbol{B}][\boldsymbol{A}]^{-1}[\boldsymbol{B}])^{-1}$$

7.3.4 Influence of the build-up of a laminate[10]

When the build-up of a laminate is random there will be two kinds of coupling. On one hand between forces in plane {N} and deformations out of plane {κ^0} and on the other hand between moment resultants {M} and deformations in plane {ε^0}. When the plate is isotropic, this coupling will not occur. There are also other coupling effects that occur for non-isotropic plates and they are caused by the terms A_{16}, A_{26}, D_{16} and D_{26} which are now not zero. Figure 46 shows the possible effects of these terms.

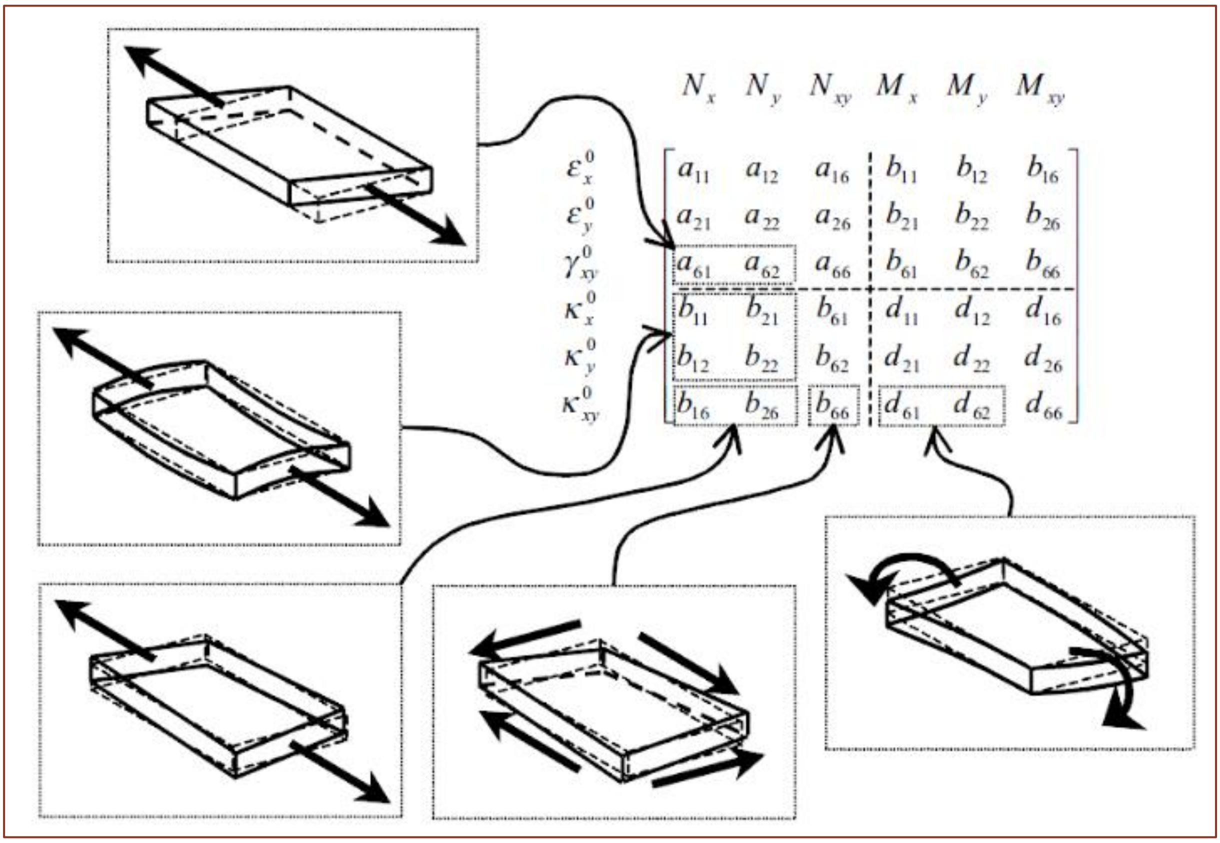


Figure 46: Possible coupling effects for a loaded laminate [Nijhof, 2004]

Due to these coupling effects the behaviour of a laminate becomes very complicated. When the plate is isotropic the coupling matrix will be zero. The result of the coupling matrix being zero is that the equations of equation 7.59 reduce to;

$$[\boldsymbol{B}] = \boldsymbol{0} \quad \rightarrow \quad [\boldsymbol{a}] = [\boldsymbol{A}]^{-1}; \quad [\boldsymbol{b}] = [\boldsymbol{0}]; \quad [\boldsymbol{d}] = [\boldsymbol{D}]^{-1}. \qquad \text{Eq. 7.60}$$

[10] [Nijhof, 2004]

8. COSTS OF FRP

This chapter will treat the costs of FRP materials. First the cost of the different types of fibre will be given. When the costs of the fibres are treated, the costs of the various types of resin will be presented. There is also information available about the total cost of a specific FRP. This includes the costs that are being made during the manufacturing of a certain FRP. This information will be presented after the costs of the various types of resins.

8.1 COSTS OF THE FIBRES

The costs of the different types of fibres are presented in Figure 47 and Figure 48. These figures are calculated on a typical price of a 300 gram woven fabric. The price on the vertical axis is presented in pounds per square meter.

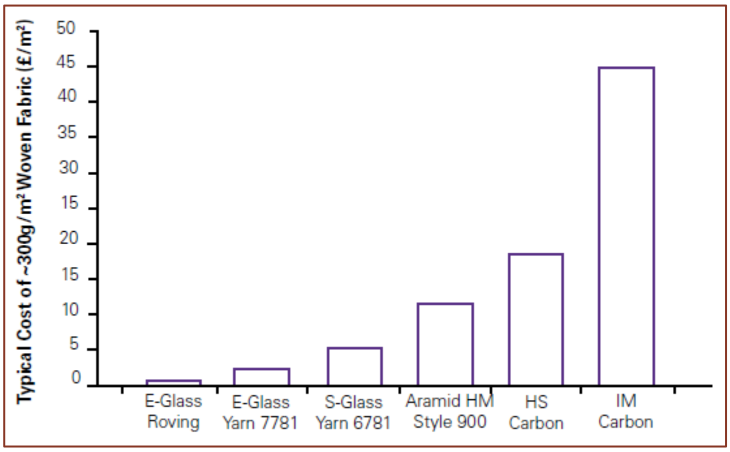


Figure 47: Overview of the costs of fibres (woven) [Gurit, 2016]

In Figure 47 the costs of fibres with woven fabrics are presented. Most fibre prices are considerably higher for the small bundle size used in lightweight fabrics. The difference in prices of the fibres can be reduced when heavier bundles of fibre can be used, such as in unidirectional fabrics. This gives a slight change in the comparison of the fibres. The price of the fibres with unidirectional fabrics is presented in Figure 48.

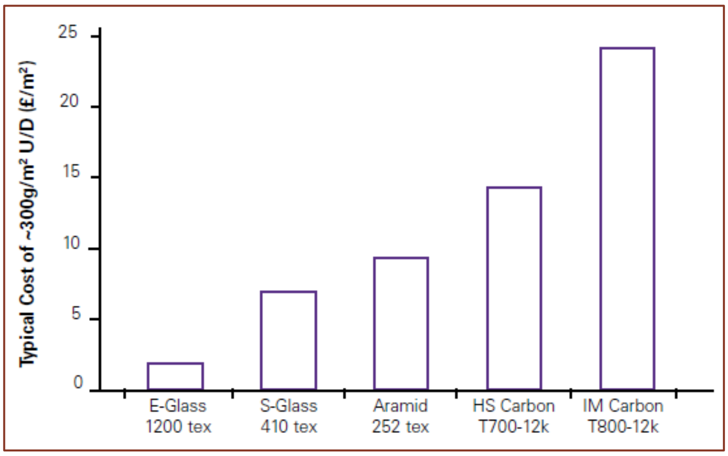


Figure 48: Overview of the costs of fibres (unidirectional) [Gurit, 2016]

Table 8 presents the range of the cost of the different types of fibres. The prices are transferred to euro with the ratio English pound to euro of 1.28 as it has been identified on the 25th of April 2016.

Table 8: The costs of different types of fibres

Type of fibre	Bulk price [€/m²]
E-glass	1.28 – 2.56
S-Glass	7.68 – 9.60
Aramid	12.80 – 16.00
Carbon	19.20 – 57.60

8.2 COSTS OF THE RESINS

The resin types polyester, vinylester and epoxy are the most applied resins in structural composites. The costs of these resins are presented in Table 9 [Cripps, 2016]. The prices are transferred to euro with the ratio English pound to euro of 1.28 as it has been identified on the 25th of April 2016.

Table 9: The costs of different types of resins

Type of resin	Bulk price [€/kg]
Polyester	1.28 – 2.56
Vinylester	2.56 – 5.12
Epoxy	3.84 – 19.20

8.3 COSTS OF A FRP CONSTRUCTION

The previous two paragraphs have treated the costs of resins and fibres. A resin and a fibre are ingredients that are needed to create a fibre reinforced polymer. To come to a FRP a certain manufacturing process will have to be carried out. This means that the fibre and resin will have to be treated with certain materials and equipment to obtain the desired end product. These additional treatments will add costs to the total price of a FRP.

[Kok, 2013] has established a range for the costs for a glass fibre-polyester product. He has done this with consultation from FiberCore Europe and they established that the costs is 4 – 7 €/kg, where the material costs are around 2 €/kg. With this range, the prices for FRP of other compositions are determined. The amount of fibres is estimated at 65% and the amount of resin is estimated at 35%. The labour costs are estimated to be equal for each composition. The different density of the fibres are adapted in the labour costs per kilogram. Table 10 gives an overview of the total costs of a fibre and resin combination. The different components of the total costs are also presented.

Table 10: Overview of construction costs

Fibre and resin	Material costs [€/kg]	Mean base material cost [€/kg]	Labour costs [€/kg]	Total costs [€/kg]
E-glass and polyester	1.3 – 2.5	1.9	2 – 5	4 – 7
E-glass and vinylester	1.7 – 3.4	2.6	2 – 5	5 – 8
E-glass and epoxy	2.1 – 8.5	5.3	2 – 5	7 – 10
S-glass and polyester	10.2 – 13.9	12.0	2 – 5	14 – 17
S-glass and vinylester	10.6 – 14.8	12.7	2 – 5	15 – 18
S-glass and epoxy	11.1 – 19.8	15.5	2 – 5	17 – 20
Aramid and polyester	12.2 – 20.4	16.3	2.8 – 7	19 – 23
Aramid and vinylester	12.6 – 21.3	16.9	2.8 – 7	20 – 24
Aramid and epoxy	13.0 – 26.3	19.7	2.8 – 7	22 – 27
Carbon and polyester	7.0 – 30.1	18.5	2.5 – 6	21 – 25
Carbon and vinylester	7.4 – 31.0	19.2	2.5 – 6	22 – 25
Carbon and epoxy	7.8 – 36.1	22.0	2.5 – 6	24 – 28

9. CODES AND GUIDELINES

There are many design codes published by the government and by the Eurocode for a large variety of topics. Codes and guidelines are there to assure that the design of structures satisfy certain safety standards. There are many books and reports available with guidelines to design FRP structures. The most of these guidelines are however focussed on glass fibres and do not teat the other types of FRP. However, there is not a Eurocode concerning the design of a FRP structure. There is a recommendation of the 'Civieltechnisch Centrum Uitvoering Research' (CUR) available concerning the FRP materials. Such a recommendation is a publication in which agreements between the parties in the construction sector are written down. Most of the properties of a FRP are given by the manufacturer. Besides the recommendation of the CUR there are other books and reports that can be used in the Netherlands. The recommendation of the CUR as well as these other codes will be treated into more detail.

9.1 EUROCOMP – DESIGN AND HANDBOOK[11]

The objective of the Eurocomp – design and handbook has been the production of a practical Design Code for the Construction Industry. The Eurocomp – design and handbook is intended for engineers who are familiar with designing using conventional structural materials such as steel and concrete. The book is based on the most up to date information at that time but does not have a legal status. The scope of the book is limited to glass fibre materials.

The Eurocomp – design and handbook consists of three parts;

1. Design Code,
2. Handbook,
3. Technical reports.

The first part is applicable for the structural design of buildings and civil engineering works in glass fibre reinforced polymetric composites. This part does not contain the requirements for thermal or sound insulation. It does contain the requirements for resistance, serviceability and durability of structures. The design methods and design data are specific to the use of glass fibres but the principles should be applicable to any FRP.

The Handbook provides additional information to supplement the Design Code so that the user can understand the decisions that have been taken during the process. It is in particular intended to cover the areas in which there is not sufficient experience.

The last part of the book shows the test results of 5 glass fibre reinforced plastics panels.

9.2 CUR 96 – FIBRE REINFORCED PLASTICS IN CIVIL LOAD BEARING STRUCTURES

The CUR report is divided into two parts. The first part is the CUR recommendation and the second part is the background report which can be consulted for background information. The report is specific written for the design of civil constructions with thermosetting glass fibre reinforced polymers or plastics. The minimum glass fibre percentage needs to be 20%. A laminate can have fibres in different directions and therefore a minimum amount of fibres is prescribed for all the directions.

The first part of the report, the recommendation is focused on the material properties and the calculation of the strength and stiffness properties. The material factors are described as well. The recommendation does not cover the design of connections in FRP structures.

[11] [Clarke, 2005]

The background report of the CUR recommendation gives the user of CUR 96 additional information to better understand the argumentation behind certain decisions.

There is currently a new version of the CUR 96 under development and it is expected that the newer version will be published in 2016.

9.3 JRC SCIENCE FOR POLICY REPORT[12]

There is a report published by the Joint Research Centre (JRC), the in-house science service of the European Commission that is a support to the implementation, harmonization and further development of the Eurocodes for the design of FRP. The report presents scientific and technical background intended to stimulate debate and serves as a basis for further work to achieve a harmonized European view on the design and verification of FRP structures. The report is however not yet in such a state that it can be used in practice.

The report applies to FRP structures made of profiles, plates and shells or sandwich panels. The report address the thermoset FRP parts with a fibre volume percentage of at least 15%.

[12] [Ascione, 2016]

10. CONCRETE

The previous chapters have treated the FRP materials into severe detail. To be able to make a comparison between FRP and the common used materials steel and concrete, the characteristics of concrete will be described in this chapter. The materials that are required to create concrete will be treated first. The manufacturing process will be treated afterwards. The paragraph with the manufacturing process will be followed by a paragraph handling the failure mechanisms of concrete. Before this chapter is concluded with a rough cost estimation the properties of concrete will be treated first. This chapter will not go into the same depth as the chapters concerning FRP materials since it is assumed that the reader is familiar with the material concrete.

10.1 MATERIALS

Concrete is an end product. It is obtained by mixing several materials in certain ratios. Concrete is a mixture of cement, aggregates, additives, admixtures and water. Each material of the mixture will be addressed shortly in this paragraph.

10.1.1 Cement

Cement is a hydraulic binding agent. This means that it is a binding agent that reacts with water to to non-water-soluble solid compounds. The 3 most important types of cement for the Netherlands are Portland cement, blast furnace slag cement (hoogovencement) and Portland fly ash cement (portlandvliegascement).

These three types of cement differ significantly in properties. It appears that in general, concrete obtained with the cement types blast furnace slag and Portland fly ash is denser than concrete obtained with Portland cement. The pores in the concrete are on the long term finer for blast furnace slag cement and Portland fly ash cement are finer than for Portland cement. Aggressive substances can penetrate the concrete through the pores, therefore it is favorable to keep the pores as fine as possible. The finer pores lead to a better durability therefore.

The heat development of blast furnace slag and Portland fly ash cement is slower than the heat development of Portland cement. The sensitivity to crack formation is therefore in general less for the blast furnace slag cement than for the Portland cement. On the other side, the slower heat generation of the blast furnace slag cement leads to a slower strength development. Therefore, the time it takes the concrete to achieve the required strength to allow the stripping of the formwork is more than for Portland cement. There is also a greater sensitivity to the quality of the after-treatment. [Bijen et al., 2007]

10.1.2 Aggregates

Aggregates can be distinguished by origin and voluminous mass. By origin we distinguish natural aggregates and artificial aggregates. Natural aggregates can be obtained by either wet extraction or by dry extraction. An example of a natural aggregate obtained by wet extraction is river gravel and for dry extraction crushed stone is an example. Examples of artificial aggregates are concrete granulate and lightweight aggregates such as expanded clay. The distinguishing by voluminous mass is as follows; normal aggregates have a voluminous mass of 2000 to 2800 kg/m^3, heavy aggregates have a voluminous mass bigger than 2800 kg/m^3 and the lightweight aggregates have a voluminous mass smaller than 2000 kg/m^3.

It shows that for the conventional concrete classes the natural stone, such as granite and gravel, the strength of the aggregate is not so important for the compressive strength of the concrete. The weakest link is related to the cement paste and this largely determines the properties of the concrete. This might change when light aggregates are applied. At higher concrete strengths it might show that the light aggregates will become less strong than the cement paste.

Aggregates have in general a higher modulus of elasticity and therefore increase the modulus of elasticity of concrete with respect to that of the cement paste. This reduces the deformation due to loading. Lightweight aggregates have the advantage that they lead to lighter concrete. This is especially important when the self-weight of the concrete structure is governing.

If lightweight aggregates are used in the mixture, the porosity of the concrete will be greater than with natural aggregates. However, this does not have to lead to a direct increase of the permeability. The spaces in which the light porous aggregates are situated are not directly connected to each other. Moreover, light aggregates are often found to have a very good bond with the cement paste, while with materials such as gravel there is a relatively porous transition layer present. Aggregates can also be used to achieve specific purposes. [Bijen et al., 2007]

10.1.3 Additives

Additives are added to the mixture that will result in concrete for improving the properties of the concrete. The most used additives are plasticizers, air entraining, retarders and accelerators. By adding a plasticizer the mixture becomes more plastic. The workability of the mixture increases, the mixture becomes more fluid. This additive has as a result that less water needs to be added to the mixture. This has a positive effect on the strength development of the concrete and also on the durability.

Air entraining additives result in a higher resistance against frost. The air bubbles work as little expansion barrels. Beside the increase in resistance against frost, the air entraining additive also has a lubricating effect and therefore improve the workability of the concrete. The air entraining additive ensures that the air bubbles remain stable.

When a retarder is added to the mixture, the workability period of the mixture will be increased. This is necessary when the distance between the concrete factory and the building site is large or when the temperature is high.

The opposite of a retarder is an accelerator. An accelerator is mostly added to the mixture when a high production rate is required.

Besides the treated additives here there are more additives available. The reader is referred to chapter 6 of [Bijen et al., 2007] for more information about those additives.

10.1.4 Admixtures

Examples of admixtures are powder coal fly ash and silica fume. Both examples are pozzolanic admixtures which means that they react with water and chalk to form water-resistant cementitious compounds. Besides pozzolanic admixtures there are also inert admixtures. They do not react with water and chalk. An admixture is added to the mixture to improve the adhesion and grain size distribution of the mixture. [Bijen et al., 2007]

10.1.5 Water

Water is added to the mixture for two reasons. One, to wrap the cement and aggregates so that the workability is improved. Two, react with the cement to hydrates that will bond the sand and gravel grains to one another. [Bijen et al., 2007]

10.2 MANUFACTURING OF CONCRETE

The manufacturing process of concrete will be elaborated in this paragraph. The first step in the process is to manufacture the cement. Figure 49 gives a representation of the manufacture process for blast furnace slag cement.

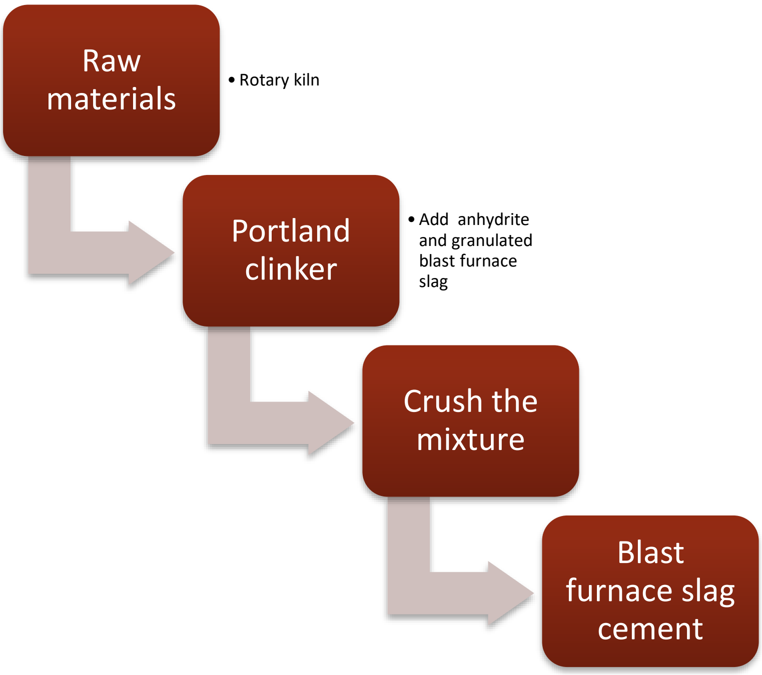


Figure 49: The manufacture process of blast furnace slag cement

The desired amount of aggregates, additives, admixtures and water has to be added to the cement. As long as the concrete mixture is not poured into the formwork it will have to remain in a fluid state. The concrete will form once the mixture is poured into the formwork. When the concrete is poured into the formwork the substance will be compacted so that the required quality of the concrete is achieved. By compacting the substance, air is pushed out of the mixture. The compacting of the concrete substance also ensures that the concrete will bond to the entire formwork and will therefore obtain the required shape. Once the concrete is poured into the formwork specified after-treatment is required to assure the quality of the concrete. So one could say that compacting of the concrete is already a measure of after-treatment. Which types of after-treatment have to be carried out are different for each building site and location.

10.3 FAILURE MECHANISMS

There are mechanical failure mechanisms and other failure mechanisms. The mechanical failure mechanisms are related to the stresses in the concrete structure. When the stresses in the concrete are above a certain limit, the concrete will fail. These stresses can be either compressive or tensile. Concrete has a high compression capacity. The tensile capacity of concrete however is very low. The low tensile stress capacity of the concrete is compensated for by applying reinforcement steel or prestressing steel. Steel will be treated in the next chapter.

When the stresses in the concrete structure are above the limit, cracks will develop in the concrete structure which will lead to failure. When the quality of the concrete is not sufficient, this will lead to failure as well. High standards for quality checks are therefore required. The environment can affect the quality of the concrete structure. For example, when pultruded water infiltrates in the concrete this will affect the strength of the structure.

10.4 PROPERTIES OF CONCRETE

The properties of concrete depend on the strength class of the concrete. The strength class of concrete is indicated by, for example, C45/55. 45 is the characteristic cylindrical compressive strength and 55 is the characteristic cubical compressive strength. Both numbers are characteristic values which means that 95% of the tested concrete has a strength bigger than the characteristic value. Table 11 gives some characteristic values for certain strength classes of concrete.

Table 11: Strength classes and material properties [Bijen et al., 2007]

Codes and guidelines	Strength class	Characteristic cubical compressive strength [MPa]	Design value compressive strength [MPa]	Mean tensile strength [MPa]	Design value tensile strength [MPa]	Young's modulus E [MPa]
NEN 6720, NEN-EN 206-1	C28/35	35	21	2.8	1.4	31000
	C35/45	45	27	3.3	1.65	33500
	C45/55	55	33	3.8	1.90	36000
CUR Aanbeveling 97	C60/75	75	45	4.5	2.25	38900
	C70/85	85	50	4.7	2.35	39300

During the design process of the concrete structure, the designer will use the stress-strain relationship of the concrete for the calculations. Each strength class has its own stress-strain relationship and corresponding diagram. An example of such a stress-strain diagram is given in Figure 50. The figure clearly represents the high compressive strength capacity with respect to the low tensile strength capacity.

The durability of concrete can be threatened by influences of chemical, physical or mechanical nature. An example of a chemical threat is pultruded water intrusion. A threat of physical nature is fire while a threat of mechanical nature are the loads acting on the structure.

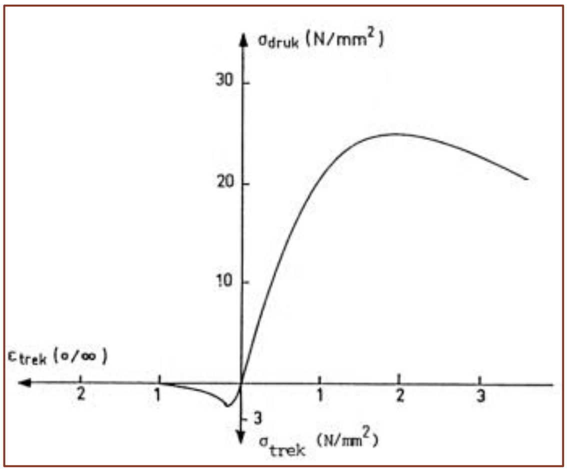


Figure 50: Example of a stress-strain diagram for concrete

When a concrete structure has served its lifetime it will most likely be demolished. Concrete is a material with a high recycling rate. The concrete will be processed into granulate. The granulate will be obtained by breaking the concrete when it is subsequently washed before it is sieved. This granulate is in the Netherlands often used in the construction of roads. The granulate will function then as a foundation layer. The granulate can also be reused in the manufacturing process of concrete itself. The granulate will have to satisfy certain standards before it can be used as an ingredient to create concrete.

10.5 COST ESTIMATION

The costs of concrete are depending on several factors. The required quality of the concrete is of influence on the price as well as the desired strength class. When reinforcement steel is required the price of concrete per cubic meter will be higher than when no reinforcement is needed.

The distance between the concrete factory and the building size is also of importance for the price of the concrete due to the distance that the concrete must be transported determines whether additives will have to be added or not.

A cubic meter of concrete that will be used as a working floor costs approximately €25,-. Concrete that is used in hydraulic structures has a price of approximately €125,- per cubic meter. The reinforcement steel costs €1.350,- per cubic meter. These prices are based on studies provided by the engineering bureau of Gemeente Rotterdam.

11. STEEL

Just as the previous chapter about concrete, this chapter will represent information concerning the common used material steel. The materials that are required to create steel will be treated first. The manufacturing process will be treated afterwards. The paragraph with the manufacturing process will be followed by a paragraph handling the failure mechanisms of steel. Before this chapter is concluded with a rough cost estimation the properties of steel will be treated first. This chapter will not go into the same depth as the chapters concerning FRP materials since it is assumed that the reader is familiar with the material steel.

11.1 MATERIALS

The material steel is just as the material concrete an end product. This means that other materials are combined in a certain way to form the end product. Steel is made out of pig iron scrap. Pig iron itself is composed with limestone, coal and iron ore. The fact that scrap is used as a base material to obtain steel is an indicator that the recycling rate of steel is very high.

Just as with concrete, there are certain additives that can be added to materials to improve the characteristics of the steel. An example of an additive is carbon. The carbon will increase the curability and hardness. For other examples of additives is referred to [Bijen et al., 2007].

11.2 MANUFACTURING OF STEEL

To be able to manufacture steel, the basic ingredients will have to be manufactured first. Scrap is already in such a state that it can be used in the manufacturing process of steel. Pig iron is the other basic ingredient that is required to manufacture steel. Pig iron consists of limestone, coal and iron ore as mentioned in the previous paragraph. The coal is crushed in the cokes factory and subsequently the cokes will be fabricated by heating the coal with exclusion from air.

The cokes, iron ore pellets and limestone are placed in the blast furnace in layers. After a detailed heating treatment inside the blast furnace, the pig iron can be obtained from the blast furnace. More information about the detailed heating treatment can be found in [Breugel, 2008]. The blast furnace, the input and the output materials are shown in Figure 51.

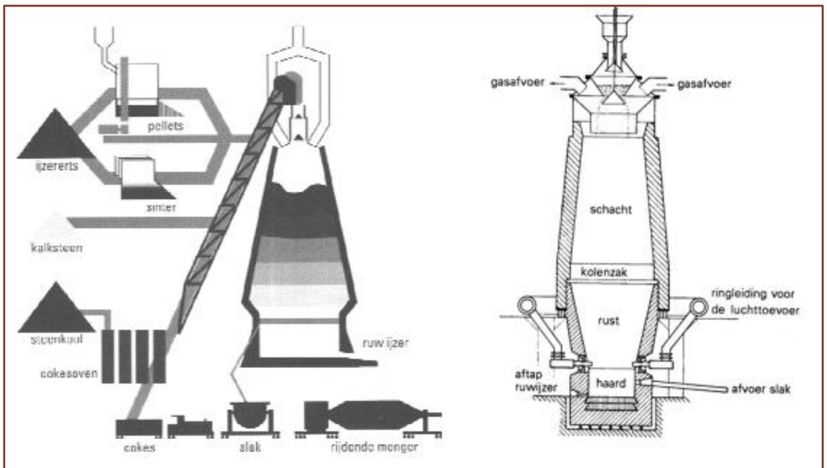


Figure 51: The blast furnace [Breugel, 2008]

11.3 FAILURE MECHANISMS

Steel is being used in concrete structures to coup with the tensile stresses in the structure. When the yielding stress is reached, the development of the strength of the steel is no longer linear. The strength of the steel is maximum when the tensile strength of the steel is reached. After this point the capacity of the steel will decrease. Steel cannot withstand compression as well as concrete can. The combination between concrete and steel is therefore based on the strongest characteristics of the two materials.

A steel rod, for example, with a small diameter will buckle when it is loaded under compression. This is a mechanical failure mechanism. There are also other failure mechanisms that are not of a mechanical nature. Water will influence the capacities of the steel because it will cause the steel to corrode. Other failure mechanisms will not be treated in this paragraph.

11.4 PROPERTIES OF STEEL

The most important properties of steel are the yielding stress, the associated yield strain, the tensile strength, the ultimate strain and the Young's modulus. These properties are not constant for each type of steel. The steel class is being indicated by Sxxx, where xxx indicates the characteristic yielding strength. The characteristic value is the 2.5% lower limit of the yield strength. The yield strength of steel is determined by a test.

The steel class is influenced by the manufacturing process. By adding certain materials characteristics can be improved as well as degraded.

Just as with concrete, a stress-strain relation is being used to construct with steel. A stress-strain diagram shows the relation between the stress and the strain. Important points such as the yielding stress are indicated in the diagram. Figure 52 shows a stress-strain diagram for steel. The yielding stress is indicated with f_y and f_t is the tensile strength of the steel. The ultimate strain is presented by the point ε_u.

The yielding stress and tensile strength of different steel classes are given in Table 12.

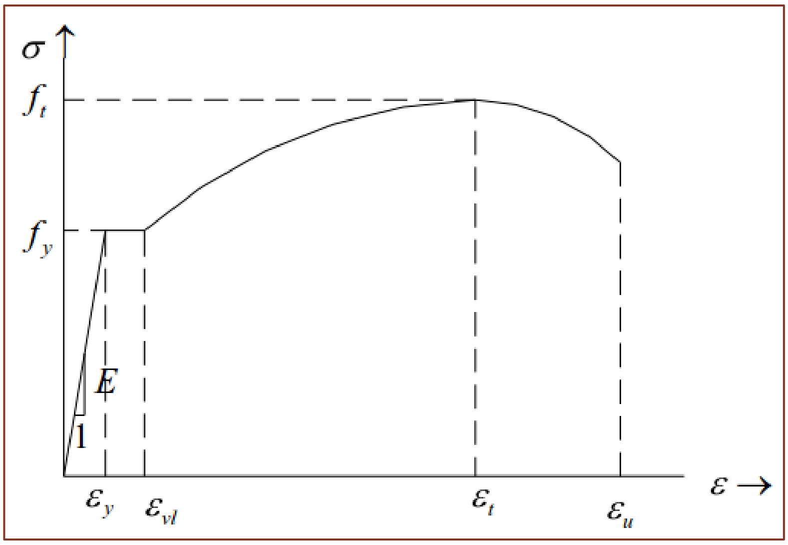


Figure 52: The stress-strain diagram of steel [Abspoel et al, 2013]

Table 12: Characteristics of steel classes [Abspoel et al, 2013]

Steel class	Yielding stress [N/mm²]	Tensile strength [N/mm²]
S235	235	360
S275	275	430
S355	355	510
S450	450	550

11.5 COST ESTIMATION

The production cost of steel depends on the desired steel class. The higher the required steel class the higher the price will be. Unlike concrete, the transport of the steel is not of influence on the total cost of the steel. There are no additives required in the manufacturing process of steel to assure certain properties of the steel when it arrives at the construction location.

According to studies of the engineering company of Gemeente Rotterdam a ton of steel costs approximately €985,-

12. QUAY WALLS

This chapter will provide background information for quay walls. First, the functions of the quay wall will be elaborated into more detail. The development of the quay walls will be treated before this chapter is concluded with an overview of the possible types of quay walls.

12.1 FUNCTIONS OF QUAY WALLS

The functional requirements of a quay wall can be divided into four categories. Namely a retaining function, a bearing function, a mooring function and a protecting function. These functions of the quay wall will be established in the program requirements of a project since they are boundary conditions for the design of the quay wall.

The quay wall has to retain a certain amount of soil and water. The retaining height of the quay wall depends on the dimensions of the anticipated vessels that will moor at the quay wall.

The bearing function of the quay wall is determined the loads imposed on the quay wall due to the cranes, vehicles and the stored cargo on the quay wall. These loads are static and dynamic loads since the loading and unloading of a vessel is a time dependent process.

The quay wall must enable vessels to moor safely and subsequently to load and unload their cargo. The required space for the mooring function of the quay wall is therefore determined by the number of ships and their dimensions that will moor at the same time as well as the wind, current and wave climate.

The protection function of the quay wall refers to the safety during the mooring of a vessel. To avoid damage to the vessels some kind of fenders will have to be constructed. To be able to moor a vessel bollards will have to be constructed on the quay wall. Scour protection must also be applied at the quay wall to prevent damage to the quay wall by the dimensions and power of the propellers of the vessels.

The loads and design features of a quay wall are presented in Figure 53.

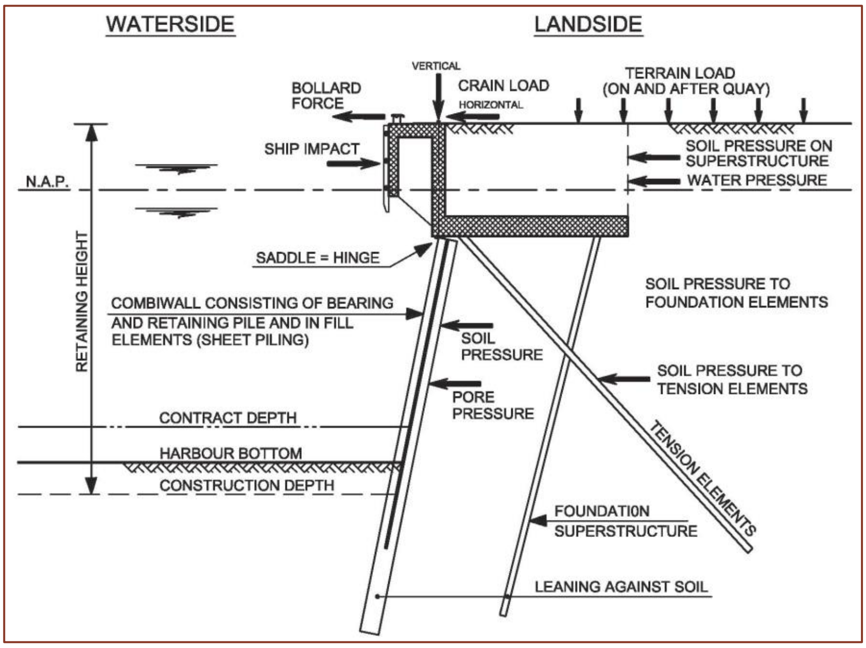


Figure 53: Principle design features and imposed loads on a quay wall [Gijt, 2010]

12.2 DEVELOPMENT OF QUAY WALLS OVER TIME

The development of quay walls runs parallel with the development of (inter)national trade, the development of the shipping industry and the growth of ports. History tells us that there has been transport over water as far back as 6000 BC when the Egyptians used the river Nile for the transportation of cargo. The first quay walls have been constructed in Lothal, India in 2400 BC. These quay walls were constructed form bricks.

During the Roman period, the quay walls were mostly constructed out of wooden pilled structures. The Romans also used caissons in the construction of quay walls. The caissons were fabricated out of puzzolanic earth. The retaining height of the quay walls was 3 to 4 metres.

After the Roman period, the development of the quay walls stagnated. Until approximately 1500 the quay walls were constructed out of locally available material such as wood and stone. The retaining height of the quay walls was 5 metres. During this period the first permanent dry dock in England was built in Portsmouth. The dry dock had a rectangular shape and was constructed out of wood and had two sets of gates. The space between the gates would be filled with clay for water tightness when a ship was in the dock. An impression of the dry dock is shown in Figure 54.

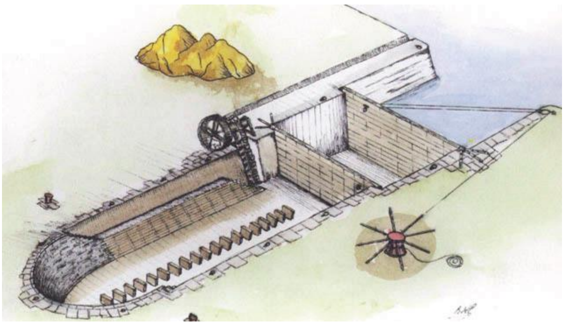


Figure 54: Impression of the dry dock [Gijt, 2010]

The period 1500 to 1950 is characterized by the rapid development of science, the industrial revolution and the invention of reinforced and precast concrete. The principles of mechanics and soil mechanics were described in this period and attention was paid to the design of quay walls. During this period steel sheet piling has been invented to replace wooden sheet piles. The retaining height increased as far as 19.5 metres for a quay wall constructed in the port in Le Havre in 1923, see Figure 55.

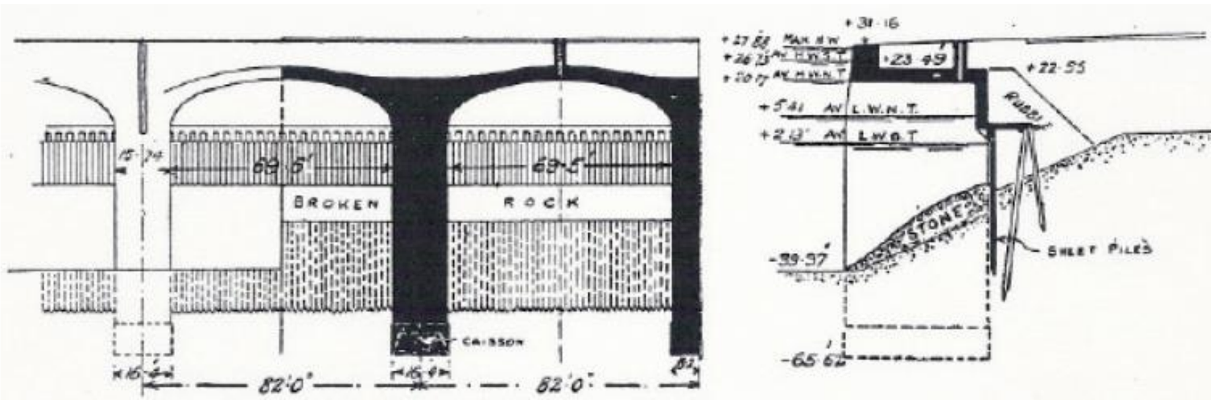


Figure 55: Front view and cross-section of the quay wall in the port of Le Havre [Gijt, 2010]

In the period after 1950 the increase in knowledge and the increased strength of the materials along with the increased lifting capacity of construction cranes resulted in an increase of the retaining height of the quay walls. The design became more efficient due to the increased strength of the materials.

Since 1900 concrete and steel have been the most applied construction materials throughout the world. This is due to the fact that almost every shape can be made with concrete, whether it is cast in situ or with prefab elements. Along with the development of very strong reinforcement steel this caused a slight change in the design of quay walls to more slender structures than before. A modern design of a quay wall is given in Figure 56. [Gijt, 2010]

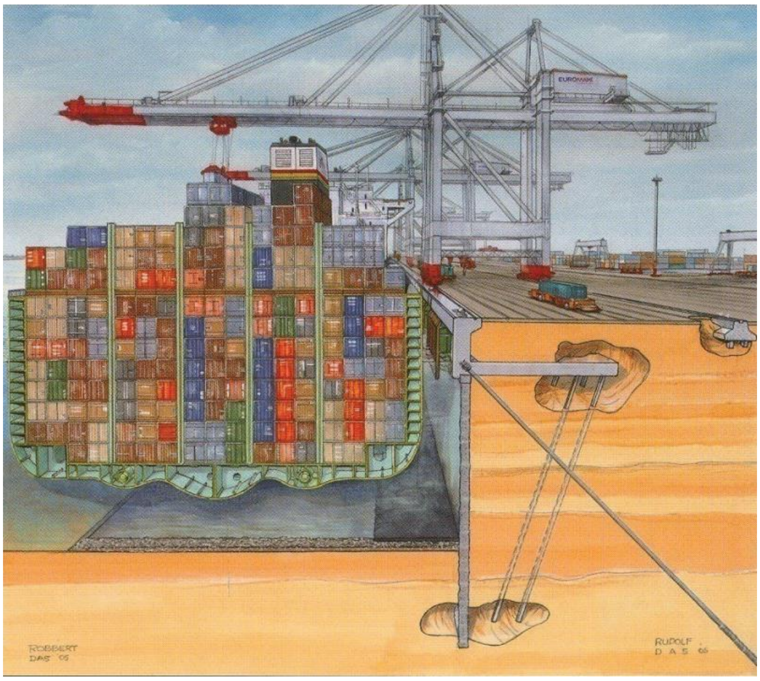


Figure 56: Cross-section of a quay wall at the Euromax terminal, Rotterdam [Gijt, 2010]

12.3 TYPES OF QUAY WALL

Nowadays there are so many different quay walls that it is convenient to categorize them. There are 4 types of quay walls, namely gravity type quay walls, sheet-pile type quay walls, piled quay walls and quay walls with a special foundation. This classification is based on the mechanical behaviour of the different types of quay walls and for comparison. Each category will be elaborated into more detail and an overview of the possibilities within the category will be presented.

12.3.1 Gravity-type structures

A gravity-type structure is often used when the foundation material does not permit pile driving or where heavy ice, waves or other environmental forces can be dangerous to the piled structures. Gravity-type quay walls may be built in the form of mass concrete walls or walls composed from heavy prefabricated concrete blocks or elements. A gravity-type structure develops its resistance to soil pressure and various loads primarily from their own weight. An overview of gravity-type structures is given in Figure 57 which is presented on the next page. [Gijt, 2004]

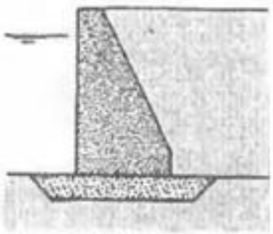
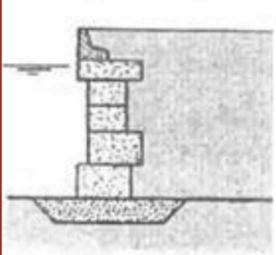
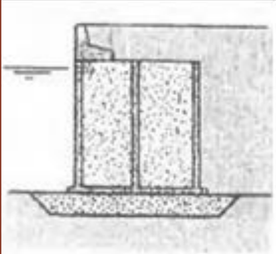
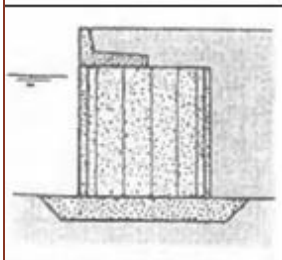
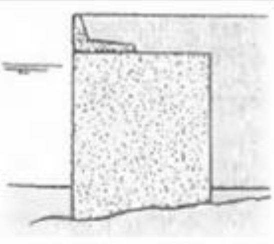
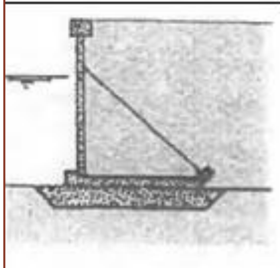
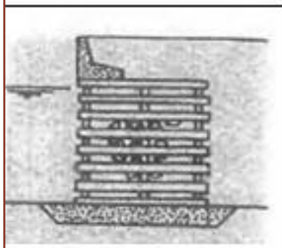
	Cast-in-Place Concrete or Masonry Wall	Material : Concrete, Natural Stone
	Prefabricated from Concrete Blocks	Material : Prefabricated Heavy Concrete Blocks
	Floated-In-Caissons	Caisons are of Prefabricated or Monolith Construction. Material : Reinforced Concrete
	Large Diameter Cylinders	Cylinders are of Prefabricated or Monolit Construction. Material: Reinforced Concrete
	Large Diameter Sheet Pile Cells	Steel Sheet Piles
	Angle Type Wall	Built from Prefabricated Elements, or Prefabricated Sections. Material: Reinforced Concrete.
	Floated in or Erected-In-Place Cribs	Material: Timber, Prefabricated Concrete Elements, Natural Stone.

Figure 57: Overview of the types of gravity structures [Gijt, 2004]

12.3.2 Sheet-pile type structures

A sheet-pile type structure is a structure formed from flexible sheeting which are restrained by an anchor system. The sheet piles are driven into the soil below the dredge line. The anchorage of a sheet-pile can be provided in a variety of ways. For example, it is possible to anchor the sheet-pile with a grout anchor or a rock anchor. It is possible to anchor a sheet-pile with a single anchor or by multiple anchors. Which type of sheet-pile has to be applied is determined by the height of the structure, the kind of foundation material and the live load. The sheet-pile is constructed out of steel but it is a possibility to construct a diaphragm wall which is constructed out of concrete. An overview of sheet-pile type structures is given in Figure 58**.** [Gijt, 2004]

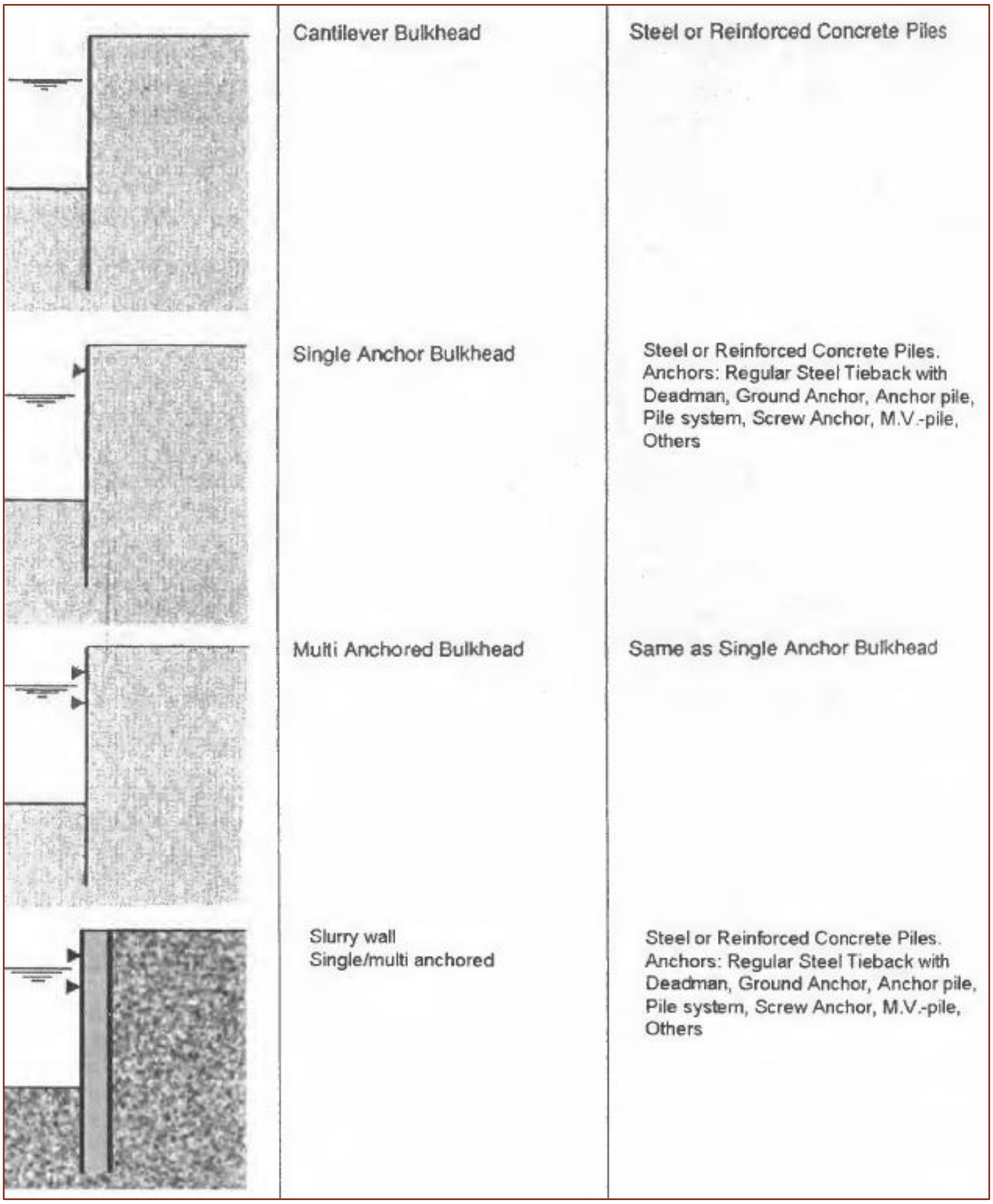


Figure 58: Overview of the sheet-pile quay walls [Gijt, 2004]

12.3.3 Piled-type structures

The stability of piled-type structures depends on the pile bearing and lateral load-carrying capacity. Piles are usually designed to carry vertical and lateral loads due to the structures deadweight, live load and various sources of lateral loads such as mooring forces. The cross-section of a pile is determined by the length of the pile, the foundation material and the pile-driving techniques. Whether the pile only has to carry vertical, lateral or a combination load plays a role as well. An overview of piled-type structures is given in Figure 59. [Gijt, 2004]

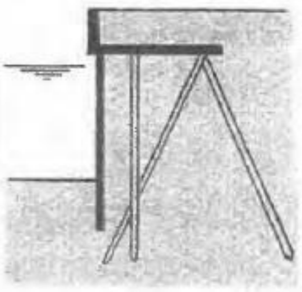
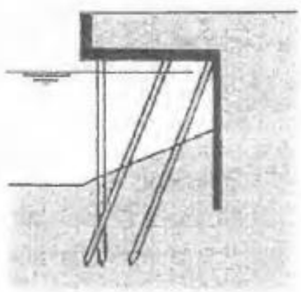
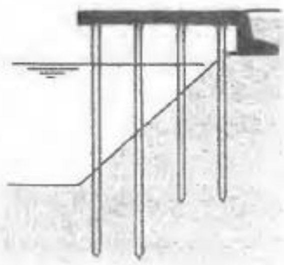
	Relieving Platform with Front Sheet Pile Wall	Monolithical or Prefabricated Concrete fo Platform Construction. Steel or Reinforce Concrete Piles and Sheet Piles
	Relieving Platform with Rear Sheet Pile Wall	Monolithical or Prefabricated Concrete fo Platform Construction. Steel or Reinforci Concrete Piles and Sheet Piles.
	Piles Supported Platform	Monolithical or Prefabricated Concrete fo Platform Construction. Steel or Reinforce Concrete Piles of Regular Construction or Large Diameter (up to 1.6m)

Figure 59: Overview of the piled-type quay walls [Gijt, 2004]

12.3.4 Quay walls with special foundations

There is also the category based on special foundations of the quay wall. The relevant quay wall is mostly one of the above treated types of quay wall. The foundation of the quay wall however is designed to meet specific local soil conditions such as for instance very soft clay deposits. An overview of quay walls with a special foundation is given in Figure 60. [Gijt, 2004]

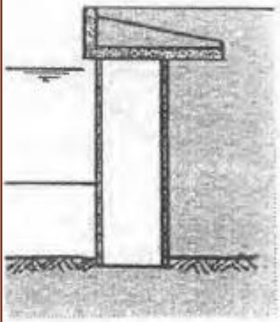
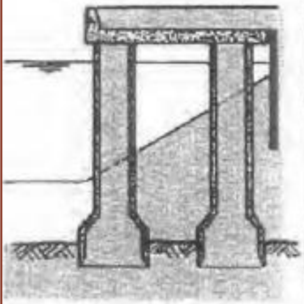
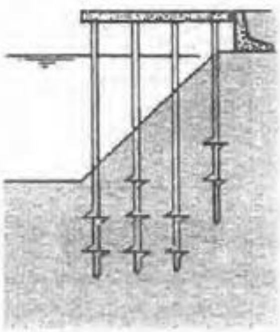
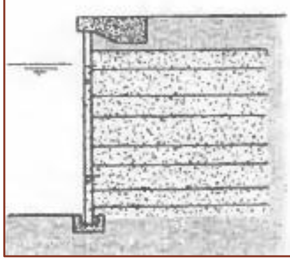
	Large Diameter Cylinders with Relieving Platform	Cylinders and Platform are of Prefabricated or Monolithic Construction . Material: Reinforced Concrete.
	Platform Supported on Deep Caissons	Steel or Concrete Caissons, Monolithical or Prefabricated Reinforced Concrete Platform
	Platform Supported on Piles with Increased Carrying Capacity	Steel or Concrete Screw Piles or Piles with Local Widenings. Monolithical or Prefabricated Reinforced Concrete Platform
	Reinforced Earth Wall	Prefabricated Concrete Elements and Metal Anchor Strips

Figure 60: Overview of quay walls with a special foundation [Gijt, 2004]

REFERENCES

Books

Abspoel, R., Vries, P. A. de & Bijlaard, F. S. K. (2013). *Staalconstructies.* Delft: Delft University of Technology.

Bijen, J. M. J. M., Hendriks, Ch. F., Fraaij, A. L. A. & Rooij, M. de. (2007). *Duurzame bouwmaterialen*. Delft: Delft University of Technology.

Breugel, K. van & Fraaij, A. (2008). *Inleiding Materiaalkunde en Duurzame Ontwikkeling.* Delft: Delft University of Technology.

Carlsson, L. A. & Kardomateas, G. A. (2011). *Structural and Failure Mechanics of Sandwich Composites*. Dordrecht: Springer.

Clarke, J. (2005). *Structural Design of Polymer Composites.* England: Taylor & Francis e-library.

Gijt, J. G. de. (2004). *Structures in hydraulic engineering, Port Infrastructure.* Delft: Delft University of Technology.

Gijt, J. G. de. (2010). *A History of Quay Walls,* Delft: Delft University of Technology.

Greene, E. (1999). *Marine composites second edition.* 2nd print. Maryland: Eric Greene Associates, Inc.

Karbhari, V. M. (2007). *Durability of Composites for Civil Structural Applications.* Cambridge: Woodhead publishing.

Kassapoglou, C. (2013). *Design and Analysis of Composite Structures*, Wiley book publishing,

Kolstein, M. H. (2008). *Fibre Reinforced Polymer (FRP) Structures.* Delft: Delft University of Technology.

Nijhof, A. H. J. (2004). *Vezelversterkte Kunststoffen–Mechanica en ontwerp*. Delft: VSSD.

Nijssen, R. P. L. (2013). *Composieten Basiskennis.* 2nd print. Delft: Hogeschool Inholland.

MSc studies

Breugel, M. P. van. (2003). *Kademuur van de Toekomst.* Delft: Delft University of Technology.

Kok, L. (2013). *Feasibility study for FRP in large hydraulic structures: Literature Study.* Delft: Delft University of Technology.

Straten, R. W. van. (2013). *Feasibility study on fibre reinforced polymer slides in the Eastern Scheldt storm surge barrier.* Delft: Delft University of Technology.

Zorgdrager, A. (2014) *Feasibility study on the application of fiber-reinforced polymers in large lock gates*. Delft: Delft University of Technology.

Reports

Ascione, L., Caron, J. F., Godonou, P., IJselmuijden, K. van, Knippers, J., Mottram, T., Oppe, M., Sorensen, M. G., Taby, J. & Tromp, L. (2016) *Prospect for new guidance in the design of FRP.* Italy: European Commission.

Articles

Bouwdienst Rijkswaterstaat. (2000). *Kunststof schuif in de Kreekraksluizen*. Product Innovatieblad.

Bouwdienst Rijkswaterstaat. (2001). *Kunststof Puntdeuren voor de Spieringsluis*. Product Innovatieblad.

Internet

Cripps, D. (2016). *Guide to Composites*. Retrieved January 11, 2016, from: http://www.netcomposites.com/guide

Fibercore Europe. (2016). www.fibercore.com

Gurit. (2016). *Guide to composites. Delivering the future of composite solutions.* Retrieved April 20, 2016 from: http://www.gurit.com/guide-to-composites.aspx

Heijmans. (2016). *Composiet toepassingen.* Retrieved January 12, 2016 from: http://heijmans.nl/nl/composiet-toepassingen/

Norwood, L. S. (2016). *Gelcoats.* Retrieved January 18, 2016 from: http://www.netcomposites.com/guide-tools/guide/coatings/gelcoats/

Rijkswaterstaat. (2016). *Wereldprimeur: grootste composietsluisdeuren geplaatst in Wilhelminakanaal Tilburg*, 11 January 2016. www.rijkswaterstaat.nl

Selvaraju, S. (2011). *Applications of composites in marine industry.* Journal of engineering studies and research, Retrieved January 7, 2016 from: http://www.technicaljournalsonline.com/jers/VOL%20II/JERS%20VOL%20II%20ISSUE%20II%20APRIL%20JUNE%202011/ARTICLE%2019%20JERS%20VOL%20II%20ISSUE%20II%20APRIL-%20JUNE%202011.pdf

Vereniging kunststof composieten Nederland. (2016) www.vkcn.nl