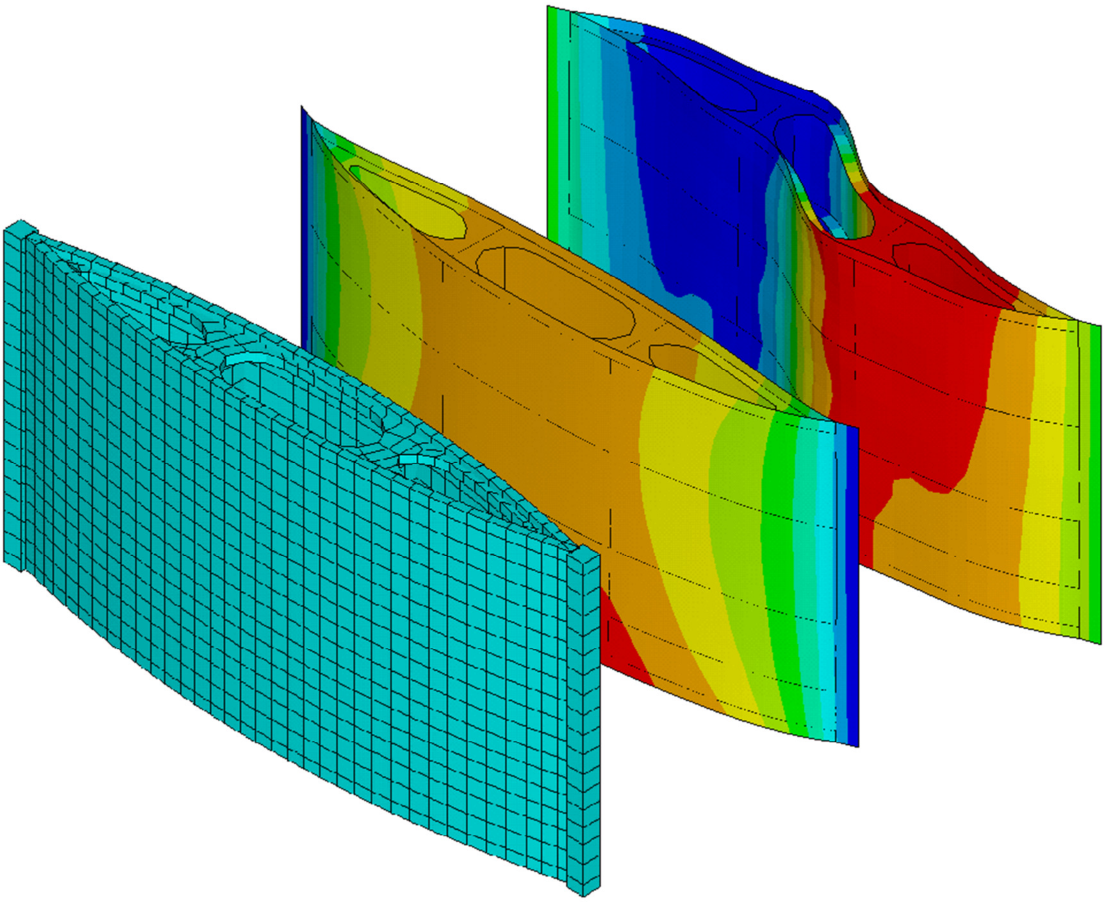


Dynamic Behaviour of Large Hydraulic Structures in FRP

"A look into the dynamic behaviour of a lift gate made in FRP for guard lock Limmel in Maastricht"

I.C. Pérez Gómez
February 2014

TU Delft Delft University of Technology

Iv-Infra

MSc Thesis Literature Study

Dynamic Behaviour of Large Hydraulic Structures in FRP

"A look into the dynamic behaviour of a lift gate made in FRP for guard lock Limmel in Maastricht"

I.C. Pérez Gómez

Submitted to:
Department of Structural Engineering
Technical University of Delft
Version 2
5 February 2014

Title
Dynamic Behaviour of Large Hydraulic Structures in FRP

Subtitle
A look into the dynamic behaviour of a lift gate made in FRP for guard lock Limmel in Maastricht.

Student
Name: Itza C. Perez Gomez
Student nr.: 4093887
Address: Rijswijkseweg 340-45
2516 HM Den Haag
Mobile Phone: 06-46644636
e-mail: itza.perezgomez@yahoo.com
Study: Civil Engineering, Technical University of Delft
MSc. Track: Structural Engineering

Study
Technical University of Delft
Faculty of Civil Engineering and Geosciences
Section of Structural engineering
Specialisation Hydraulic Structures

Graduate company
Iv-Infra
Trapezium 322
3364 DL Sliedrecht

Graduation committee
Prof. ir. F.S.K Bijlaard (Chairman)
TU delft CiTG, Department of Steel, Hybrid and Composite Structures
Ir. A. van der Toorn
CiTG, Department of Hydraulic Structures
Dr. M.H. Kolstein
CiTG, Department of Structural and Building Engineering, Steel Structures
Ir. J.R. Augustijn
Iv-Infra, Senior project manager

TABLE OF CONTENTS

1. INTRODUCTION

The question for the reduction of maintenance of structures especially those in marine environments is increasing and more is asked of structures in terms of durability and capacity. Fibre reinforced polymers can be a good alternatives to current materials to fulfil these demands. Since its use in other markets/industry has proved that it is a highly resistant material. But due to the fact that the material is relatively new in the civil engineering market, there is still much to be researched in order for it to become an accepted structural material.

In the past years some FRP lock gates have been carried out in the Netherlands. These lock gates are relatively small mitre gates that have been made in this material to reduce maintenance. For this type of gates the advantages when looking at the structural behaviour is less friction due to the light weight.
One of the main reasons why this material isn't being used more frequently is the lack of design knowledge and experience working with this material, and also the uncertainty regarding its durability. Many researches on the durability and sustainability of it have been carried out though they are based on accelerated laboratory tests, in reality the behaviour may be significantly different. Because of this no definitive conclusion can be drawn. Although due to the resistance and durability it has proved to have in other industry like the aerospace industry, marine industry and the chemical industry it is expected durability not to be a problem.

In this literature study was done to obtain knowledge regarding this material and other information needed in order to start the main part of the thesis research. The outline of this report is as follows: In chapter 2 a short description is given about lock gates, the types and the choice made for the main research is explain. In chapter 3, 4, and 5 an overview of different aspects of fibre reinforced polymers is given. First the materials from which FRP can be made and the manufacturing processes available are described. Then the material properties, i.e. determining mechanical properties, durability of FRP and fatigue are described, followed by a description of the types of connections available. In chapter 6 the dynamics are studied, in this chapter an overview will be given of the different types of dynamic loading for structures in water and what this means for the basic calculations. Finally in chapter 7 examples of project where FRP gates have or will be implemented are presented.

2. LOCK GATES

At first lock gates were made of wood and they were limited to small gates, because of the limitations of allowable stresses of the wood, the lack of power needed to open large gates and the costs. With the new developments in mechanical power and material knowledge larger lock gates are possible. Nowadays most lock gates are constructed of steel. However a drawback of steel is that it requires to be conserved to avoid corrosion, thus a lot of maintenance is needed.

In this chapter the most common types of gates will be described of these a choice is then made regarding the type of gate that will be developed in the case study. This has been a lift gate, reasons are the possibility to open it under a differential head and the clear advantage it would have regarding the lightweight of FRP. Lift gates will then be further described in greater detail.

Based on: (Molenaar, 2011), (Vrijburcht, 2000)

2.1. Types

There are different types of gates each having different features and characteristics in this chapter a short description of some of the most important types of gates will be giving.

2.1.1. Mitre gates

Mitre gates are flat gates consisting of two leaves, that when closed lean against each other pointing in upstream direction (see fig. 2.1).
The gates rotate around their vertical axis, transferring forces through the pivots to the chamber walls. The axis of rotation at the recess is eccentric, to guarantee room between the gate and the lock chamber when opening the gate, and when closed this space should be as small as possible to retain water.

They are only intended for one-sided water retention and can retain a limited negative head when hydraulic cylinders are used. This type of gate is not applicable when there are high water currents or wave action, like is the case for flood gates or weirs. The limited width of mitre gates is approximately 20-25 metres, which is 10-12.5 metres per door. Of great importance is the height/width ratio, when it is smaller than 1 the forces on the pivot points are relatively large.

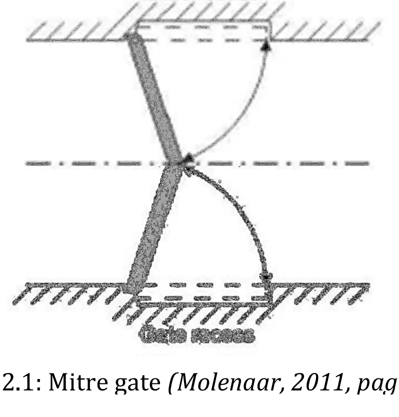


Figure 2.1: Mitre gate *(Molenaar, 2011, page 93)*

Advantages
- No limitations regarding vertical clearance
- Functions as a three pivot girder, resulting in relatively light gate structures
- Shallow gate recess
- Simple operating mechanism
- The mechanism doesn't have to carry the weight of the gate

Disadvantages
- Length of the lock chamber, because of the way the gate opens.
- Exact dimensions (accurate mounting and frequently checking of the contact points of load transmission is necessary).
- Sensitivity to waste and ice, it may get trapped in between the gates stopping them from closing properly.
- They cannot be opened or closed under a head differential.
- Possibility of collision is greater because of the shape of the gate, it points to the outside.

2.1.2. Single leaf gate

A single leaf gate is a flat single pivot gate, similar to half a mitre gate (see fig. 2.2). Unlike a mitre gate where forces are mostly transferred by horizontal forces, for a single leaf gate the transfer of forces is mostly by bending moments.

Advantages:
- Simple construction and operation, suitable for small locks
- No limitations regarding vertical clearance
- Retention in both directions when gate is lock at the free end
- Forces are transferred parallel to the lock wall (when closed gate is perpendicular to the lock axis

Disadvantages:
- Recesses are longer than for mitre gates.
- Opening and closing of the gate results and a lot of water displacement
- More rigid and those heavy construction needed for the pivots, socket and collar strap
- Sensitivity to waste and ice
- Not suitable for wide locks because the supports (pivot points/hinges) would have to be very heavy.

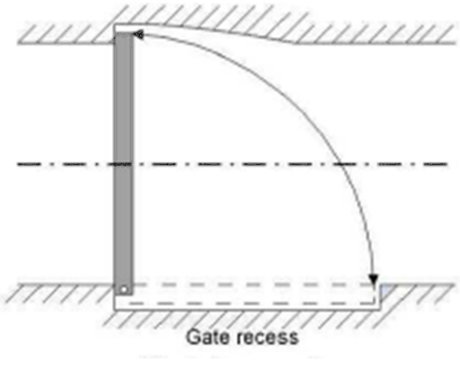


Figure 2.2: Single leaf gate (*Molenaar, 2011, page 93)*

2.1.3. Lift gate

Lift gates are lifted along guide towers to open the lock (see fig. 2.3). Guide towers are required to guide the door into position. The weight of the gate can be balanced by counterweights to reduce the operating forces of the lifting mechanism.

Advantages:

- Little space is needed for the lock head, enabling the total lock length to be reduced
- Short heads
- Possibility of water retention in both direction
- Possibility to open the gate under a head difference, because the force directions are in a different plane
- Good inspection and maintenance possibilities
- Little sensitivity to waste and ice

Disadvantages:

- Limited vertical clearance
- Complicated gate guides and operating system
- Large, heavy and expensive superstructure
- Lifting the whole gate under differential head results in very strong underflow
- Spillage of water on vessels passing the gate
- Difficulties with the roller tracks because of the deflection of the gates when under full head
- Balancing the gate can be complicated and expensive. When opening floating debris or ice as well as ice frozen to the gate can increase its weight and negatively influence the balance with the counterweights. Also risk of debris falling on ships when passing underneath gate.

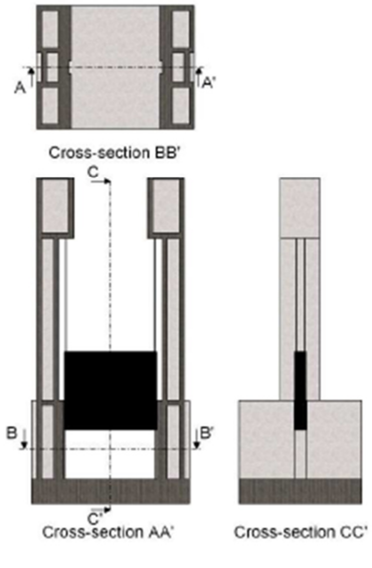


Figure 2.3: Lift gate *(Molenaar, 2011, page 95)*

2.1.4. Submersible gate

Submersible gates, like lift gates, move vertically with the exception that submergible gates move downward when opening. They are often used as upstream gate in very high head locks, where the sill of the lock is so high that there is no need to for a recess in the bottom lock chamber. When a recess is needed major excavation would be required, limiting their application for larger locks. *(Doeksen, 2012)*

There are two types of submersible gates: single leaf and multiple leaf gates.
The double leaf gate is the most commonly used. This gate is composed of a down-stream leaf used for normal lock operation and an upstream leaf used as a movable sill or as an operating leaf in case of an emergency, also referred to as an emergency leaf. (See figure 2.4).
This type of gate is useful for skimming ice and drift from the lock approaches when necessary or to regulate the flow of flood water by opening the gates. *(USACE [1], [2])*

Advantages:

- No limitations in vertical clearance
- Possibility to open the gate under a (large) head difference, because the force directions are in a different plane
- Little space is needed for the lock head, enabling the total lock length to be reduced

Disadvantages:

- Large excavation needed for gate recess.
- Sedimentation and erosion at the bottom of the sill may create problems, e.g. impediment in the movement of the gate and gate not closing properly.
- Maintenance of the gates is difficult since they are always under the (upstream) water level.

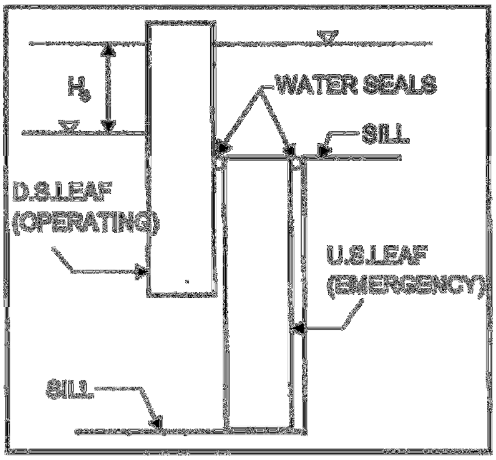


Figure 2.4: Schematization of a double leaf submersible gate, *(USACE [2], 2013, page 3.4)*

Figure 2.5: Lift gate *(USACE [1], 2013, page 7.3)*

2.1.5. Rolling or sliding gate

Rolling gates are preferred where large widths are required, without limiting the vertical clearance. They close the passage perpendicularly and when opened they are stored in a deep gate chamber at one of the chamber walls, on the other chamber wall there is a gate recess. Because of this it can only be applied where sufficient space besides the lock is available (see fig. 2.4).
The gate rests on two roller carriages, each fitted with four wheels that are guided along rails by means of flanges on the wheels or by means of roller guides or guide blocks. For sliding doors the roller carriages are replaced by hydrostatic slide bearings.

Usually the gate is equipped with float control chambers, which result in a decrease of the weight and frictional forces on the roller carriages as well as reducing wear and tear. When the gate is closed these chambers can be filled, serving as ballast tanks, ensuring the necessary contact pressure.
During opening the upper corner of the gate is unsupported when a force is on this area the gate may become unstable. Forces on this area can be a result of e.g. a remaining water level difference or a large flow. To provide stability a certain gate thickness is required.

Advantages:
- Water retention in both directions
- Possibility for two sided turning
- Light operating mechanism

Disadvantages:
- Expensive, deep gate recess
- Expensive guiding system
- Large area needed for storage of the gate when open
- The minor overweight requirement could make the gate sensitive to waves during movement of the gate
- The gate can be obstructed due to accumulation of sediment or debris on the tracks

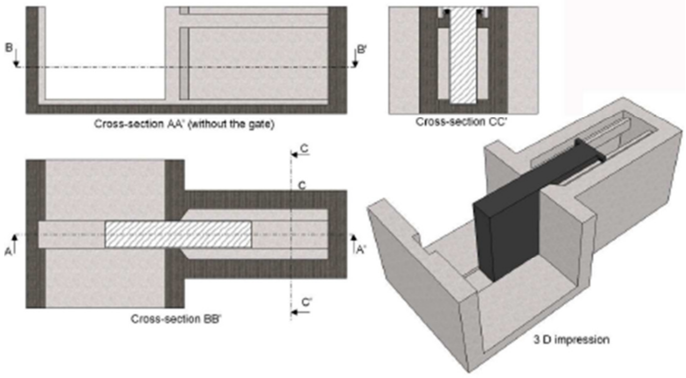


Figure 2.6: Rolling gate *(Molenaar, 2011, page 96)*

2.1.6. Radial gate

2.1.6.1. Sector gate (Rotation about the vertical axis)

Sector gates have curved shaped skin plates that are stiffened in order to resist the hydrostatic water pressures. The skin plate is supported both vertically and horizontally by arms, triangular shape trusses in the horizontal plane. Upper and lower arms are connected by braces to provide the required vertical stiffness (see fig. 2.5).
Generally two gates are used, one on each side with a rotation point on the chamber wall, along which the forces are transferred. Sector gates can be pushed into movement mechanically or hydraulically like mitre gates. But unlike the mitre gates, that have to push the water in front of the gate, the sector gate cuts through the water. Therefore the driving mechanism can be designed relatively lighter.
Another option, instead of a mechanical operating mechanism, is to use the hydrostatic water pressure difference due to differing water levels on either side of the gate.
First the recesses are closed off and the water level is raised by letting water in through culverts. Because the water level is then higher in the recesses the gate is pushed out, vice versa if water is let out of the recesses and the water level in the lock would be higher than in the recess the gate will move into the recess.

Advantages:
- Can retain water on two sides
- Possibility to close under flow conditions
- Can move under water pressure
- Light operating mechanism
- Statically determinate
- Can be operated when there is a water head
- Can resist negative heads
- Unlimited vertical clearance
- Opening and closing of the gates can be done in a short time

Disadvantages:
- Expensive gates, large amount of material
- Large area needed for gate recesses
- The gates are heavier than mitre gates, making them more expensive
- Sensitivity to debris and ice

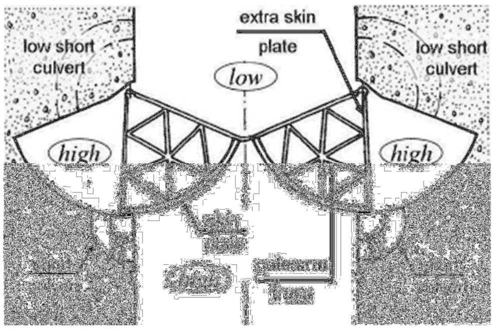


Figure 2.7: Sector gate *(Molenaar, 2011, page 93)*

2.1.6.2. Tainter gate (Rotation about the horizontal axis)

These types of radial gates also have a circular cross section. On the chamber walls short arms are positioned that go through pivoting points that coincide with the centre of the circle (see fig. 2.6).
If counterweights are present they are applied on the opposite side of the extended arms. The arms rotate on rotation points positioned about halfway of the water depth. Sometimes the gates are not balanced by counterweights, in that case the arms are longer.
The gate can be dropped to the bottom of the lock by turning downwards into a slot in the bottom or into a stilling chamber. Or it can be turned up, but this results in a limited clearance.
The gate is mostly applied, when there is a very high lift, in combination with an energy dissipation chamber.

Advantages:
- Short, shallow gate chambers
- Water retention on both sides

Disadvantages:
- Recess on the bottom of the lock head, as a result a deeper foundation is needed. This increases the costs
- Entire weight of the gate has to be carried by the equipment unless counterweights or floating elements are used.

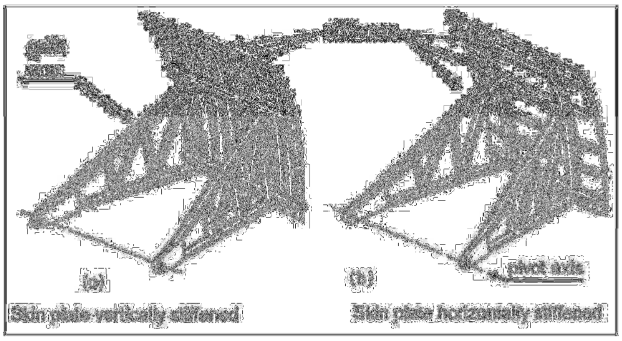


Figure 2.8: Tainter gate *(Molenaar, 2011, page 94)*

2.2. Choice of gate

For the location Limmel it was decided that the most attractive type of gate to design in FRP would be a lift gate, because of its lightweight the moving mechanism of the gate could be designed much lighter. This does not mean that the application of FRP in other types of gates does not have advantages. For example when applying mitre gates or rolling gates in FRP the supports and hinges have to carry less weight resulting in less abrasion, thus making the gates more durable.
Since the choice has been for lift gates other types of gates will not be discussed any further.

2.3. Lift gates

Lift gates are lifted vertically out of the lock chamber allowing ships to pass underneath. Therefore they can only be applied when the height limitation for passage is not too grand. And they are commonly selected when there isn't the required space for other door types.

2.3.1. Gate guides

Usually the gates are lifted through sliding or rolling guides. They function as tracks, supports at the end position, and as the sealing. Guides are placed at both sides of the gate to avoid that the gate start running next to the rails. They required extra tensile force in the hoisting direction because of the load against the lift gate during movement. During loading, extra weight may be required to drop the gate.

Gates experiencing heavier loads often have rolling guide systems. Rolling guides require less tensile force, because of their lower friction. However the rotating parts under water require more attention and maintenance and they tend to be more expensive and heavier. The weight to be balanced is therefore heavier and deeper recesses are required.

2.3.2. Lifting mechanism

In order to lift the gate it is partly balanced by counterweights used to limit the weight on the winch gear. The winch gear is positioned in the towers on both sides of the lock chamber and connected to the lifting cables and to the counterweight. Usually more than one lifting cable is used in order to limit the size of the winch gear, this way the needed machine room is smaller. However this requires extra provision to ensure that the load is distributed equally over the cables (as much as possible).

The gate has to be heavier than the counterweights and the upward force, to ensure that there will be no leakage at the bottom edge of the gate. Overweight is also needed to surmount the resistance of the gate guides, the upward force of the gate under water and the resistance against the bending of the cables around the drums and pulleys.

3. FIBRE REINFORCED POLYMERS

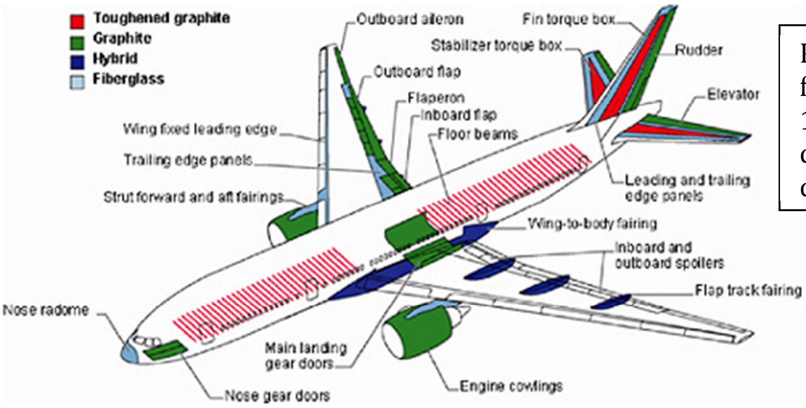
In this chapter we will focus on Fibre Reinforced Polymers (FRP), to gain a better understanding of FRP as a building material. First the history of FRP and the uses at has in different industries will be shortly described in chapter 3.1. In chapter 3.2 the main characteristics of FRP will be given and in chapter 3.3 the materials used to make FRP composites are described. The materials described in this chapter are the reinforcement, namely: glass, polyaramid and carbon fibres; the matrix: polyester, vinyl ester and epoxy resin; and cores that may be used for the manufacturing of sandwich panel. Then the different manufacturing processes with which FRP elements can be made are given in chapter 3.5.

3.1. History

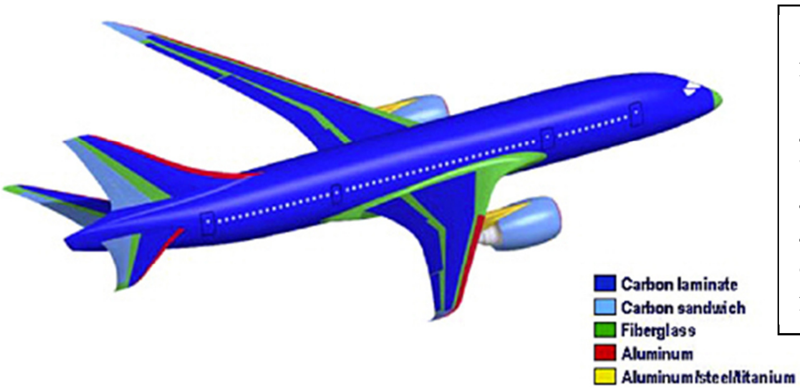
Composites have been around for many centuries; however composites consisting of polymers have a starting point with the introduction of phenolic in the beginning of the 20th century. But the birth of polymer composites was in 1935 when Owens Corning introduced the first glass fibre, Fiberglas®.
It was in the 1940's with the development of polyester resins that the industry of polymer matrix composites had a rapid development and has been growing ever since. During the Second World War the need for strong and lightweight materials for aircraft first arose, resulting in the discovery that FRP wasn't only strong and lightweight but that it also was transparent for radio frequencies and it was soon used in the development of so called radomes (protective domes for electronic radar equipment). By 1944 the first boat hull in glass fibre reinforced polymer (GFRP), was made and in 1946 more everyday products were been made in GFRP, e.g. fishing rods and serving trays. [*(Kolstein, 2008), (Chlosta, 2012)*]

Nowadays it is used in a variety of different applications, from applications in the sport sector to the aerospace industry. An example is the automotive industry where, like the example in figure 3.1, composites are not only used in interior component, but also to build the car's body. Another industry it is often used is in the energy sector where e.g. pipes are made of composite.

Figure 3.1: 'superbus' a project by Wubbo Ockels in cooperation with the TU Delft. *(Nedcam)*



Primary and secondary structure for the Boeing 777, an example of 1990s commercial application of composites (15-30% made in composites)



Projections for composites used in the Boeing 787 (50%), Currently the usage is approaching 70% on the 'Eurofighter' and other advanced aircraft, with entire airframes and support structures being constructed of PMC's (polymer matrix composites)

Figure 3.2: The figure above shows how fast the use of FRP in the aviation industry has increased in the last two decades. *(Committee on Durability and Life Prediction of Polymer Matrix Composites in Extreme Environments, National Research Council, 2005)*

Figure 3.3: Filament Wound Boeing 787 Fuselage *(Groh, 2012)*

These figures give an idea how fast the growth that composites have had over the last 2 centuries within the aviation industry.

Figure 3.4: View of wind turbines equipped with FRP rotor blades *(Solico)*

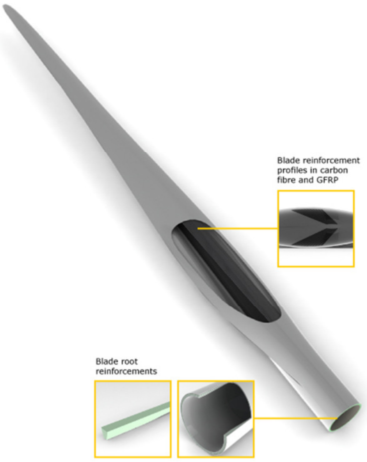


Figure 3.5: Rotor blade of wind turbines made of FRP, made by Fiberline *(Fiberline [1])*

Figure 3.6 & 3.7: Van Dutch project, yacht build out of FRP composites *(Nedcam)*

3.2. General characteristics of FRP

FRP has certain properties that cannot be achieved by other materials, this is one of the reasons its use has grown so rapidly in the last 50 years. Some of these properties are mentioned below:

- Easily formed into shapes.
- Ability to make large sections.
- Lightweight.
- Good environmental resistance.
- Corrosion resistance.
- Lower life cycle costs, because of the good environmental and chemical resistance it is expected that composites require less maintenance and thus have lower life cycle costs (though this is still an area of uncertainty).
- Low thermal conductivity, it is a good thermal insulator strains due to temperature fluctuations are controlled.
- High tensile strength and compressive strength of the fibres at a relatively low weight. (Resin serves to: bond all fibres together, the loads can be spread to all fibres; provide protection to the fibres from impact loading and to provide chemical resistance).
- Improved strength-to-weight ratios, high stiffness-to-weight ratios.
  Possibility to consider new design concepts, where larger spans can be achieved and lighter more cost efficient foundations and substructures can be build.
- Low tooling costs.
- It is possible to design sections to have the required properties in the required direction, making it more efficient and economic by the placing direction of the fibres.
- Longer fatigue life. Unlike other materials FRP can exhibit gradual softening and loss of stiffness when subjected to cyclic loading due to microscopic damage before visible cracks appear.
- It has non-Magnetic properties, unlike steel members that are prone to caused interference under electromagnetic properties, which is often a problem where radar or other sensitive electronic equipment is housed.
- Possibility for parts integration. Larger sections can be made reducing the number of joints and increasing the overall safety.
- Faster field installation, because of their lightweight large composites sections can be fabricated off site, making the construction on site faster. Fabrication off site means also that construction is not dependent on seasonal changes, making it possible for year-round installation. Though attention should still be paid to the joining of the structural components.
  (Lopez-Anido, 2000), (Kolstein, 2008)

However one of the main drawbacks is that the properties of FRP are highly dependent on the manufacturing process and the environment. These properties can therefore not be guaranteed, unless the composite is produced under a controlled environment and by skilled personnel.
Other disadvantages that can affect the composite are:

- Higher initial material cost
  Composite materials are more expensive per unit of weight than other conventional materials. However these costs should be looked at more closely since strength-to-weight and stiffness-to-weight ratios of composites are higher than that of other materials, and so less material is needed. Also composites can be fabricated with processes that minimize the labour and thus minimizing the costs of production.

- Poor ductility, especially those made of a thermoset.
  However some components can be developed to exhibit damage before failure.
- Thermoplastic based materials have limited recycling ability.
- Lack of design experience
  Due to the differing properties in different directions the standardizing of the material properties is not possible. Also the dependency of the properties on weaknesses that may occur during manufacturing (e.g. voids) makes it difficult to make a structural design.
- Lack of knowledge on design of composite structures.
  Unlike with conventional materials both the geometry of the structure and the material has to be designed. This can be a hindrance to use composites.
- Lack of comprehensive standards and design guidelines.
  (Lopez-Anido, 2000), (Kolstein, 2008)

3.3. Materials

Composites consist of at least two materials a bulk material and reinforcing material and can be divided into 3 main groups, namely:

- Polymer Matrix Composites (PMC's) or Fibre Reinforced Polymers (FRP);
- Metal Matrix Composites (MMC's);
- Ceramic Matrix Composites (CMC's).

Fibre reinforced polymers consist of two materials: reinforcing fibres and a matrix (in this case a polymer resin). Fibres act as reinforcement providing the strength and stiffness of the FRP. While the matrix both forms a solid material from the fibres making it possible to transfer loads between the fibres, and protects them from environmental influences. To ensure collaboration between these two components the bond and interaction between the two is of great importance.
Next to these to materials also additives are used such as curing agents (e.g. hardeners and binders) and fillers. They serve to control and aid the reaction of the matrix in order to get the desired consistency of the resin and the required material properties.

In the following paragraphs the most often used reinforcing fibres and resins will be discussed. Other components like gel coats and additives will not be discussed further, since they have little or no influence on the materials characteristics as long as they are added properly. They only influence the appearance, though in some cases they may also improve the fire/chemical resistance of the composite.
Based on: (Weatherhead, 1980), (Hancox, 1981), (Kolstein, 2008), (Chlosta, 2012)

3.3.1. Reinforcement

Fibres give the composite the main bearing capacity, strength and stiffness. Due to their high strength and light weight, composites have a good strength to weight ratio that is superior to that of steel. The mechanical properties of the fibres within the matrix are determined by the type, thickness, length, and form and orientation of the fibres.
First the different types of fibres, namely glass, poly aramid, carbon and natural fibres used in industrial applications will be looked at followed by the different forms in which these fibres are available.

3.3.1.1. Glass fibre reinforcement

Glass fibres as reinforcement where first introduced in the 1950's, although they were being produced commercially before that. They are the most commonly used type of reinforcement, due to its lower cost. In comparison with other fibre types they have higher elongation to failure but a lower strength and moduli. Glass fibres come in a variety of forms and compositions.
The compositions used in composites are:

- **A-glass:** Alkali glass, once widely used has been replaced by E-glass in many applications.
- **C-glass:** Chemical resistant glass used mostly as surface tissue because of its superior resistance to environmental conditions, impact and abrasion.
- **D-glass:** Mainly used in electronics industry due to its good dielectric properties.
- **E-glass:** Electrical grade glass (low alkali content borosilicate glass, good electrical, mechanical and chemical properties).
- **R- and S-glass:** High strength glasses used mostly for aerospace applications.

E-glass is the most often used type of reinforcement because of its good strength and stiffness properties at low costs. Despite of this E-glass is susceptible to chemical corrosion. It is therefore mostly protected by applying a resin surface layer with C-glass reinforcements.
Because of this a new type of fibre glass has been developed, the so-called E-CR glass, which has high resistant against chemical attack and similar properties to E-glass.

In the table below the main properties of the different types of glass are giving. It can be seen that the high strength glass gives the best performance and that the most commercially used E-glass has good properties in comparison with the other types of glasses.

Table 3.1: Material properties of different types of glass reinforcements

Property	A-glass	C-glass	D-glass	E-glass	R-glass	S-glass	E-CR glass
Specific gravity	2.68 [c]	2.5 [a]	2.16 [b]	2.45 [a]	2.53 [c]	2.49 [b]	2.71 [a]
Tensile strength [GPa]							
- Filament (not coated)	3.1 [d]	3.0 [a]	2.4 [b]	3.4 [a]	4.4 [d]	4.6 [b]	3.3 [a]
- Roving (coated)	2.76 [d]	2.35 [d]	-	2.4 [d]	3.1 [d]	3.91 [d]	-
Tensile modulus [GPa]	73 [c]	69 [a]	52 [b]	72 [a]	85 [d]	86 [b]	72 [a]
Fracture strain [%]	4.4 [c]	4.8 [a]	4.7 [b]	4.8 [a]	4.8 [c]	5.4 [b]	4.8 [a]
Softening point [°C]	773 [c]	700 [d]	-	850 [d]	990 [d]	-	882 [c]

Table sources: a: (Clarke, 1996; page 56), b: (Nijhof, 1981; page 2.2), c: (Chlosta, 2012, page 28), d: (Weatherhead, 1980; page 47)

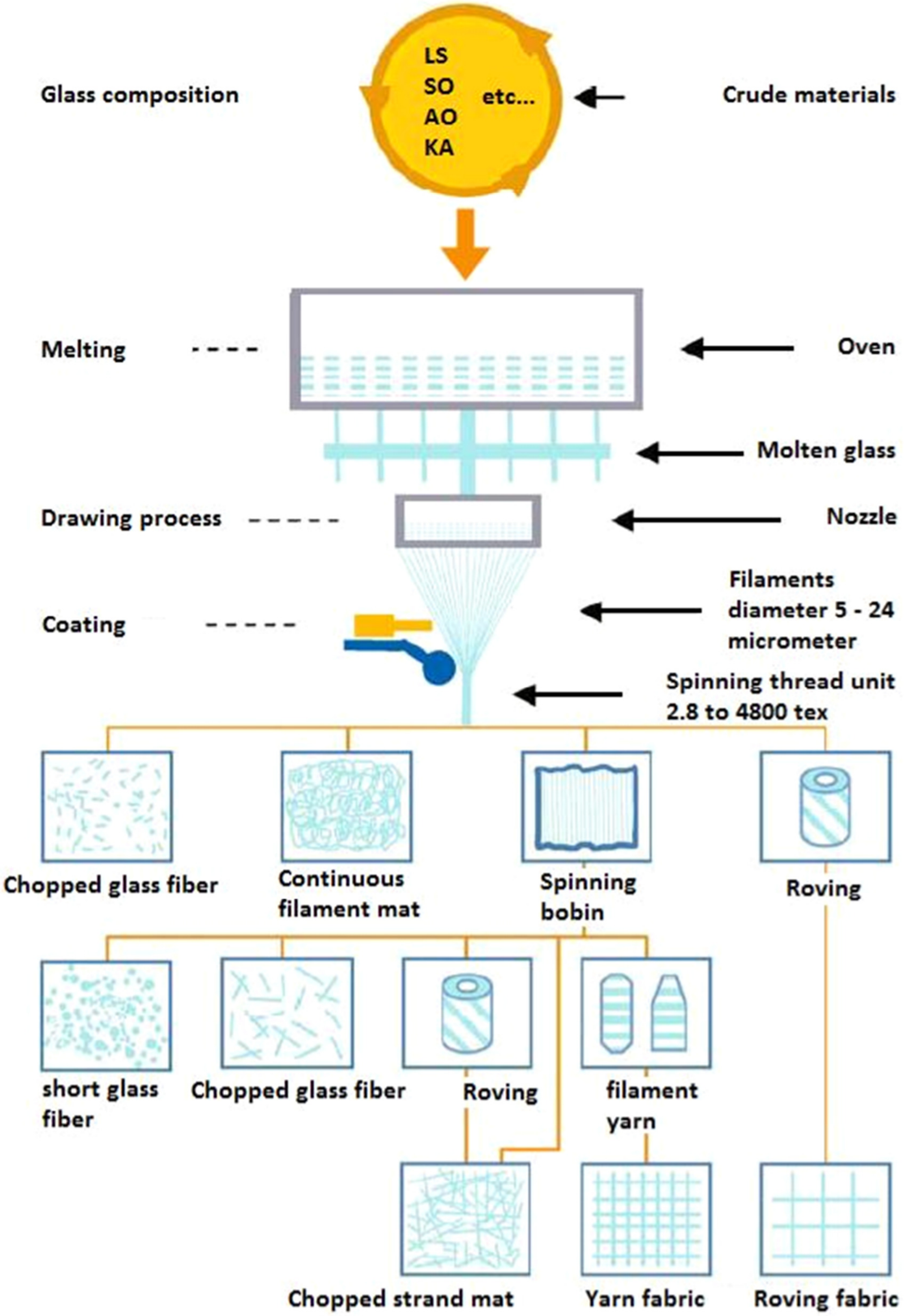


Figure 3.15: Illustration of production of glass fibres *(Chlosta, 2013, page 27)*

3.3.1.2. Carbon fibre reinforcement

Carbon fibres have been known for many years, in the 1880's they were used by Thomas Edison in incandescent lamps, which was later replaced by tungsten. But it was in the 1960's with the need for high strength, lightweight and thermally stable materials for the aerospace industry that the development of the carbon fibres known today took flight.

The production of carbon fibres takes place by a controlled oxidation and carbonization of the precursor material at temperatures of up to 2600°C. When increased to 3000°C carbon fibres are converted to high modulus graphite fibres. Materials used to obtain carbon fibres (precursor materials) are:

- Cellulose fibre
- Polyacrylonitrile (PAN) fibre (thermoplastic)
- Lignin
- Hydrocarbon pitch

Properties of fibres resulting from these precursors are given in the table 3.2.

Table 3.2: Material properties of different types of carbon fibre reinforcements

Property	PAN	PAN	Cellulose	Lignin*	Hydrocarbon pitch*
Fibre type	Graphite	Carbon	Carbon	Carbon	Carbon
Diameter [µm]	8	8	6.6	10-15	10.5
Specific gravity	1.87	1.76	1.67	1.5	1.6
Tensile strength [GPa]	2.4	3.2	2	0.6	1.03
Tensile modulus [GPa]	330	230	390	-	-
Elongation [%]	0.74	1.34	0.6	1.5	2.5

*Lignin and Hydrocarbon pitch precursors produce lower strength fibres

Table sources: (Weatherhead, 1980)

Carbon reinforcing fibres are commonly used despite of their high cost, this due to their high strength properties. However a disadvantage of carbon fibres is that their smooth surface gives low bonding strength between the fibre and the matrix. In order to improve the bonding carbon fibres are surface treated. They are also often sized with a resin to improve handling and to prevent damage during processing.

3.3.1.3. Polyaramid fibre reinforcement

Polyaramid fibres, shortly known as aramid fibres, are man-made organic fibres. They were mostly known under their trade name KEVLAR by DuPont in the 1970's, because they were one of the first to developed aramid fibres, but this changed with the production of other aramid fibres.

Their main feature is high tensile strength with low density. Some other advantages are:

- Strength and stiffness/weight ratio: 30% weight saving over glass and 50% over aluminium alloys, although lower compression strength
- Good thermal stability
- High impact resistance
- Good fatigue resistance and good vibration damping
- Superior insulating properties to glass
- Fracture in ductile manner unlike glass and carbon fibres
- However they have a lower compressive strength and are therefore more susceptible to fibre breaking in bending by a compressive mode

A disadvantage of aramid fibres is the low compression strength. Fibres under compressive stresses break at an elongation of about 0.5%.

3.3.1.4. Other reinforcing fibres

Glass, carbon and aramid fibres are the mostly used for FRP. However other less known fibres existed usually used in applications. Some examples are:

- **Polyester fibres** are of low cost, high impact, chemical and abrasion resistance but with low modulus. Often used in surfacing tissue.
- **Nylon fibres** are used to reinforce epoxy resin, they also have high impact, chemical and abrasion resistance
- **Boron fibres** are used in epoxy resins, with much better properties than other fibres but very expensive, for this reason they are currently used in specialized aerospace applications only.
- **Ceramic fibres** have high chemical and abrasion resistance, and high temperature stability. Often used where high temperature resistance is required. Often associated with metal alloys instead of polymer matrices.
- **Natural fibres** are mostly used in surfacing tissue and rarely as reinforcement, only in 'low-tech' applications.

In the following paragraph a short elaboration follows on the types of natural fibres used in many fibre reinforced polymers.
Based on: (FAO, 2009), (Kolstein 2008)

Natural fibres can be divided in plant fibres, animal fibres and mineral fibres. Animal fibres are mostly used in the textile industry. Those used for industrial and structural purposes are plant fibres, especially those made from the stem and leaves of plants.
Plant fibres include seed hairs (trichome) such as cotton, stem fibres, leafs fibres, and husk fibres such as coconut.

Some of the natural fibres used are:

- **Abaca:** Abaca is made from the leaves of the abaca plant also called Manila hemp (*Musa Textilis).*
- **Coir:** Obtained from the tissue surrounding the seed of the coconut palm.
- **Sisal:** Inexpensive natural fibres used in phenolic based matrix but rarely with polyester or epoxy. Produced from the leaves of the agave plant (*Agave Sisalana*)
- **Jute:** Naturally occurring cheap fibres used in mostly in third world countries. Advised not to use in thermoplastic resin due to its low bonding strength properties. Extracted from the bark of the white jute plant (*Corchorus Capsularis*).
- **Hemp:** Obtained from the stem of the *Cannabis Sativa* plant
- **Flax:** Obtained from the stem of the (*Litnum Usitatissimum*) plant.
- **Ramie:** Made from the bark of the commonly known China grass (*Boehmeria Nivea*).

3.3.1.5. Application of reinforcements

Reinforcement can be applied in different forms. Each form can provide the composite with different mechanical properties. Some of these forms are:

- **Continuous filament roving.** Spool of filament made of consistent parallel strands.
- **Chopped strands** are mostly used for coating to give a more equal surface to the composite using a spray lay-up method (by hand or with the use of automotive machines).
- **Chopped strand mat [CSM]**, also known as needle mat, consists of chopped rovings spread uniformly and bonded together to form a mat. In order to bond the rovings together two types of binders can be used, namely powder or liquid. Examples are polyvinyl acetate emulsion (liquid) and bi-phenol polyester (powder). Usually the binder content is between 3-6%
  CSM's have good wet-out characteristics. They are compatible with polyester resins, though not with epoxy resins except for mats with powder binders.
- **Continuous strand mat/Continuous filament mat [CFM] c**onsists of multiple layers of continuous glass fibres randomly deposited in a swirl-like pattern. The fibres are bonded in a similar way as with CSM.
- **Woven fabrics** can be divided into two classes, one made by rovings and the other made from yarn. Yarn is made twisting sized continuous filament.

Woven fabrics are available in different weaves, see figures 3.16 to 3.21:

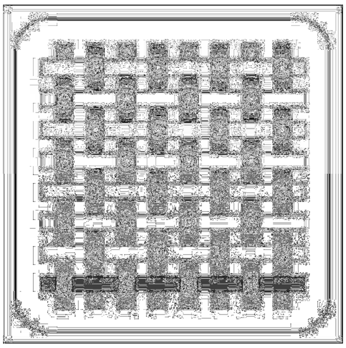


Fig. 3.16: Plain weave
(Gurit, 2013, page 35)

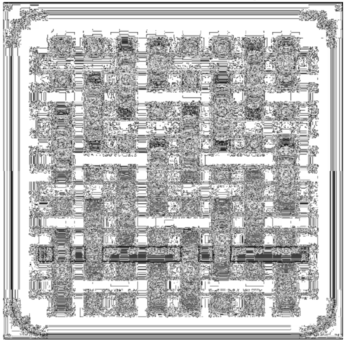


Fig. 3.17: Twill weave
(Gurit, 2013, page 35)

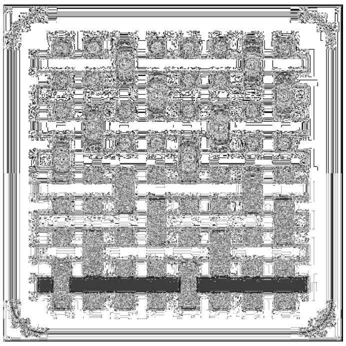


Fig. 3.18: Satin weave
(Gurit, 2013, page 36)

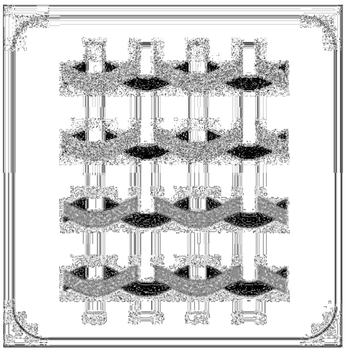


Fig. 3.19: Leno weave
(Gurit, 2013, page 36)

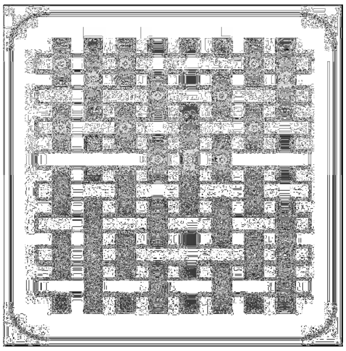


Fig. 3.20: Mock leno weave
(Gurit, 2013, page 36)

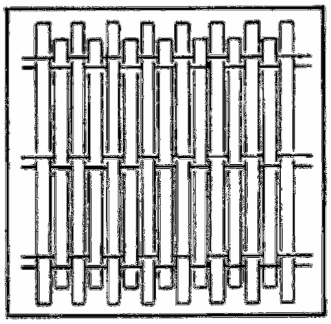


Fig. 3.21: Unidirectional weave
(Kolstein, 2008, page 3.7)

If woven mats are used alone there is a tendency for delamination, to prevent this chopped strand mats are laid in between the each layer. This is especially done when the composite is thick.

3.3.2. Resins

Resins are used to bind the fibres into a single unit providing the mechanical properties and preventing the fibres to buckle under compression. They also serve as protection against chemical and environmental agents. Two types of resins can be distinguished: thermosets and thermoplastics.

Thermoplastics soften every time they're heated, that is why curing needs to be done at higher temperatures. Thermosets permanently set after curing and do not soften or dissolve afterwards, so they can be cured at room temperature. This is one of the main reasons they are used in Civil Engineering. Because of the size of the structures it would be difficult to cure them at high temperatures, however, there is also a growing interest because of their toughness, resilience and corrosion resistance.

3.3.2.1. Unsaturated polyester resins

Unsaturated polyester resins, also known as polyester resins, are the most often used type of resin. They are especially used in the marine industry because of their good water resistance properties and they are also easily available, and economical.

Polyester resins are polymer chains dissolved in a reactive solvent (such as styrene), a catalyst and accelerator are added to form a solid. The addition of styrene reduces the viscosity of the resin making it easier to handle. It also allows the resin to cure without the use of high pressure equipment. Therefore they are referred to as low density resins. Mainly two types of polyester resins are used:

- Ortho-phthalate polyester is standard economic resin used by many people
- Iso-phthalate polyester resin is now becoming preferred due to its superior water resistance.

Other polyester resins have been developed, such as bi-phenol, with improved mechanical and chemical properties.

3.3.2.2. Vinyl ester resins

Vinyl esters are similar to polyester resins that were especially developed for the manufacture of plastic components in corrosive environments. They have a higher chemical resistance, high resilience and toughness, and a uniformed cured structure with reduced internal stresses. The reason for this is that they have less 'ester-groups', which are the parts that couple to each other through the styrene. Due to a better water and chemical resistance it is sometimes used as a protective coat for polyester laminates. In order to achieve a tougher material it has to be post-cured at a higher temperature.

3.3.2.3. Epoxy resins

One of the main advantages over polyester resins are: higher mechanical properties, resistance to environmental degradation, and low shrinkage during cure. Shrinkage during curing is about 1-2% but can be reduced to virtually zero by adding fillers. Another advantage is that they can be obtained from a wide range of components giving them great versatility.

A cured epoxy is resistant to moisture and chemicals, has good insulating properties, and when cured above service temperature better properties can be reached. A disadvantage of this type of resin is their higher viscosity which makes them harder to apply.

3.3.2.4. Other Thermosetting resins

- **Polyimide resins**
  Best thermally stable organic resin, low chemical resistance and high water absorption. Post-cured at 400C° to obtain thermal stability. Condensation during curing makes them difficult to process, they are brittle after curing and are extremely costly.
- **Phenolic resins**
  Have high fire resistance performance, good thermal stability, acceptable electrical properties, and good water and chemical resistance except for alkalis. Condensation during curing can lead to inclusion of voids and surface defects. No high mechanical properties and brittle behaviour. Frequently used in laminating applications.
- **Furane resins**
  Have exceptional chemical resistance except in oxidizing conditions. Requires acidic catalyst to cure like phenolic resins.
- **Silicone resins**
  Based on inorganic material, silicon. They have outstanding thermal stability and good electrical properties. Though compared to other resins they have poor mechanical strength, poor chemical resistance, and higher costs.

3.3.3. Cores

Sandwich constructions are often used to improve the structural efficiency of composites. Core materials can provide stiffness, thermal insulation, and light weight properties to composite structures.
Cores come in different types and can be made out of different materials.

3.3.3.1. Solid cores

Lightweight materials such as balsawood and cedar are often used.

3.3.3.2. Foams

Foams are often used is core material because of their lightweight. They are mostly made of plastics such as PVC and PVDC (polyvinyl chloride and polyvinylidene chloride). Foams can divided into three types

- **Non-structural foams** have low density and can be applied where no/low compression and shear rigidity is required.
- **Structural foams** consist of full density skins and cellular cores, thus have good compression and shear rigidity.
- **Reinforced foams** are usually reinforced with short glass fibres, applied to increase stiffness of the foam.

3.3.3.3. Honeycombs

Honeycombs can be made from paper, glass fibre laminate, metal, or other thin sheet material. They are made in the shape of ‘honeycombs’, which provides high structural performance in direct compression and shear.

3.4. Manufacturing processes

The end properties of a composite are not only a function of the properties of the individual materials that form the composite, but also of the design of the material and the manufacturing process used.
Based on: (Weatherhead, 1980), (Hancox, 1981), (Kolstein, 2008)

3.4.1. Open mould

3.4.1.1. Contact moulding

Hand lay-up

Initially a gel coat is laid on the mould, it is then left to gelatinise. Alternative layer of resin and reinforcement are then laid by hand. Fibres are laid and impregnated with resin by hand. Although low in productivity and little control of the thickness uniformity over the area this method is widely used because of the flexibility and the low cost of the needed tools.

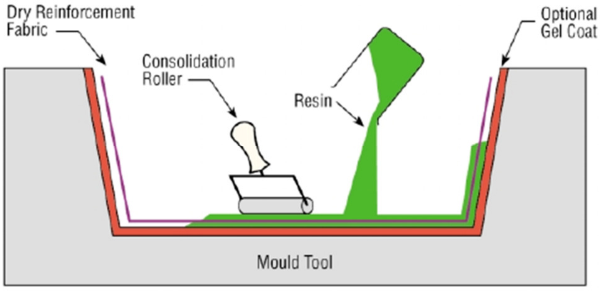


Figure 3.22: Hand lay-up *(Gurit, 2013, page 49)*

Spray lay-up

Chopped fibres and resin are sprayed onto the mould with a spray gun. The spray gun can be man or machine operative. Like with hand lay-up tooling is rather inexpensive and there is little control over the uniformity of the laminate. Although if spray gun is machine operated the process can be quite fast. Also uniformity in the thickness and a more controlled composition of the resin/fibres mixture of the laminate can be achieved.
Disadvantages are that it consists of short fibres and a high resin concentration with low viscosity limiting the mechanical properties.

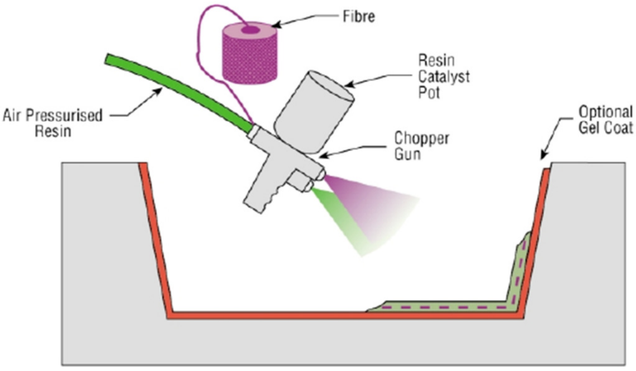


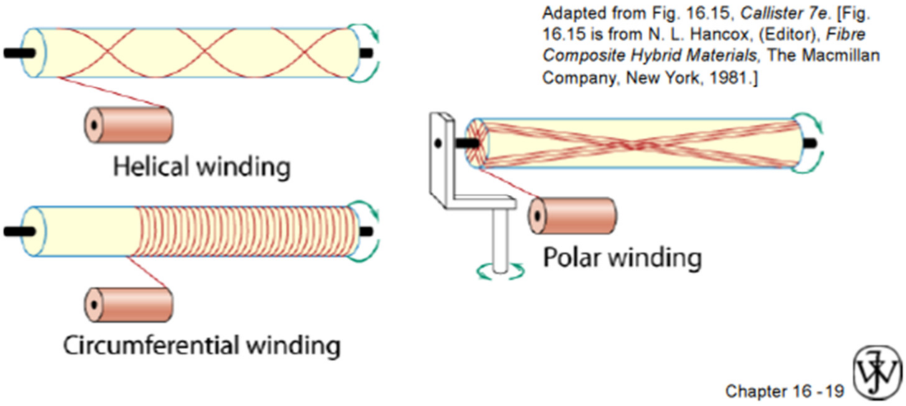
Figure 3.23: Spray lay-up *(Gurit, 2013, page 48)*

3.4.1.2. Saturation

Saturation is similar to hand lay-up, the difference is that in this case the resin is not applied by pouring it on to the mould but by making use of a spray gun. The resin and the catalyst are mixed in the gun, making it only possible to use low viscosity resins. An advantage, above the hand lay-up process, is a better resin control.

3.4.1.3. Filament winding

Filament windings are feed through a resin bath, the excess resin is removed by nip rollers and then they are wraps around a rotating mould (mandrel). The properties the section will have are controlled by orientation of the fibres, the speed of the fibre feeding mechanism, and the rotation rate of the mandrel. The orientation of the fibres gives the laminate certain structural properties, so that the fibres can be laid to match the applied loads/ the needed properties.
This manufacturing process is used for hollow, circular or oval sections e.g. pipes.



Adapted from Fig. 16.15, *Callister 7e*. [Fig. 16.15 is from N. L. Hancox, (Editor), *Fibre Composite Hybrid Materials*, The Macmillan Company, New York, 1981.]

Figure 3.24: Filament winding *(Schumacher, 2009)*

Figure 3.25: FRP pipe production, by filament winding *(Fibrex)*

3.4.1.4. Spray winding

This method combines both spray lay-up and filament winding. Alternating layers of chopped fibre and continuous fibre strands wound on to a rotating former. It is more costs effective than filament winding, though the chopped fibre components have lower strength than continuous strands components.

3.4.1.5. Centrifugal moulding

Used to produce hollow sections, resin and fibres are sprayed onto the moulding while it rotates at high speed. The centrifugal acceleration forces the material onto the mould resulting in dense material, the fibres, to concentrate at the outer surface, making the inner part resin rich.

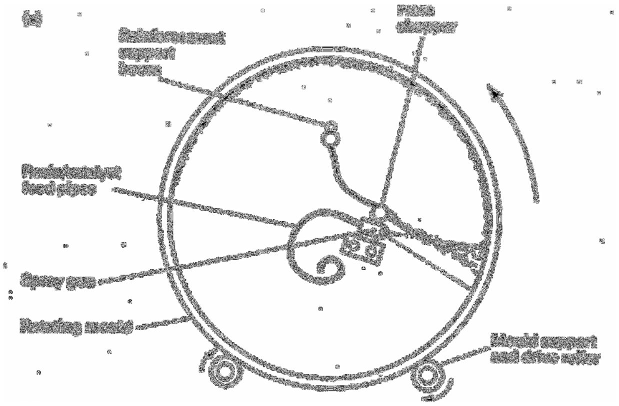


Figure 3.26: Centrifugal moulding *(Kolstein, 2008, page 4.8)*

3.4.2. Closed mould

3.4.2.1. Vacuum bag moulding

This can be considered an extension of the hand laminating process. After laminate is done a release film followed by a bag is placed over the mould clamped at both sides. The air is then pumped out of the area between the mould and the bag creating a vacuum, consolidating the laminate. Rolling on the outside of the bag will give a better consolidation. However, atmospheric pressure is not sufficient to distribute the resin and impregnate the fibres, so a good hand lay-up needs to be performed. Another advantage is that emissions during curing are reduced.

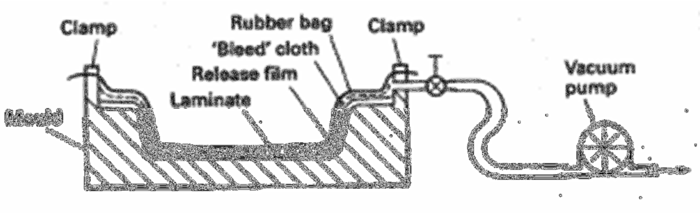


Figure 3.27: Vacuum bag moulding *(Kolstein, 2008, page 4.10)*

3.4.2.2. Pressure bag moulding

Similar to vacuum moulding, only in this case more pressure is applied providing a better consolidation and fibre content of the laminate. Although because of the higher pressure the mould must be stronger. This method also allows for the use of prepreg (pre-impregnated) systems.

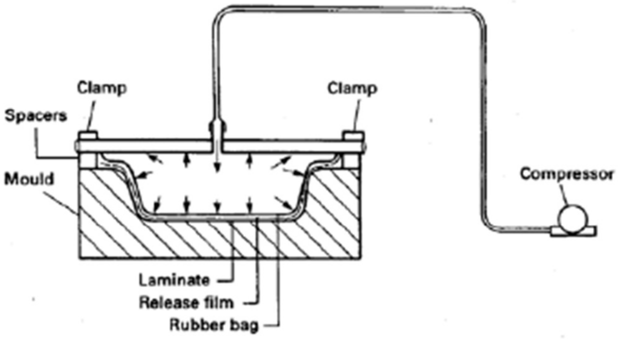


Figure 3.28: Pressure bag moulding *(Kolstein, 2008, page 4.11)*

3.4.2.3. Autoclave

The autoclave process is a combination of both vacuum and pressure bag moulding, exclusively used with prepreg systems. The laminate is build out of prepreg fibres, which are placed on the mould. Then a vacuum bag is placed over the mould and is partially vacuumed. The mould is then placed in a vacuum, pressurized and heated in a chamber to speed up curing. This method ensures that no air remains in the laminate. An advantage is that mould is not subjected to large pressures.

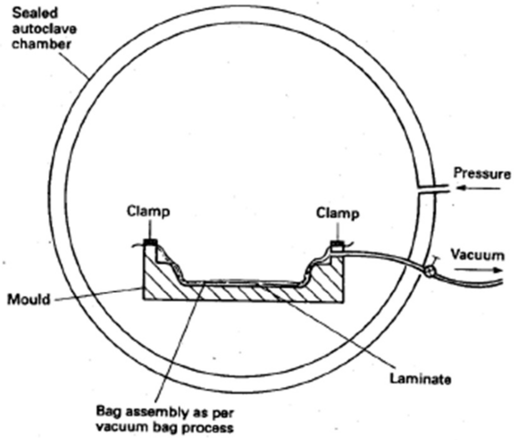


Figure 3.29: Autoclave *(Kolstein, 2008, page 4.12)*

3.4.2.4. Resin injection or resin transfer moulding (RTM)

Dry fibres are loaded on to the mould, the mould is then closed and resin is pumped in between the mould. Vacuum may be applied to help the resin to better penetrate the fibres and make the resin injection faster. This method is also called vacuum assisted resin injection (VARI).
Can also be done by vacuum bagging an open mould, this is called vacuum impregnation/injection.

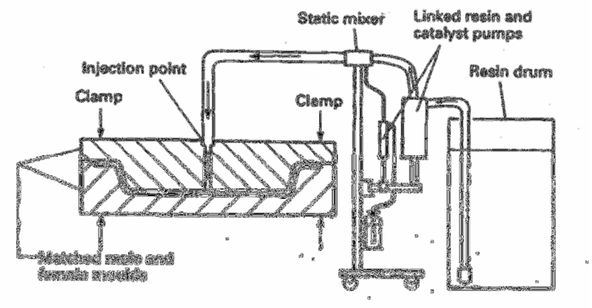


Figure 3.30: Resin injection moulding *(Kolstein, 2008, page 4.18)*

3.4.2.5. Leaky mould

The fibres and resin are placed in the female part of a mould by hand laminating. The male part is then pressed onto the female part. The mould is clamped together and let to cure. This method gives accurate dimensions and a good and smooth finish on both sides of the laminate.

3.4.2.6. Cold press moulding

Dry fibres are loaded on to the mould and the required amount of resin is poured on the mould, the mould is then closed and pressure is applied. After curing, the mould is opened and the parts are taken out. Cold press moulding allows for two smooth sides and requires the set of mould to it properly.

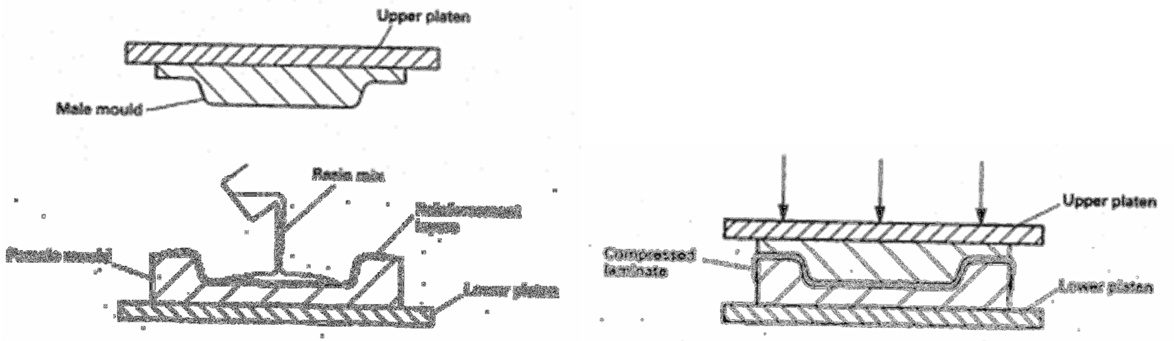


Figure 3.31: Cold/Hot press moulding *(Kolstein, 2008, page 4.14)*

3.4.2.7. Hot press/matched metal moulding

Hot press moulding can be carried out as cold press moulding with dry fibres and liquid resin or with preperg systems. The added temperature makes the curing process faster.

3.4.2.8. Injection moulding

Usually used with thermoplastic resins, could be adapted for the use of thermosets. When making a composite, the fibre and resin mixture is loaded into the hopper and forced into the mould by a piston. This may cause degradation of the fibres. Another disadvantage is that the orientation of the fibres cannot be controlled.

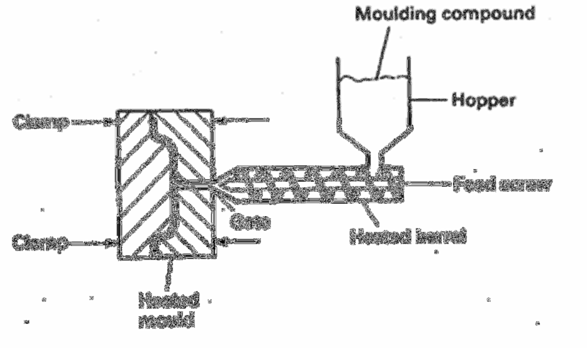


Figure 3.32: Injection moulding *(Kolstein, 2008, page 4.21)*

3.4.3. Continuous Processes

3.4.3.1. Continuous sheet manufacture

Impregnated fibres between two layers of release film are pulled through needing rollers into a curing oven and as they emerge from the oven the release film is pulled off and the laminate is cut to the desired length. This process can be cost attractive, due to the continuous process, although only simple shapes are possible.

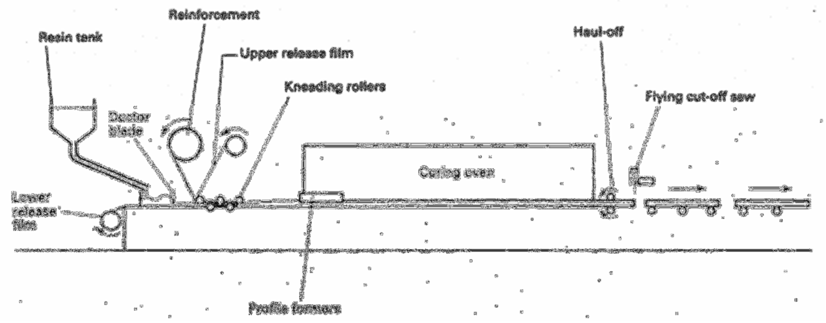


Figure 3.33: Continuous sheet manufacture *(Kolstein, 2008, page 4.23)*

3.4.3.2. Pultrusion

Fibres are pulled through a resin bath into a heated die. In the die the fibres are cured into the final shape. The tension imposed on the fibres gives good longitudinal properties, where transverse strength is required woven fabrics or mechanically bound mats can be incorporated. Because of the continuous pulling of the fibres through the die, only constant cross-sections can be made. Manufacturing costs can be low.

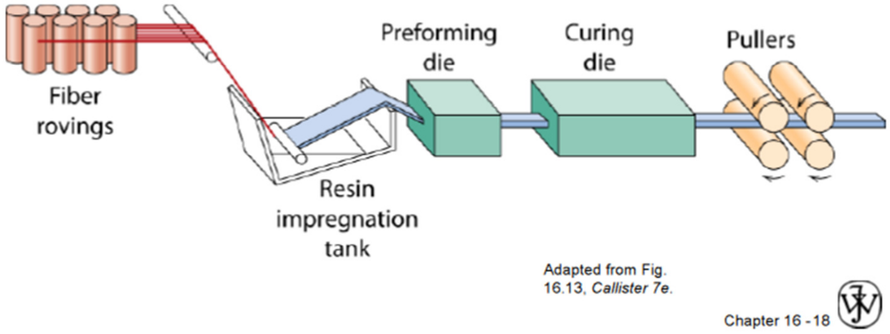


Figure 3.34: Pultrusion *(Schumacher, 2009)*

3.4.3.3. Continuous filament winding

Like described under filament winding, continuous filaments are wound-up around a rotating mandrel. In this case the mandrel continuously collapses at the end of the process, after emerging from a curing oven, and reform at the beginning of the process into a cylindrical form.

Figure 3.35: Continuous filament winding *(ZCT)*

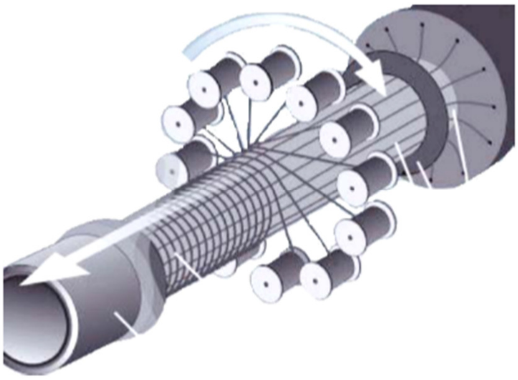


Figure 3.36: Schematization Continuous filament winding *(Chlosta, 2012, page 70)*

4. MATERIAL PROPERTIES OF FRP

4.1. Mechanical properties

Based on: (Clarke, 1996), (Nijhof, 2004), (Chlosta, 2012), (CUR, 2009), (Zenkert, 1995), (Gurit, 2013)

FRP is anisotropic this means that the properties of the material are different in every direction, and they are also heterogeneous. However commonly in calculations the material is assumed to be homogeneous, not taking into account the effects of load variations. Due to the fact that they have a small effect on the mechanical properties, the assumption that for design purposes the laminate can be seen as homogeneous is quite accurate. (For the dynamic behaviour this could be of importance because the effects of loading variations on the material properties also alter the eigen frequencies of the gate.)

Although the material properties are different in every direction the assumption is made, to simplify the calculations, by assuming an orthotropic (with different properties in only 2 directions) material. This means that there are two principle directions where the material properties vary.

Mechanical properties are determined by:

- The properties of the fibre
- The properties of the resin
- The ratio fibre to resin (FVF – Fibre Volume Fraction)
  The FVF is mostly determined by the manufacturing process, in the boat-building industry FVF values of 30-40% can be reached and in the aerospace industry where better manufacturing processes have been developed FVF values of up to 70% can be achieved.
- The geometry and the orientation of the fibres
  The highest mechanical properties are parallel to the fibres.

4.1.1. Fibre/Resin ratio

Prior to the prediction of the elastic properties the volume fractions have to be determinate.
Based on: (Clarke, 1996), (Nijhof, 2004), (Chlosta, 2012), (CUR, 2009), (Zenkert, 1995) and (Gurit, 2013)

Weight fractions:

$$\mathrm{w_f} + \mathrm{w_m} = 1 \tag{4.01}$$

$$\mathrm{w_f} = \frac{\mathrm{W_f}}{\mathrm{W}} \quad ; \quad \mathrm{w_m} = \frac{\mathrm{W_m}}{\mathrm{W}} \qquad (4.02)\&(4.03)$$

$$\rho = \frac{\mathrm{W_f} + \mathrm{W_m}}{\mathrm{V_f} + \mathrm{V_m}} = \frac{\mathrm{V_f} \cdot \rho_\mathrm{f} + \mathrm{V_m} \cdot \rho_\mathrm{m}}{\mathrm{V_f} + \mathrm{V_m}} \tag{4.04}$$

$$\rho = \mathrm{v_f} \cdot \rho_\mathrm{f} + \mathrm{v_m} \cdot \rho_\mathrm{m} \tag{4.05}$$

$$\mathrm{v_f} = \frac{\frac{\mathrm{W_f}}{\rho_\mathrm{f}}}{\frac{\mathrm{W_m}}{\rho_\mathrm{m}} + \frac{\mathrm{W_f}}{\rho_\mathrm{f}}} = \frac{\mathrm{w_m} \cdot \rho_\mathrm{f}}{\mathrm{w_m} \cdot \rho_\mathrm{m} + \mathrm{w_f} \cdot \rho_\mathrm{f}} \quad ; \quad \mathrm{v_m} = \frac{\frac{\mathrm{W_f}}{\rho_\mathrm{f}}}{\frac{\mathrm{W_m}}{\rho_\mathrm{m}} + \frac{\mathrm{W_f}}{\rho_\mathrm{f}}} = \frac{\rho_\mathrm{f}}{\mathrm{w_m} \cdot \rho_\mathrm{m} + \mathrm{w_f} \cdot \rho_\mathrm{f}} \qquad (4.06)\&(4.07)$$

$$w_f = \frac{W_f}{W} = \frac{V_f \cdot \rho_f}{V \cdot \rho} = \frac{\rho_f}{\rho} \cdot v_f \quad ; \quad w_m = \frac{W_m}{W} = \frac{V_m \cdot \rho_m}{V \cdot \rho} = \frac{\rho_m}{\rho} \cdot v_f \qquad (4.08)\&(4.09)$$

$$\frac{1}{\rho} = \frac{v_f + v_m}{\rho} = \frac{m_f}{\rho_f} + \frac{m_m}{\rho_m} \qquad (4.10)$$

Volume fractions:

$$v_f + v_m = 1 \qquad (4.11)$$

$$v_f = \frac{A_f}{A} \quad ; \quad v_m = \frac{A_m}{A} \qquad (4.12)\&(4.13)$$

With: $A = A_f + A_m$ (4.14)

4.1.2. *Stiffness analysis*

Assumption of material behaviour is that for short term loading material behaves linear elastic to ultimate failure. And under long term loading the material is linear viscoelastic with recovery on removal of load, providing the strain does not cause permanent material deterioration.
(Clarke, 1996)

In this chapter the models for the determination of properties of unidirectional composites will be given.
Unidirectional composites have a principal direction, the longitudinal direction (giving by a subscript L), and the transverse direction (giving by a subscript T). For more than two components the expressions below can be extended.
Definition unidirectional continuous lamina: *(EUROCOMP, page 99)*

- Has higher stiffness and strength in the direction of the fibre
- Stiffness and strength dominating by the matrix properties in the transverse direction
- Idealised as orthotropic

4.1.2.1. Lamina stiffness

Several methods exist to predict the elastic properties of unidirectional reinforced composites. Some of the most commonly used methods will be described below.
(The properties of the fibre and the matrix are indicated by a subscript f and m respectively.)

RoM method *[(Gurit, 2013) and (Nijhof, 2004)]*
The Rule of Mixtures method is based on the assumptions that there are no voids or imperfections, that there is a uniform stress and strain distribution and it can only be used for determining the upper and lower bounds. The method doesn't contain geometric terms (fibre spacing, fibre shape, packing geometry, etc.) or the degree of bonding, which due influence the properties of the laminates but it is conservative method, values will always be higher.

In longitudinal direction the strain of both components is equal. $\varepsilon_L = \varepsilon_f = \varepsilon_m$

Average stress in the longitudinal direction, when subjected to a force P:

$$\sigma_L = \frac{P}{A} = E_L \cdot \varepsilon_L = \frac{\sigma_f \cdot A_f + \sigma_m \cdot A_m}{A} = v_f \cdot \sigma_f + v_m \cdot \sigma_m = v_f \cdot E_f \cdot \varepsilon_L + v_m \cdot E_m \cdot \varepsilon_L \qquad (4.15)$$

With:

$$E_L = \frac{\sigma_L}{\varepsilon_L} = v_f \cdot E_f + v_m \cdot E_m \qquad (4.16)$$

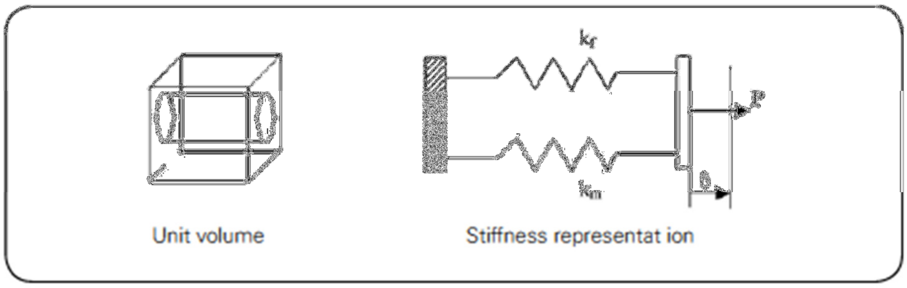


Figure 4.1: Schematization of RoM model for longitudinal properties *(Gurit, 2013, page 13)*

In transverse direction the elastic modulus is as follow:

$$\frac{1}{\mathrm{E_T}}=\frac{\varepsilon_\mathrm{T}}{\sigma_\mathrm{T}}=\frac{\mathrm{v_f}\cdot\varepsilon_\mathrm{f}+\mathrm{v_m}\cdot\varepsilon_\mathrm{m}}{\sigma_\mathrm{T}}=\frac{\mathrm{v_f}\cdot\varepsilon_\mathrm{f}}{\sigma_\mathrm{f}}+\frac{\mathrm{v_m}\cdot\varepsilon_\mathrm{m}}{\sigma_\mathrm{m}}=\frac{\mathrm{v_f}}{\mathrm{E_f}}+\frac{\mathrm{v_m}}{\mathrm{E_m}} \tag{4.17}$$

$$\mathrm{E_T}=\frac{\mathrm{E_m}\cdot\mathrm{E_f}}{\mathrm{v_f}\cdot\mathrm{E_m}+\mathrm{v_m}\cdot\mathrm{E_f}}=\frac{\mathrm{E_m}\cdot\mathrm{E_f}}{\mathrm{v_f}\cdot\mathrm{E_m}+(1-\mathrm{v_f})\cdot\mathrm{E_f}} \tag{4.18}$$

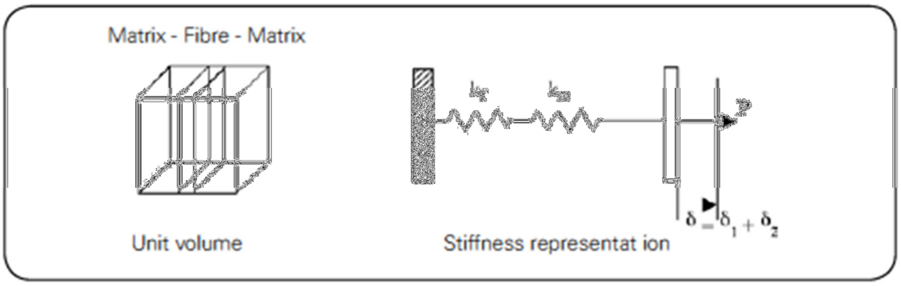


Figure 4.2: Schematization of RoM model for transverse properties *(Gurit, 2013, page 13)*

Longitudinal-transverse Poisson ratio:

$$\nu_\mathrm{LT}=\mathrm{v_f}\cdot\nu_\mathrm{f}+\mathrm{v_m}\cdot\nu_\mathrm{m} \tag{4.19}$$

Transverse Poisson ratio:

$$\nu_\mathrm{T}=\frac{\mathrm{E_T}\cdot\nu_\mathrm{LT}}{\mathrm{E_L}} \tag{4.20}$$

Shear modulus:

$$\mathrm{G_L}=\frac{\mathrm{E_L}}{2\cdot(1+\nu_\mathrm{L})} \quad ; \qquad \mathrm{G_T}=\frac{\mathrm{E_T}}{2\cdot(1+\nu_\mathrm{T})} \qquad (4.21)\ \&\ (4.22)$$

Halpin-Tsai method *(Nijhof, 2004)*
With this method the properties of the lamina are expressed in terms of the properties of the components with the use of only one formula.

$$\mathrm{P} = \frac{\mathrm{P_m} \cdot [\mathrm{P_f} + \xi \cdot \mathrm{P_m} + \xi \cdot \mathrm{v_f} \cdot (\mathrm{P_f} - \mathrm{P_m})]}{[\mathrm{P_f} + \xi \cdot \mathrm{P_m} - \mathrm{v_f} \cdot (\mathrm{P_f} - \mathrm{P_m})} \tag{4.23}$$

P: property
ξ: reinforcing efficiency parameter of the composite material, the extent to which the load is transmitted to the reinforcing phase. Expressed differently depending on the property to be calculated (see table 4.1)

Table 4.1: *(Nijhof, 2004, page 92)*

P	$\mathrm{P_f}$	$\mathrm{P_m}$	ξ
$\mathrm{E_L}$	$\mathrm{E_{L,f}}$	$\mathrm{E_L}$	$2 \cdot \frac{l}{\mathrm{d}}$ ∞ (for filaments)
ν_{LT}	$\nu_{\mathrm{LT,f}}$	$\nu_{\mathrm{LT,m}}$	∞
$\mathrm{E_T}$	$\mathrm{E_{T,f}}$	$\mathrm{E_{T,m}}$	$2 \cdot \frac{\mathrm{a}}{\mathrm{b}}$
$\mathrm{G_{LT}}$	$\mathrm{G_{LT,f}}$	$\mathrm{G_{LT,m}}$	$\left(\frac{\mathrm{a}}{\mathrm{b}}\right)^{\sqrt{3}}$
$\mathrm{G_{TT}}$	$\mathrm{G_{TT,f}}$	$\mathrm{G_{TT,m}}$	$\frac{\mathrm{k}_m}{\mathrm{k}_m + 2 \cdot \mathrm{G_{TT,m}}}$ $\xi = \frac{1}{3 - 4 \cdot \nu_{\mathrm{m}}}$ (for isotropic matrix)

k: compression modulus

As a simplification it can be assumed that the components are isotropic, the formulas of Halpin and Tsai then become:

$$\mathrm{E_L} = \mathrm{v_f} \cdot \mathrm{E_f} + \mathrm{v_m} \cdot \mathrm{E_m} = \mathrm{v_f} \cdot \mathrm{E_f} + (1 - \mathrm{v_f}) \cdot \mathrm{E_m} \tag{4.24}$$

$$\nu_{\mathrm{LT}} = \mathrm{v_f} \cdot \nu_{\mathrm{f}} + \mathrm{v_m} \cdot \nu_{\mathrm{m}} \tag{4.25}$$

$$\mathrm{E_T} = \mathrm{E_m} \cdot \frac{\mathrm{E_f} + 2(\mathrm{v_f} \cdot \mathrm{E_f} + \mathrm{v_m} \cdot \mathrm{E_m})}{\mathrm{v_m} \cdot \mathrm{E_f} + \mathrm{v_f} \cdot \mathrm{E_m} + 2\mathrm{E_m}} \tag{4.26}$$

$$\mathrm{G_{LT}} = \mathrm{G_m} \cdot \frac{\mathrm{G_f} + \mathrm{v_f} \cdot \mathrm{G_f} + \mathrm{v_m} \cdot \mathrm{G_m}}{\mathrm{v_m} \cdot \mathrm{G_f} + \mathrm{v_f} \cdot \mathrm{G_m} + \mathrm{G_m}} \tag{4.27}$$

$$\mathrm{G_{TT}} = \mathrm{G_m} \cdot \frac{(3 - 4\nu_{\mathrm{m}})\mathrm{G_f} + \mathrm{v_f} \cdot \mathrm{G_f} + \mathrm{v_m} \cdot \mathrm{G_m}}{(3 - 4\nu_{\mathrm{m}}) \cdot (\mathrm{v_m} \cdot \mathrm{G_f} + \mathrm{v_f} \cdot \mathrm{G_m}) + \mathrm{G_m}} \tag{4.28}$$

Other methods are: the Tsai-Hahn method, Hashin and Shtrikman method and Puck's Empirical formulas. For an elaborated description of these and other method reference is made to *(Clarke, 1996)*, *(Nijhof, 2004)* and *(CUR, 2009)*.

4.1.2.2. Laminate stiffness

The stiffness is then determined for the laminate making use of the laminate theory.
With the laminate theory the strength and stiffness properties of the laminate (in this case the composite) can be determined.

4.1.3. Laminate theory

Properties of laminate are determined by the properties of the laminas that compose it.
Here it is assumed that the laminas are orthotropic and under a plane, that they have a constant thickness, and there is no shift between the laminas. The laminate works as a whole.

The analysis has its basis on the (orthotropic) plate theory which states that for a thin plate the shear/normal forces in the z-direction in the plate are negligible, because it has a negligible bending stiffness through the thickness. ($\sigma_z = \tau_{xz} = \tau_{yz}=0$)
Based on: (Nijhof, 2004)

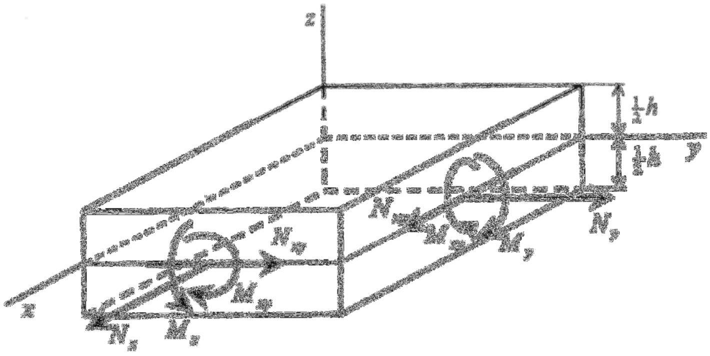


Figure 4.3: Schematization forces acting on plate element *(Nijhof, 2004, page168)*

$$N_x = \int_{-\frac{1}{2}h}^{\frac{1}{2}h} \sigma_x \, dz \quad ; \qquad N_y = \int_{-\frac{1}{2}h}^{\frac{1}{2}h} \sigma_y \, dz \quad ; \qquad N_{xy} = \int_{-\frac{1}{2}h}^{\frac{1}{2}h} \tau_{xy} \, dz$$

$$(4.29) - (4.34)$$

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

Laminas can be regarded as homogeneous and anisotropic. Because of this the stresses in the laminas will be linear. With Hooke's law and these properties the relation between the strains and stresses can be determined.

Strains and stresses:

$$\sigma = E \cdot \varepsilon \ \rightarrow \ \varepsilon = \frac{1}{E} \cdot \sigma \qquad (4.35)$$

$$\tau = G \cdot \gamma \;\rightarrow\; \gamma = \frac{1}{G} \cdot \tau \tag{4.36}$$

$$\varepsilon_x = \frac{du_x}{dx} \quad ; \quad \varepsilon_y = \frac{du_y}{dy} \quad ; \quad \varepsilon_z = \frac{du_z}{dz} \qquad (4.37)-(4.39)$$

$$\gamma_{xy} = \gamma_{yx} = \frac{du_x}{dy} + \frac{du_y}{dx} \quad ; \quad \gamma_{xz} = \gamma_{zx} = \frac{du_x}{dz} + \frac{du_z}{dx} \quad ; \quad \gamma_{yz} = \gamma_{zy} = \frac{du_y}{dz} + \frac{du_z}{dy} \qquad (4.40)-(4.42)$$

Relation between the strains and the stresses:

$$\begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{pmatrix} = \underbrace{\begin{bmatrix} 1/E_x & -\upsilon_{yx}/E_x & 0 \\ -\upsilon_{xy}/E_y & 1/E_y & 0 \\ 0 & 0 & 1/G_{xy} \end{bmatrix}}_{\text{Stiffness matrix}} \begin{pmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{pmatrix} \tag{4.43}$$

$$\begin{pmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{pmatrix} = \underbrace{\frac{1}{1-\upsilon_{xy} \cdot \upsilon_{yx}} \begin{bmatrix} E_x & \upsilon_{yx} \cdot E_x & 0 \\ \upsilon_{xy} \cdot E_y & E_y & 0 \\ 0 & 0 & G_{xy}(1-\upsilon_{xy} \cdot \upsilon_{yx}) \end{bmatrix}}_{\text{Compliances matrix}} \begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{pmatrix} \tag{4.44}$$

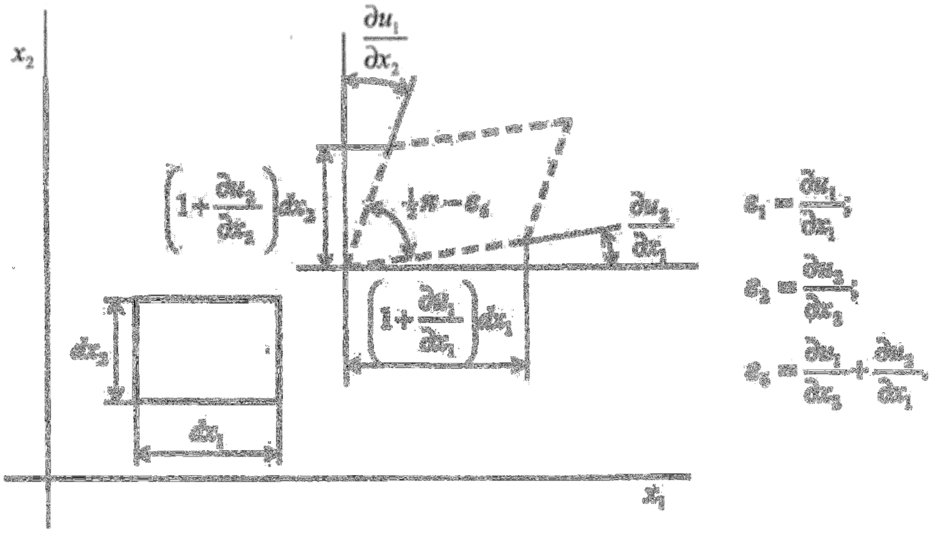


Figure 4.4: Strains present in a plate element *(Nijhof, 2004, page 27)*

The matrices can then be transformed from the local to the global coordinate system through the transformation matrix [T].

$$[T] = [T]^{-1} = \begin{bmatrix} \cos^2\theta & \sin^2\theta & 2\sin\theta\cos\theta \\ \sin^2\theta & \cos^2\theta & -2\sin\theta\cos\theta \\ -\sin\theta\cos\theta & \sin\theta\cos\theta & \cos^2\theta - \sin^2\theta \end{bmatrix} = \begin{bmatrix} c^2 & s^2 & 2sc \\ s^2 & c^2 & -2sc \\ -sc & sc & c^2 - s^2 \end{bmatrix} \tag{4.45}$$

Where θ is the angle of the fibres relative to the main direction within the global coordinate system (the x-direction).
The transformation of the strains and stresses from the local to the global coordinate system is:

$$\begin{pmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{pmatrix}_{\text{Local}} = \begin{bmatrix} c^2 & s^2 & 2sc \\ s^2 & c^2 & -2sc \\ -sc & sc & c^2 - s^2 \end{bmatrix} \begin{pmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{pmatrix}_{\text{Global}} \tag{4.46}$$

$$\begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{pmatrix}_{\text{Local}} = \begin{bmatrix} c^2 & s^2 & 2sc \\ s^2 & c^2 & -2sc \\ -sc & sc & c^2 - s^2 \end{bmatrix} \begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{pmatrix}_{\text{Global}} \tag{4.47}$$

Curvatures:

$$\kappa_x = -\frac{\partial^2 w}{\partial x^2} \quad ; \quad \kappa_y = -\frac{\partial^2 w}{\partial y^2} \quad ; \quad \kappa_{xy} = -2\frac{\partial^2 w}{\partial x \, \partial y} \qquad (4.48) - (4.50)$$

Depending on the position and the thickness of each lamina there contribution to the laminate stiffness is determined. Using the relations given in equations (4.29) to (4.34) and the stress-strain relations in equations (4.43) and (4.44) a matrix can be derived for the relation between forces and bending moments to strains and curvatures.
This relation is then used to determine the deformations of the laminate with respect to the global coordinate. Then the can be transformed with the transformation matrix [T] and checked against the failure criteria.

In the chart below (figure 4.5) an overview is given of the steps to be taken when designing a laminate with the laminate theory. First the properties of each lamina are derived, depending on their composition and fibre orientation. Then the properties of the laminate are determined for a chosen configuration of the laminas that form the laminate, deriving the stiffness matrix and then the compliances matrix. From which the strains and stresses in the laminate can be derived.

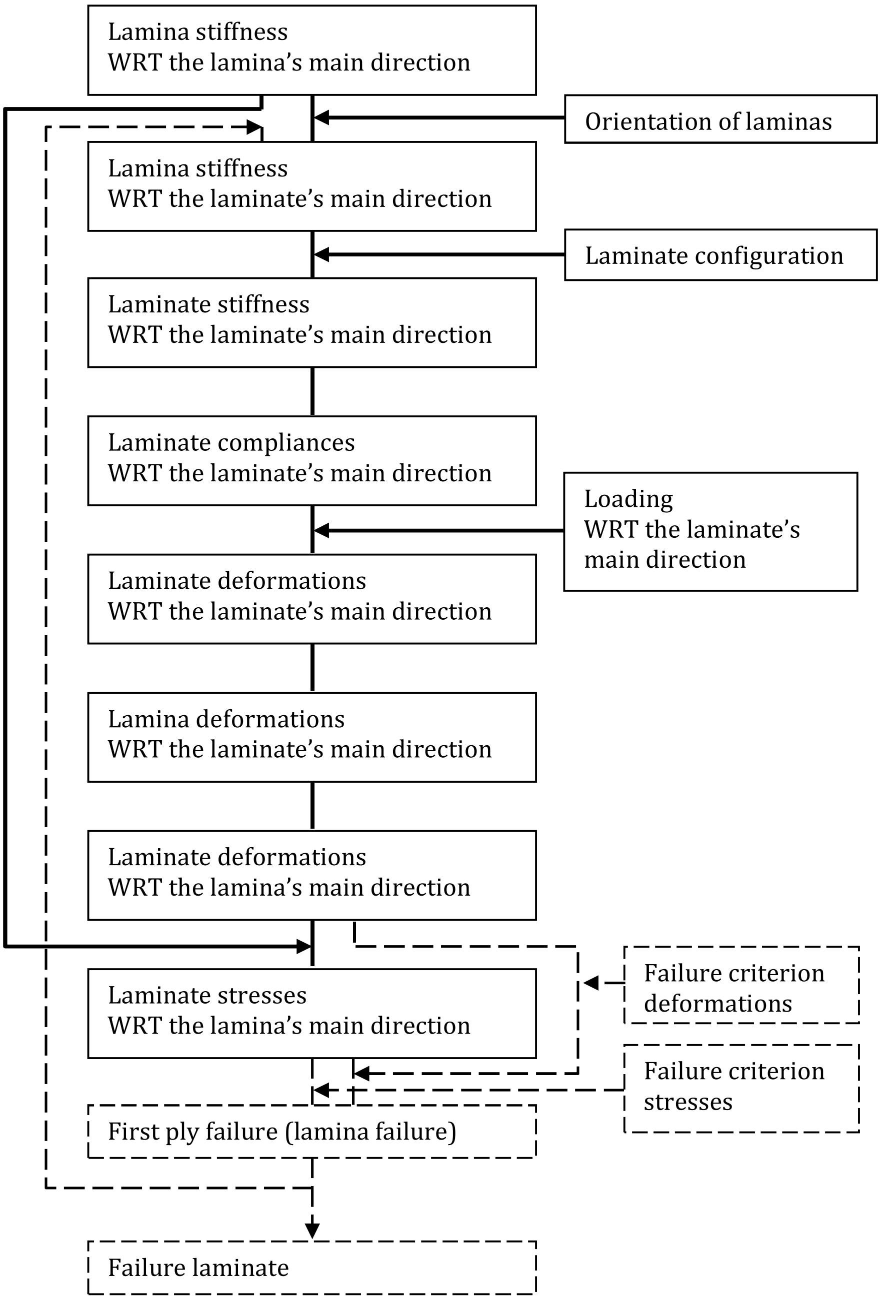


Figure 4.5: Flow chart for stiffness and strength analysis of a laminate with the use of the Laminate Theory. *(Nijhof, 2004, page 177)*

4.1.4. Strength analysis

Strength analysis can also be done with the use of the laminate theory. After determining the laminate stresses, see figure 46, the laminate can be check with the use of failure criteria. Some of these failure mechanisms will be described below.

Tsai-Wu *(Nijhof, 2004)*
The Tsai-Wu failure mechanism makes a global analysis of the structural system by using the interaction between the various strength components.
The criterion for the plan stresses is given by:

$$\left(\frac{1}{\sigma_{1,t,R}}+\frac{1}{\sigma_{1,c,R}}\right)\cdot\sigma_{1,j,S}+\left(\frac{1}{\sigma_{2,t,R}}+\frac{1}{\sigma_{2,c,R}}\right)\cdot\sigma_{2,j,S}-\frac{\sigma_{1,j,S}^2}{\sigma_{1,t,R}\cdot\sigma_{1,c,R}}-\frac{\sigma_{2,j,S}^2}{\sigma_{2,t,R}\cdot\sigma_{2,c,R}}+\frac{\tau_{12,S}^2}{\tau_{12,R}^2}-\frac{\frac{1}{2}\cdot\sigma_{1,j,S}\cdot\sigma_{2,j,S}}{\sqrt{\sigma_{1,t,R}\cdot\sigma_{1,c,R}\cdot\sigma_{2,t,R}\cdot\tau_{2,c,R}}}\leq\left(\frac{1}{\gamma_m\cdot\gamma_f\cdot\gamma_c}\right)^2 \qquad (4.51)$$

Formula (4.51) considers interaction between the various stress components and requires prior knowledge of the lamina's longitudinal tension and compression strength, and transverse tension and compression strengths and shear strengths in the longitudinal-transverse plane.
For multiple ply laminates it should be evaluated for both stress components parallel to and perpendicular to the fibre directions, for each lamina.

Hart-Smith *(EUROCOMP, 1996)*
This theory considers multiple failure modes by superposition in contrast to Tsai-Wu where there is assumed there is interaction between the various stress components.
In case of laminate design the stresses in plane are typically zero and can thus be neglected, the maximum-shear-stress criterion imposes a limit in the remaining two principal stresses.
The maximum-shear-stress criterion states that yield occurs whenever the maximum shear stress, reaches a critical point.
The failure envelope can be adjusted with different Poisson's ratios for an orthotropic material.
Failure envelope of laminate is constructed by superimposing the failure envelopes of the lamina.

First ply failure criterion *(Nijhof, 2004)*
The strength of the laminate is related to the manner of loading. To make a stress analysis first the stiffness analysis has to be done per lamina (w.r.t. the main direction of the lamina) for a given load. These results are then compared with the result obtained from the calculation of the failure criteria on the level of the lamina.
Because the relations given in the laminate theory are linear, it is sufficient to apply a unity load to reach the ultimate strength criterion of the lamina. The smallest factor determines the loading at which the first lamina will fail, the so-called 'first ply failure' (F.P.F.) load. The load at which the laminate fails is also the load at which the lamina fails.

Although in reality the laminate doesn't always fail at this load, but the other laminas can take up the additional load. To calculate the ultimate strength if this load can be exceeded, the strength analysis is carried out again but this time assuming that the strength of the lamina that fail is equal to zero.

4.2. Durability

The durability of FRP composites is assumed to be high due to its use in the aerospace industry, where FRP components are subjected to high stresses and tough environmental conditions e.g. high temperatures, UV radiation, and humidity. Also their use in the chemical industry where they endure corrosive/acrid chemicals, have proven FRP to be quite resistant. The high resistance of this material can also be seen in the marine industry where FRP composites have been successfully used for many centuries.

Despite of this the limited experience with this material means that the durability in the long term is not yet fully known, because it has only been used for about 60 years. Besides the fibre reinforced polymers used in other markets varies from those for structural use. FRP has only been used in civil engineering for the last 20 years, thus substantiated data of the long term durability of FRP structures is unavailable.

One of the degradation agents that have a great effect on FRP is water, especially water vapour. In wet conditions the rate of growth of fatigue cracks in cyclic loading accelerates. Other factors that contribute to degradation of FRP are: oxidation, UV radiation, frost, thermal aging/cycling, exposure to high temperatures, fatigue resistance, creep and relaxation, and chemical attack. *(Hancox, 1981)*

Because lock gates are constantly in a wet environment the focus in this chapter will be on the degradation due to water and UV-radiation will also be discussed.

Based on: (Gurit, 2013), (Clarke, 1996), (Walter, 1982), (Campbell 2010), (Weatherhead, 1980) and (Karbhari, 2003)

4.2.1. Water degradation

All laminates in a wet environment will permit low quantities of water to pass through them in vapour form. Water absorption leads to an increase in weight and a decrease in stiffness, and in time this also affects the ultimate mechanical properties of the FRP. Water absorption can especially be a problem for polyester based resins.

Degradation can happen at different levels of a composite, at different rates, and having different consequences.

At the resin level properties of the matrix are affected in several ways:

- Water absorption causes the composite to swell, producing strains in the through-thickness direction.
- Plasticization can be beneficial to a certain point because it makes the resin more ductile.
- If water is trapped in micro-cracks or delamination, when the water freezes it expands causing extra pressure, leading to larger cracks or delamination.
- On the other hand when exposed to high temperatures, e.g. for high temperature repairs, the water in the composite will vaporize increasing the pressure also leading to cracks and delamination. This leads to more water absorption. Therefore one has to be careful, when repairing FRP composites with bonded adhesives, that the composite is properly dried.

- Another mechanism is osmosis. Water passing through the composite reacts with any hydrolysable (that can be dissolved in water) components that can be present inside the laminate, forming tiny cells of concentrated solution.
  During the cycle of osmosis more water is drawn in to dilute this solution, increasing the water pressure in the cell. Eventually causing the laminate or gel coat to distort and even burst. Some hydrolysable components are dirt and debris that has been trapped during manufacturing, but also the ester linkages in cured polyester and to a lesser extent vinyl ester.

Between the resin and the fibres, at the fibre-matrix interface water intrusion can cause loss of integrity of the bond, which can have consequences for the mechanical properties of the laminate. In a carbon fibre reinforced composite the fibre-matrix interface is usually relatively stable.

At the fibre level the effect of moisture is highly dependent on the fibre type applied. Carbon fibres are generally unaffected by most moisture conditions, while moisture and chemicals have shown that in the case of aramid and glass fibres they cause degradation at the fibre level. In glass fibres the effects are mostly on the surface.

The effects of water degradation can be minimized in sometimes avoided by applying a resin with a low water transmission rate and high resistance against water, reinforcements with similar resistant surface treatment and laminated to a very high standard, and through the selection of appropriate resin systems, processing conditions, and the application of gel coats and protective coatings.

4.2.2. UV resistance

UV radiation has wavelength from 290-400nm at this range polymers have bond dissociation energies, bond dissociation energy is the energy that is required to break a molecule of the bond, decomposing it into atoms, because of this they are greatly affected by it. This damage is generally limited to darkening of the resin at the surface layer. In general polyester resins are more resistant to UV radiation than epoxies. The great danger with UV-radiation is that in affected areas the moisture ingress increases. This can lead to loss in mechanical properties. (See chapter 4.2.1.)

To prevent UV damage standard marine paint, pigmented gel coatings, and poly-urethanes has been used. However, it must be noted that the use of polymeric protective coating does not prevent UV-induced damage from occurring, but rather serves as a "self-sacrificing" layer to prevent the FRP composite from being directly exposed to UV radiation. This protective coating will eventually degrade and will have to be maintained.

Another method that has been used in the past to overcome degradation due to exposure to sunlight is adding up to 1% UV light stabiliser to the resin system. The compounds used for this purpose are hydroxybenzophenone derivatives such as 2-hydroxy-4-methoxybenzophenone, phenyl salicylate and acetylsalicylic acid. These compounds may be used in combination with thriethyl phosphite and epoxidised oils.

4.2.3. Fatigue

Fatigue is the degradation on mechanical properties due to cyclic stresses, much lower than the stress required to cause failure during a single application. Cyclic stresses are stresses that fluctuate in time. These stresses lead to cracking of the material, the number of cracks and their size increases in time, eventually leading to failure.

Factors needed to cause fatigue are:

- A maximum stress of sufficiently high value.
- A large enough fluctuation in the applied stress.
- A sufficiently large amount of cycles of the applied stress.

There are three types of fluctuating stresses:

- Fully reversed stress cycle; applied where maximum and minimum stresses are equal.
- Repeated stress cycle; a mean stress applied on top of the max and min stresses.
- Random or spectrum stress cycle; subjected to random loads.

In comparison with metals FRP composites exhibit better fatigue resistance due to their high fatigue limit. Fatigue limit is the stress amplitude below which failure doesn't occur even after large numbers of cycles. This limit is found to be around 10^7 cycles in comparison with metal which is 10^6 cycles.

Fatigue failure mechanisms in composites are different from those in metals. In metals a single crack appears and continues to grow until it becomes so long that the remaining section cannot support the load. While in composites different kinds of damage occur at different locations and eventually link up causing failure.
There are 5 main failure mechanism, namely matrix cracking, fibre fracture, crack coupling, delamination initiation, delamination growth and fracture. These failure mechanisms are divided under three phases of damage progression:

- **Phase 1**: Matrix cracks develop due to tension loads in the off-axis plies until they reach a steady state, this steady state is a function of the lamina/ply thickness and the material properties. These cracks can be a source of moisture ingression, which accelerates the failure process.
- **Phase 2**: Fibre fracture is initiated by high concentration stresses caused by the matrix cracks in the off-axis laminas reaching the zero-degree lamina, which stop the cracks and leads to high stress concentrations. This also induces longitudinal cracks running parallel to the fibres and perpendicular to the matrix cracks. The combination of longitudinal and matrix cracks is called crack coupling. Later on in phase 2 large interlaminar stresses at the intersection between longitudinal and matrix cracks develop due to crack coupling, leading to initiation of delamination.
- **Phase 3**: Delamination start growing between the lamina interfaces, eventually leading to isolation and eventually failure of the zero-degree lamina, and failure of the composite.

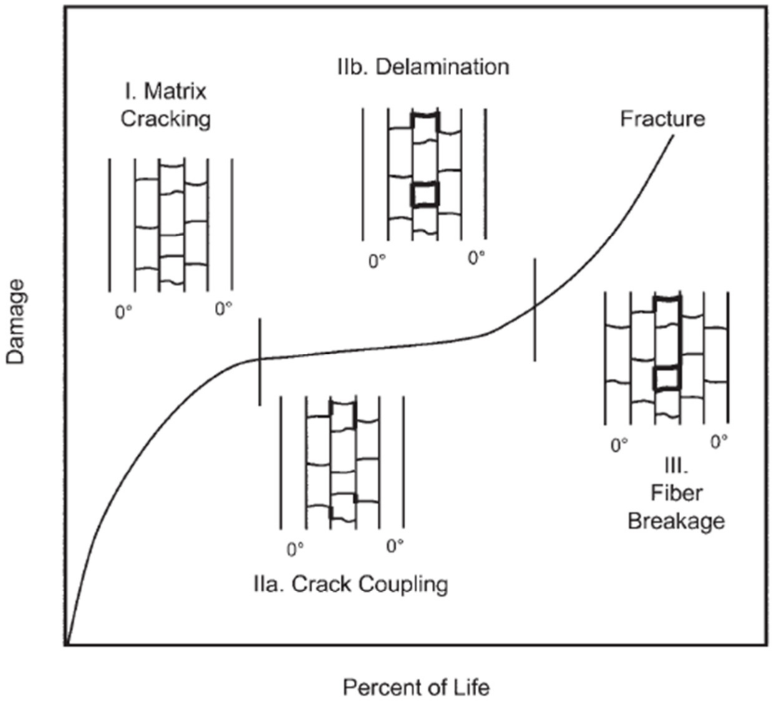


Figure 4.6: Progressive fatigue failure. *(Campbell, 2010, page 386)*

In conclusion fatigue behaviour is difficult to predict, because of the limited data available and the complex interaction of the loading conditions (e.g. type of matrix and reinforcement, nature of fatigue loading and its frequency, and the environment) under consideration.

5. FRP CONNECTIONS

Based on: (Mosallam, 2011), (Campbell, 2010), (Kolstein, 2008)

Connections are critical parts of a structure where high stress concentrations occur and are avoided wherever possible. They may be needed because of limitations in material size, due to manufacturing or transportation, to provide access, or to link sub-assemblies.

Efficiency of the joints depends on:

- Type of adhesive
- Surface preparation
- Curing process
- Surrounding environment
- Applied torque
- Edge distance
- And other geometrical ratios.

For composites the same types of connections are used as those in steel structures, namely: bolted connections, adhesively bonded connections, combined connections, and welded connections. Welded connections are only applicable for thermoplastics and are therefore not discussed here.

5.1. Mechanical connections

Mechanically fastened connections are difficult to design for strength greater than 50% of that of the composite. To obtain acceptable efficiency, local reinforcement may be needed, because of the high concentration stresses occurring at the position of the fastener.

Advantages:

- Straightforward method, less dependence on pre-treatment of the adherents and less affected by environmental exposure.
- Less sensitive to peel off stresses or residual-stress effects.
- Disassembly is possible.
- Repair of these joints is easier because they required no specific environmental conditions, like the curing of adhesives, which is difficult to achieve on site.

Disadvantages:

- Lower joint efficiency (strength to stress concentrations), about 50% of laminate strength.
- Lower bearing capacity of composites in comparison to the fasteners causes elongation of holes and can result in delamination.
- Assembly can be time consuming
- Corrosion and wear of the connection can be a problem. Also metal parts are susceptible to fatigue cracking.
- Galvanic corrosion may occur at the interface between the composite and the fastener when using Carbon fibre reinforcement, use of sealant or corrosion protection is recommended. (Galvanic corrosion is the corrosion resulting from contact between two metals or alloys.)

Failure modes

The emphasis here will be on connections subjected to tensile stresses, the reason for this is that composite connections subjected to compressive loading are less sensitive to joint geometry and are generally stronger than those subjected to tensile loading.

- **Bearing failure:** Characteristic by localized damage, e.g. delamination and hairline cracks of the matrix around the hole. Localized compression leads to buckling of the fibres followed by crushing of the matrix.
- **Shear-out failure**: As a result from insufficient edge distance or because of having too many laminas oriented in the load direction.
- **Net tension failure:** Caused by insufficient width or by having too many laminas oriented in the load direction.
- **Cleavage tension failure (tension and shear out failure):** Due to insufficient edge distance and width or insufficient number of cross-plies.
- **Bolt/Fastener failure:** Happens when the fastener is too small relative to the laminate thickness, unshimmed or improperly shimmed gaps or if there is insufficient fastener clamp-up.
- *Punching failure*: Can occur when countersink is too deep or when a shear head fastener is used.

Of these failure modes the most significant is the tension failure.

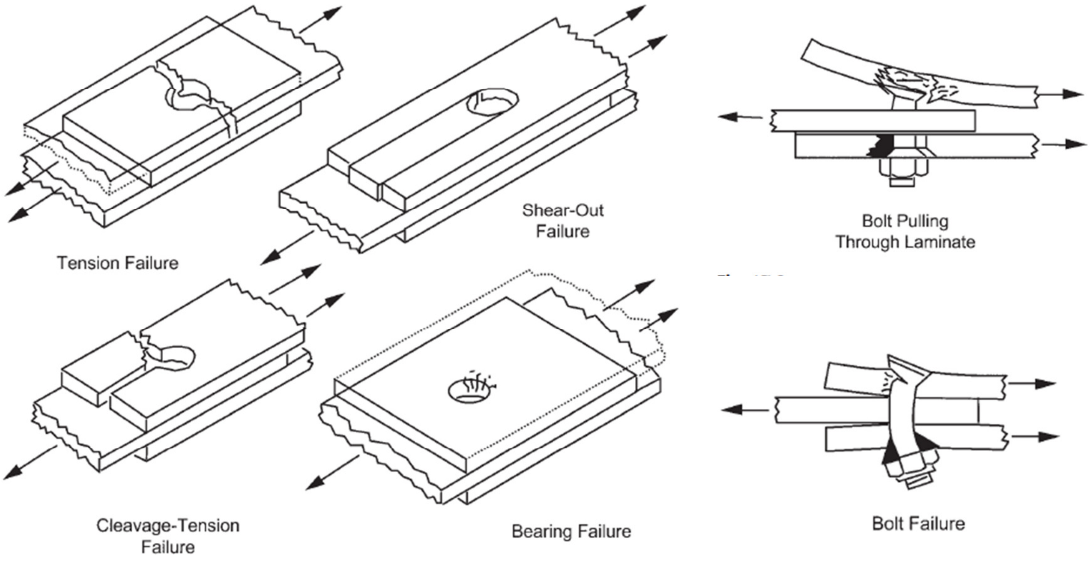


Figure 5.1: Possible failure mechanism of bolted connections (*Campbell, 2010, page 451)*

5.2. Bonded connections

Bonded connections can be considered the most 'natural', because they are made like FRP's matrix from resin. Examples of adhesive used are: epoxies, polyurethane adhesives, cyanoacrylates (so-called 'super glues'), methacrylate, solvent cements.

Some advantages are:

- Ease to make aesthetic joints.
- Strength may be greater for some adhesive than when using mechanical connections.
- Fluid and weather tightness.
- Weight saving
- More uniform stress distribution, leading to better fatigue life.
- Can provide connections with better vibration and damping capability.
- Rigid/stiff connection.

However, some disadvantages are:

- Adhesives tend to be brittle, giving a brittle failure or creep related problems when using a more ductile adhesive.
- Disassembly not possible.
- Pre-treatment and adequate environmental conditions are needed for a good joint assembly.
- Susceptibility to environmental degradation.
- The use is limited because of lack of analysis methods, reliable material properties and knowledge of long-term joint behaviour.

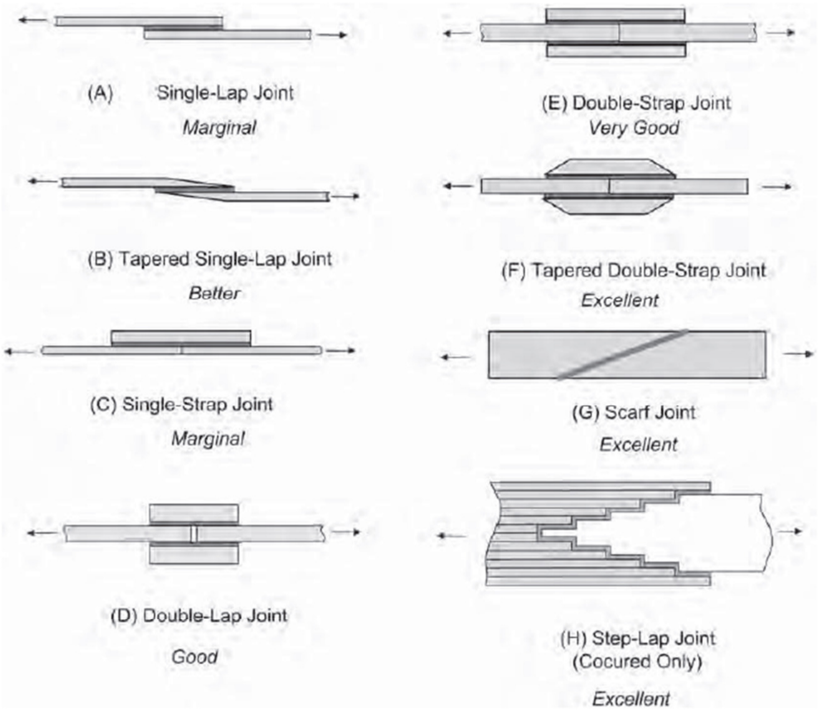


Figure 5.2: Basic joint types for bonded connections *(Campbell, 2010, page 469)*

In bonded connections load transfer occurs by shear between the laminates to be connected. Thus bonded connections should be designed so that they are primarily stressed in shear or compression since they can take up shear and compression better than tensile stresses. Therefore one should avoid high tensile stresses, where this is not possible these connections should be carefully evaluated.

Failure modes

Failure can occur in the adherent by tensile or transverse failure, or in the adhesive through interlaminar or cohesive failure as illustrated in figure 5.3.
Cohesive failure (i.e. within the adhesive) occurs by brittle fracture or rubbery tearing depending on the type of adhesive used. Interlaminar failure may be caused by poor processing, voids, delamination, or thermal stresses. And by in plane through-the-thickness stresses. Adhesive failure will be in shear or peel.

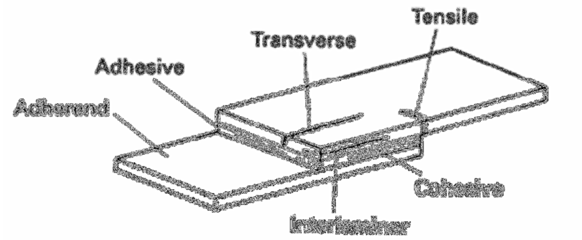


Figure 5.3: Possible failure mechanisms of bonded connections *(Kolstein, 2008, page 6.7)*

To achieve a satisfactory bonded joint a carefully developed fabrication process is needed, providing:

- Proper selection of an adhesive
- Proper surface preparation
- Proper conditions of temperature and humidity control
- A curing process as recommended by the adhesive supplier, to ensure that they provide the required properties when in service.
- Also of great importance are the overlap length of the joint and the thickness of the adherent.

Bonded joint configurations

The weakest type of joint configuration is the unsupported single lap joint and the strongest and most complicated is the stepped lap joint.

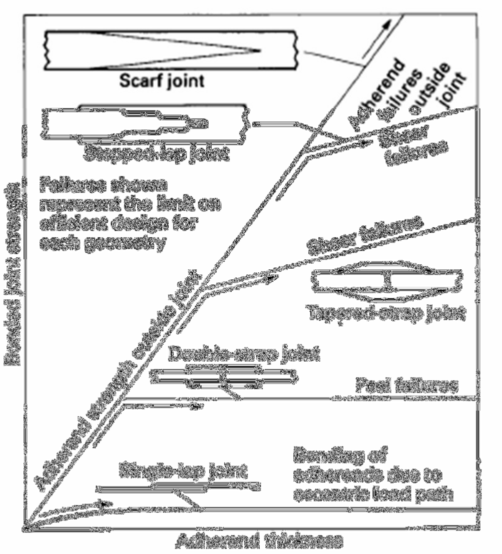


Figure 5.4: Influence of member size on selection of optimum joint configuration *(Mosallam, 2011, 162)*

5.3. Combined connections

In combined connections both adhesives and mechanical fasteners are used. The used of both provides a joint with greater capacity and more reliability, acting as a fail save system. The adhesive is usually stronger than the adherents. Therefore no significant loads are expected to develop in the fasteners until the failure of the bond line. The reason for this is that the connection through the fastener is much less stiff than that through the adhesive. Therefore combined connections are only applied when redundancy is needed or to prevent peel stresses. Only when dealing with and adhesive with lower modulus, which allows for load sharing between adhesive and the bolt, one may have better strength, stiffness, and fatigue life in comparison to bonded connections.

Combined connections can also offer advantages during erection: fastener can provide the needed pressure needed for curing the adhesive and the adhesive serves as a means to maintain alignment for the mechanical fastener.

The analysis of combined connections is really complex and requires the use of non-linear techniques. Also the load transfer is complicated due to the difference in stiffness.
Because of the lack of information and the complexity of the design analysis, it is recommended to design these joints taking into account only one type of connection and regard the other only as an additional benefit.

Which type of connection it should be designed as is still ambiguous. In the ‘Design guide for FRP Composite Connections’ *(Mosallam, 2011)* it is recommended to design them as bolted-only, since on-site the curing condition for the adhesives cannot properly be controlled. Hence, based on the inherent brittle failure behaviour of the bond lines, it is better to design the composite connection as bolted-only. And in the ‘EUROCOMP design code’ *(Clarke, 1996)* the recommendation is to design them as being adhesively bonded connections, because the adhesive takes up the loads in first instance.
A better understanding of these types of connections is needed to take advantages of the better performance they may offer.

6. DYNAMICS

In the main thesis research the focus will be on the dynamic behaviour of a lift gate. In order to achieve a better understand on this subject. This chapter of the literature study will shortly described what the different sources of dynamic loading can be and how to take into account the surrounding water into the calculations.

6.1. Excitation sources

There are different sources that can cause vibration in gates:

1. Flow- induced: Initial turbulence and turbulence in the wake including vortex trail behind the structure.
2. Flow instability resulting from separation of flow, separation point thus shape of structure is important.
3. Self-excitation, movement induced vibrations/ self-excitation is smaller the stiffer structure.
4. Amplification of the excitation due to the resonant rise of the water.
5. Fluid resonance due to self-excitation
6. Waves: oscillations of waves and wave impact

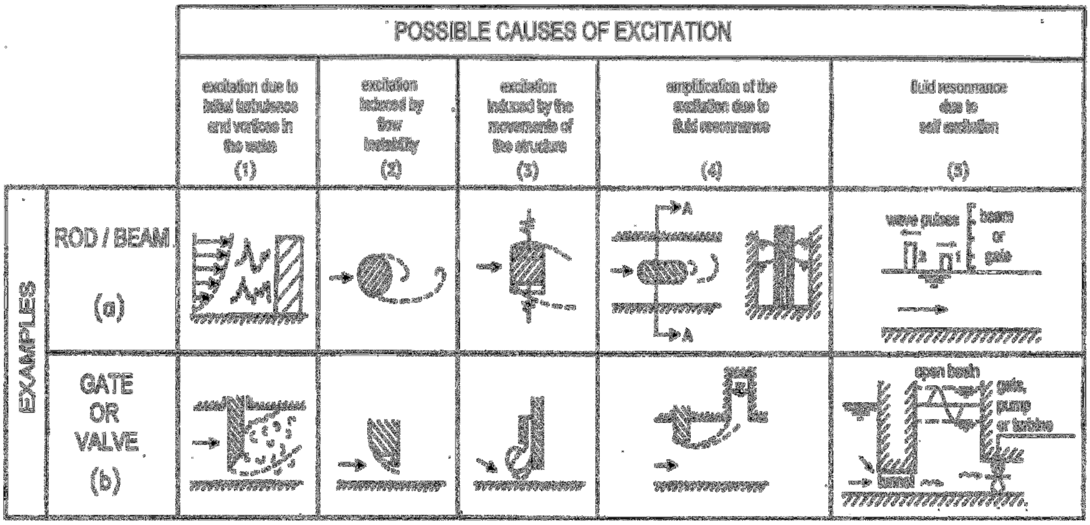


Figure 6.1: Possible causes of excitation. *(Kolkman [Part A], 2007, page 13)*

When dealing with the dynamic loading caused by these sources important are the magnitude of the pressure fluctuations and if the dominant frequency is close to the resonance frequency of the structure.

6.1.1. Flow-induced: Excitation due to turbulence

Excitation due to turbulence may be caused by turbulence in the approach flow, or by what happens around the part of the structure concerned. In case of gates, the excitation due to turbulence usually is of little significance, because as a rule the resonance frequency of the gate is high in relation to the frequency of the flow-induced excitation and because the excitation is spread out across a wider frequency band.

For the description of excitation due to turbulence, two characteristic values are important: the Strouhal number and the 'dynamic force coefficient'. The dynamic force coefficient relates to the amplitude of the dynamic load and the Strouhal number is a measure for the excitation frequency. It can be defined as:

$$S = \frac{fL}{V} \tag{6.01}$$

In this equation **f** is the excitation frequency due to the flow, **L** is a measure for the size of the gate or the component of the gate that experiences the excitation, and **V** is the approach flow velocity.

6.1.2. Excitation due to flow instability

Flow-instability is related to the separation of the flow and when the flow attaches further on. Where this happens is coupled to the specific shape of the object. In case of round shapes the separation point is undefined, causing the flow to be very instable. Also, a vibration of the structure may cause the point of separation to shift periodically, generating a change of force, which is triggered exactly at the point of the resonance frequency.
The zone between the point of separation and the point of attachment may be governed by an under-pressure, creating great force fluctuations when these points alternate. This means that the periodic shift of these the point of separation and the point of attachment due to the movement of the structure results in periodic excitation.

Flow instability generates a strong periodic excitation, in case of gates this occurs in the following cases:

1. if the point of separation is not fixed by a sharp edge, but consists of a rounded shape;
2. if, after release, the flow attaches again (further down) against a wall of the structure, in which the point of attachment is not fixed;
3. if the flow attaches again and the location of this is fixed, then a free boundary layer with undulations is generated. Periodic pressure fluctuations with discrete frequencies are generated within the enclosed vortices;
4. at a gate, in case of overflow, and a flow pattern that is between a situation of 'diving nappe' and a situation of 'nappe deflected toward the water surface';
5. at a gate with an overflowing nappe, beneath which there is an enclosed volume of air.

A small gate vibration may be, under certain conditions, already sufficient to cause the separation of the flow or the periodic attachment to vary with the frequency of the gate vibration.

6.1.3. Self-excitation

Self-excitation occurs in case both the vibration of the structure or the fluid, e.g. standing wave, and the exciting force are harmonic. And the magnitude of the frequency of the exciting force is coupled with the vibration. This excitation is referred to as 'movement-induced excitation', or also as feedback vibration, self-excitation vibration or negative damping.

Self-excitation at a structure occurs when the excitation force is caused by the movement of the structure itself. An initial vibration can become gradually stronger since the stronger the movement the more amplification there is. This is also true in case of a standing wave, only in case of great amplitude damping forces are generated.
In case of movement-induced vibrations, both the amplitude of the vibration and the excitation coupled to it, grow exponentially, until a boundary is reached, as an example, when the flow pattern changes.
Because this type of vibration may reach very high amplitudes, the prevention of self-excitation vibrations is the first requirement when designing a structure.

6.1.4. Amplification of the excitation due to fluid resonance

Amplification of the excitation may be caused when the water has a clear resonance frequency.
In case of communicating vessels (this includes a surge shaft together with the outer water), a standing wave, an air bubble enclosed in water, again and again there is an inertia and a stiffness component of the water (or of the air bubble) and during the amplification, kinetic energy is alternatingly converted into potential energy and vice versa.
When this fluid resonance system is periodically loaded in the resonance frequency, strong oscillations may be caused that generate yet more load on the structure.

An example is when enclosed air, combined with a culvert of a finite length filled with water, causes the water-air system to have a resonance frequency. Because of this or because of the vibration, the turbulence downstream of the gate may cause amplification when frequencies approach each other.

6.1.5. Self-excitation in case of fluid oscillations

"A fluid oscillator is here defined as a limited fluid area, in which a resonant rise or a standing wave may occur, without kinetic or potential energy radiating outward from that oscillation or being added externally." *Kolkman [Part A] (2007).*
Fluid oscillations are only dampened due to damping factors within the system itself. Depending on the number of degrees of freedom, an oscillator may resonate in different frequencies. These fluid resonances reside in the structure. Despite of this the resonance is completely determined by the natural period of the resonant rise of the fluid, which may be the period of a standing wave or the period of the resonance of communicating vessels.

Instable fluid resonances can occur when two preconditions are met:

- *Precondition 1*
  The situation needs to be such, that a low-damped resonance of a fluid oscillator or of a standing wave is possible.

- *Precondition 2*
  In case of increased pressure, the floating gate generates an extra discharge in the direction of the basin or the pipe in which the standing wave may be caused. In reality this means that, when the basin is situated upstream of a gate, the gate discharge decreases in case of a pressure increase upstream. If the basin is situated downstream of the gate, instability occurs when the gate discharge increases in case of a pressure increase downstream of the gate.

6.1.6. Waves

Waves impacting a structure cause loads that vary in time, the magnitude of these loads is dependent on wave height, wave period and wave direction, and the dimensions of the surface of the structure on which these loads operates. Also the shape and the surface properties of the structure, the foreland geometry and the presence of other structures play a role in this (in relation to reflection, diffraction and refraction, wave overtopping and the dissipation of wave energy). Wave loads may be differentiated into quasi-static loads and wave impact loads.

6.1.6.1. Quasi-Static wave load

Quasi-static loads are loads that move with the same period as the waves themselves.

6.1.6.2. Wave impact

Wave impacts occur when a wave is suddenly blocked. The momentum in the water is then cancelled out, converting it into energy. The structure should provide the strength to dissipate this energy. Depending on the stiffness the structure will be distorted to some extent, causing the structure in some cases to displace. However in practice the water may run off sideways and part of the momentum takes on a different direction. If the water cannot run off sideways, high pressures are generated. The magnitude of these pressures is dependent on the elastic elements present, i.e.:

- The compressibility of the water itself;
- This compressibility increases when there are air bubbles in the water;
- Air pockets enclosed between the water front and the structure operate as an elastic element;
- The elasticity of the structure.

The weakest element determines the magnitude of the impact pressure.

Another significant fact is that a structure isn't always hit simultaneously across the whole surface area, therefore a spreading of the impact occurs over time, which results in a longer impact duration and a lower peak pressure. The distortion of the structure may therefore influence the magnitude of the impact pressure. This distortion (i.e. the response of the structure) is also dependent on the elastic properties of the structure, thus resulting in an interaction between the generated wave loads and the structure (response).

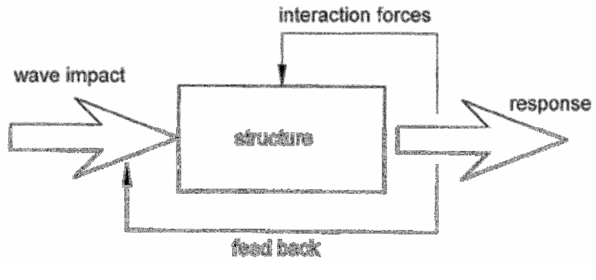


Figure 6.2: Schematic of wave impact on structure. *(Kolkman [Part B], 2007, page 31)*

There are many factors that influence the occurrence of wave impacts, the magnitude of impact pressures, and the progress of the impact in time and space. Some of these factors are:

Geometric factors:

- The shape of the structure (with reference to air enclosures, the possibility of water flowing away sideways, the dimension of the affected surface area);
- The angle with and the position in relation to the average water surface (as an example, components that protrude over the water surface, levee slopes, walls);
- The depth and the course of the foreland (with reference to the propagation of the waves, refraction and breaking).

Factors in relation to rigidity:

- The elasticity of the structure and the compressibility of the water;
- The presence of air pockets between the water surface and the structure or the presence of air bubbles in the water.

Factors in relation to the incoming wave:

- The wave height and the wave period (the greater the wave height and the shorter the wave period, the higher the velocity of the water surface);
- The wave direction (the greater the angle between the normal on the structure and the wave direction, the smaller the probability of wave impacts);
- Wave directional dispersion;
- The shape of the local wave, which is co-determined by preceding waves travelling back.

Factors in relation to the water:

- The salinity of the water (the salinity influences the size and the distribution of air bubbles in the water and thereby the celerity of shock waves; also the density depends on the salinity);
- Flow of the water (flow influences the wave field, but also the waves that are locally present at the structure);
- The water level.

Different types of wave impacts can be differentiated:

- Hammer shocks
  Incoming water runs parallel to the surface of the structure in which the water cannot run off sideways. And there is little or no air inclusion between the water and the structure.
- Ventilated shocks
  Air may escape from between the water surface and the structure and water can run off sideways. This phenomenon is predominantly determined by inertia forces and gravity.
- Compression shocks
  Air is enclosed and compressed between the water front and the structure. This air bubble later oscillates generating an oscillating pressure distribution in the downward flank of the wave impact. The maximum pressure is however, smaller than that of the hammer and ventilated shocks.

6.2. Dynamics of structures in water

6.2.1. Mass-spring- damper system equations

The classic equation for a (1 dimensional) mass-spring-damper system is:

$$m\frac{d^2y}{dt^2} + c\frac{dy}{dt} + ky = F(t) \qquad (6.02)$$

Here the y is the displacement of the mass from a reference point, m is the mass, c is the damping, k is the stiffness, and F is defined as the external force(s).

The terms on the left are called the inertia term, the damping term and the stiffness term respectively, while on the right there is the external force that here does not depend on the movement of the structure.

Figure 6.3 is a schematic representation of an elastically suspended gate in a flowing fluid, illustrating the symbols used. The most basic assumption is that the flowing water causes the external force.

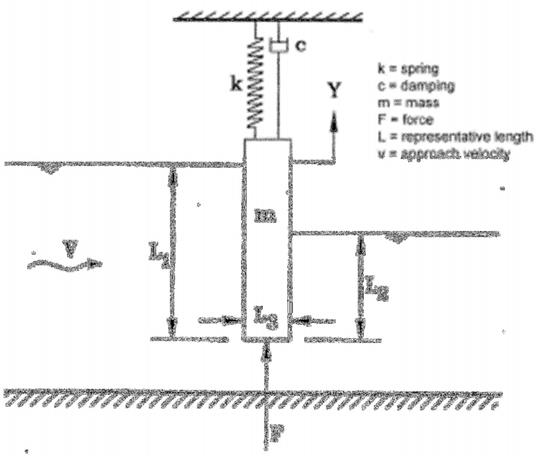


Figure 6.3: Schematization of a gate in flowing fluid. *(Kolkman [Part A], 2007, page 16)*

The damping force (in which c is positive) is in anti-phase to the vibration velocity, dy/dt; in magnitude it is proportional to this velocity, but it operates in the opposite direction. When a force like this operates in-phase with the vibration velocity, then the term negative damping is used (c is negative in that case). In that case, a vibration is generated with ever increasing amplitude, which is also referred to as self-excitation. Negative damping can only occur if a source is included in the system that produces energy.

For a system in water the mass spring system, in equation (6.02) changes into:

$$(m + m_w)\frac{d^2y}{dt^2} + (c + c_w)\frac{dy}{dt} + (k + k_w)y = F_{1,w}(t) + F_{2,w}\left(y, \frac{dy}{dt}, \frac{d^2y}{dt^2}\right) \qquad (6.03)$$

The index w indicates that the magnitude concerned relates to the water.

On the right, sometimes the term $F_{1,w}(t)$ may be distinguished for those forces that are not coupled to the movement of the mass. While the other term, $F_{2,w}(y, dy/dt, d^2y/dt^2)$, represent coupled forces for as far as these are non-linear.

On the left the m_w is the so-called added water mass, c_w is the added water damping and k_w is the added spring stiffness. These are the passive forces influencing the dynamic behaviour of a structure in water. Each of these magnitudes can be frequency dependent and may be either positive or negative. In the following chapter these added terms are further discussed.

6.2.2. Added water forces

6.2.2.1. Added water mass

The added water mass is the water that moves along with the structure. This definition is simplified by *Kolkman et al.[Part A] (2007)* taking as an example a piston in a cylindrical vessel, in figure 6.4, the added water mass in that case is the water on top of the piston. If the piston moves the water has to move along, as it is locked in sideways, and the acceleration forces results in an extra pressure on the piston surface.

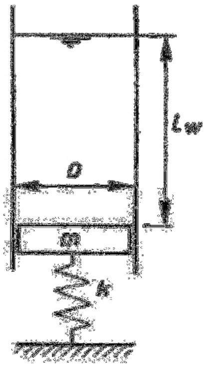


Figure 6.4: Added water mass in case of a piston. *(Kolkman [Part A], 2007, page 53)*

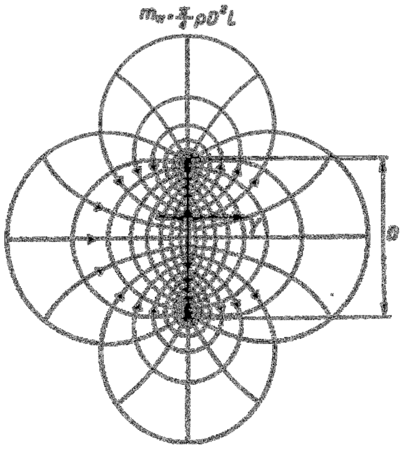


Figure 6.5: Potential flow in case of a vibrating strip. *(Kolkman [Part A], 2007, page 54)*

In case of an infinitely long strip, see figure 6.5, the added water mass equals the mass of water in the imaginary surrounding circular cylinder of the strip. This is a different situation from the one of the vibrating piston. The contribution of the kinetic energy is proportional to the square of the flow velocities. These flow velocities are, due to the flow pattern, smaller further away from the strip. The extra kinetic energy determines the magnitude of the added water mass. This magnitude can also be determined by considering the pressures at the surface of the strip in relation to its acceleration. The added water length, L_w, depends on the vibration direction, and is always coupled to the dimensions of the vibrating body, varying across the width of the strip.

6.2.2.2. Added stiffness

Added stiffness can be divided into three types. These are the stiffness due to immersion, the stiffness due to quasi-stationary flow forces and the stiffness that is generated when an object suddenly experiences a change of position (the so-called sudden stiffness).

Stiffness due to immersion

The stiffness of an object that is vertically immersed may be described as:
$K_{w,float} = \rho \cdot g \cdot A_{cross\text{-}section}$.
The surface of the cross-section with the free water level is normative for this stiffness.

Stiffness due to flow

The flow force (i.e. the force coefficient) may vary relative to the position.
The flow stiffness is generally proportional to the squared flow velocity or, in case of gates (where the flow velocity is proportional to the root of the hydraulic head), proportional to the hydraulic head.

Sudden stiffness

The so-called sudden stiffness is a stiffness that only occurs at gates, particularly at culvert gates, where the discharge in the culvert has such inertia, that it does not immediately adapt to the changed position of the gate.

6.2.2.3. Added damping

Added damping is mainly caused by the flow. Flow induced added damping can include:

- **Added damping due to flow in case of an object vibrating in flow direction**
  The flow forces, that are square with the flow velocity, change due to the velocity of movement of the vibrating structure. As a consequence of this vibration velocity, both the magnitude of the relative approach flow velocity and the angle of approach change.
- **Added damping due to flow in case of the vibration direction differs from the flow direction**
  In case of a circular cylinder or a sphere, the damping may also be calculated when the vibration direction is not the same as the flow direction.

However for gates, the quantified positive water damping is of little significance, because strong vibrations only occur when the water damping is negative.

7. FRP IN STRUCTURAL APPLICATIONS

7.1. Examples of FRP structures

In the late 20th century FRP started being used in infrastructures. In the 1970's the first bridges incorporating composite elements were constructed, although it was in the 1990's that the use of FRP in structural applications really started.
Below some examples of infrastructure build in FRP or with FRP components (e.g. cables, structural profiles, bridge decks, etc.) are presented.

7.1.1. Pedestrian and cyclist bridge at Kolding in Denmark

This bridge was developed by Fiberline and opened in 1997. It is made out of glass fibre reinforced polyester (GFRP) profiles, except for the bolds and abutments which were made of stainless steel. It has a width of 3.2m and a span of 40m divided over 2 sections one of 27m and the other of 13m. *(Fiberline [2], s.d.)*

Figure 3.8: Pedestrian and Cyclist Bridge at Kolding in Denmark. *(Fiberline [2])*

7.1.2. Bridge-in-a-Backpack

"The Bridge-in-a-Backpack is a lightweight, corrosion resistant system for short to medium span bridge construction using FRP composite arch tubes that act as reinforcement and formwork for cast-in-place concrete. The arches are easily transportable, rapidly deployable and do not require the heavy equipment or large crews needed to handle the weight of traditional construction materials".
Citation from University of Maine website.

This system was developed by the Advanced Structures and Composites Centre at the University of Maine and patented by Advanced Infrastructure Technologies (AIT).

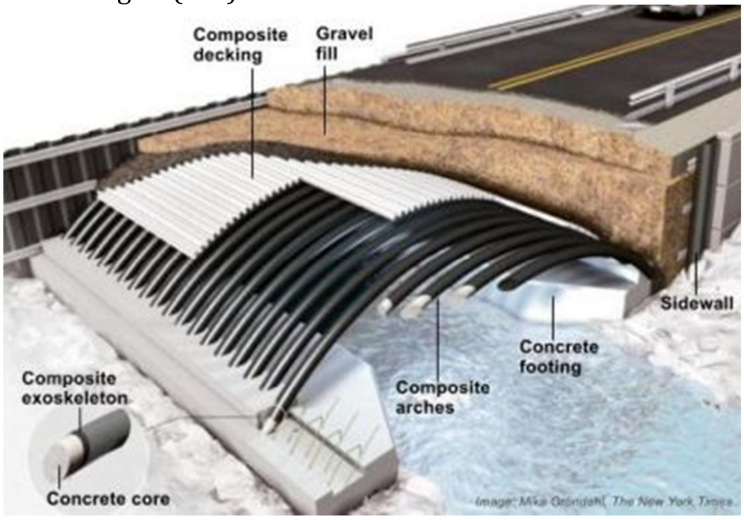


Figure 3.9 (above):
Illustration of the 'Bridge-in-a-Backpack' system. *(AIT)*

Figures 3.10 and 3.11 (right):
The McGee Bridge Arch build with the so-called 'Bridge-in-a-Backpack' system in Maine, USA. *(GCE)*

7.1.3. Bus station 'The Giant Whale Jaw'

This is a bus station in Hoofddorp build in FRP. The bus station is 50 m long, 10m wide and 5m tall and is made out of one single piece. Build on site with blocks of polystyrene foam, most commonly known as Styrofoam, and coated with a 6mm thick glass reinforced polyester using the spray-up method.

Figure 3.12: Bus station 'The Giant Whale Jaw'. *(Poly Products)*

7.1.4. Column mould parking garage Amsterdam

Developed for by Nedcam for the columns (see figure 3.13) in a parking garage under the Oosterdokseiland in Amsterdam, showing the ease in forming different shape in FRP. The moulds were made of a polystyrene foam (Styrofoam) core with a reinforced polyester resin.

Figure 3.13: Columns in a parking garage under Oosterdokseiland in Amsterdam. *(Nedcam)*

7.1.5. Façade 'Building X' Windesheim University in Zwolle

This façade consists of 50 % glass, made out of triangular glass sections glued to a sandwich structure. The sandwich structure has dimensions of 12.5 by 3.5 m and a thickness of 300mm.

Figure 3.14: Façade Windesheim University as viewed from the inside. *(Hollands Composites)*

7.2. Examples of hydraulic structures in FRP

7.2.1. Valves in the Kreekraksluizen

The Kreekraksluizen had a fresh-salt water separation system consisting of 256 steel valves, with dimensions 1.8 by 0.8 metres. One of these steel slides was replaced by a composite one from 1993 until the closure of this water separation system.
The slide was designed for a head level of 3.2m when closed and 0.3m when opening. To ensure water tightness the deflection of the slide had to be limited to 0.1mm when closed and while moving 8mm. They were designed with a service life of 50 years.
It was made of glass fibre reinforcement with a matrix vinyl ester resin, and stiffened on the outside edge using a core made of polymer concrete. As seen in figure below.
The manufacturing process used was RTM-resin transfer moulding, with an applied pressure of 15 to 20bar. *(Honselaar, 1999)*

Foto: Jan Kos, Rotet

Figure 7.1: Composite steel slide in the Kreekraksluizen (1993-1997). *(Honselaar, 1999, page 9)*

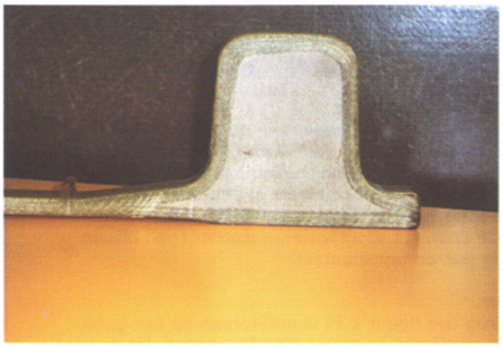


Figure 7.2: Cross-section of stiffeners applied on the edge of the valve. *(Honselaar, 1999, page 9)*

7.2.2. Spieringsluis

The “Spieringsluis” dates back to 1953, it forms a connection between the “Nieuwe Merwede” and the “Biesbosch”in Noord Brabant in the Netherlands. In 2000 the timber mitre gates were replaced by composite ones, they were chosen to try to suppress the costs of maintenance. It was the first time in the Netherlands that FRP gates where used.
Laminates for these gates were build-out of E-glass fibres and an iso-phthalics polyester resin, which has better resistance to wet conditions.
The GFRP gates are chosen with a configuration of [0/90/+45/-45] with 55% of fibres in the main direction and 15% in the other directions. The laminates where made by hand lamination and weighs 5100 kilos, which is less than the replaced timber ones (14000 kilos). *(Nagtegaal, 2001)*

Figure 7.3: Lock gates Spieringsluis. *(Nagtegaal, 2001)*

7.2.3. Golbey gate replacement, France

Located in the Canal des Voges in France, in a lock dating back to 1925, the Golbey gates originally build of steel where replace in 2000 by composite mitre gates. The composite gates are composed of circular shaped skin plates made out of glass fibre reinforced polymer (GFRP) stiffened by blocks of sandwiched glass fibre and foam. The gates are hinged to the old masonry with an adjustable stainless steel U- shaped frame. *(InCom, 2009)*

Figure 7.4: right, the lock dating from the origin of the channel (1853) and now abandoned. Left the lock built in 1925 and equipped with composite doors in 2000. *(Website: Bord à Bord asbl)*

Figure 7.5: Composite gate with visible hinges *(Website: Bord à Bord asbl)*

Figure 7.6: Adjustment of composite gates downstream *(InCom, 2009, page 18)*

7.2.4. Erica-Ter Apel lock gates

The Erica-Ter Apel lock gates are situated in the Erica-Ter Apel canal in the vicinity of Emmen in the Netherlands. They were placed in March of 2012.
This project was an assignment from the provinces of Drenthe and Groningen. The gates, 4 in total, were designed and fabricated by FiberCore Europe. They are 5 meters tall by 3.6 meters wide and made with InfraCore® Inside (patented by FiberCore Europe). They are dimensioned so that the specific weight corresponds to the buoyancy force of the water, this way the driving mechanism is loaded as little as possible. *(Visser, 2012), (FiberCore [1])*

Figure 7.7: Placing of the Erica-Ter Apel gates *(FiberCore [1])*

7.2.5. Wilhelminakanaal gates in Tilburg

Plans are being made for the biggest FRP gates yet to be build it will be situated in the Wilhelminakanaal in Tilburg in the Netherlands, being 12.5 meters tall and having 6.2 meters in wide. The gates will be a design of FiberCore and will be placed by Heijmans, who together with Boskalis will develop the entire canal and the lock. This would be the third project in the Netherlands where composite gates will be used. The production of the gates is plant to start in 2014 and are planned to be put into their final place by mid-2015.
The composite gates will consist of a foam core with 30mm thick skins made out of glass fibre reinforced polyester, this will be done using the InfraCore® Inside-technology patented by FiberCore. The gates will be provided a beige/yellow gel coat.
(FiberCore [2])

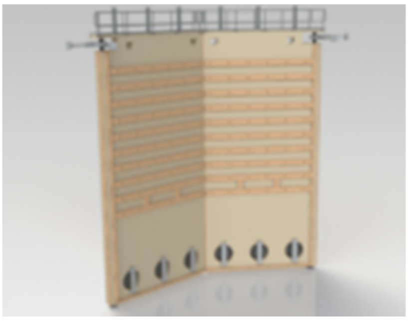


Figure 7.8: Illustration of the gates for the Wilhelmina canal. *(FiberCore [2])*

7.2.6. Composite vertical lift arch gates research in France

CETMEF (France) has studied an arched vertical lift gate made out of composite materials.
The downstream gate is divided into 3 identical monolithic sections, In order to make the manufacture, transport and installation of the gate easier. Each section is reinforced on the downstream side with two horizontal stiffeners, 600mm in height. Consisting of an omega shaped skin made out of CVR composite, with a thickness of 30 to 40mm, and filled with foam.

The sections are connected on site. With all sections connected the gate's height is 12.4m in height. The gate is placed in a lock with a width of 12m.

Due to its cylindrical shape the structure transmits most of the thrust stress, load from the differential head, as compression.
The hydrostatic load reaches 20000kN. The weight of the gate (composite part only) is 400kN and totally equipped (with steel devices and cylinder) the weight to be lifted is 600kN with friction forces. The gate is guided by the sliding of the arches extremities on fixed parts.

(InCom, 2009)

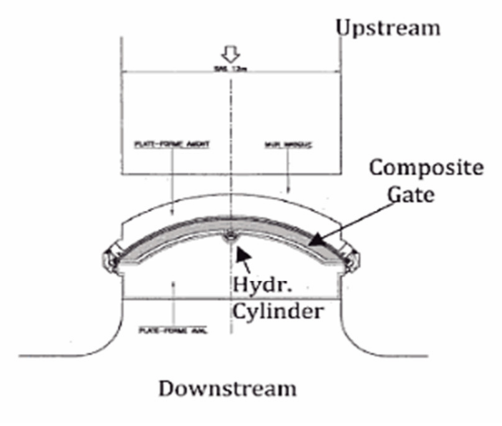


Figure 7.9: Composite vertical lift gate. *(InCom, 2009, page 135)*

BIBLIOGRAPHY

Books

Campbell, F.C., 2010. *Structural Composite Materials*. AMS international.

Clarke, J.L., 1996. *Structural design of polymer composites; EUROCOMP design code handbook.* SPON.

Hancox, L., 1981. *Fibre composite Hybrid Materials*. London, Applied Science Publishers LTD.

Kolkman, P.A. & Jongeling, T.H.G., 2007. *Dynamic behaviour of hydraulic structure Part A: Structures in flowing water*. Delft, Delft hydraulics.

Kolkman, P.A. & Jongeling, T.H.G., 2007. *Dynamic behaviour of hydraulic structure Part B: Structures in waves*. Delft, Delft hydraulics.

Kolstein, M.H., 2008. *FRP Structures*. Delft, Technical University of Delft.

Lopez-Anido, R.A. & Karbhari, V.M., (2000) In: Lopez-Anido, R.A. & Naik, T.R., 2000. *Emerging materials for Civil Infrastructures: State of the Art*. Virginia, ASCE, [Pages: 41-78].

Molenaar, W.F. et al, 2011. *Hydraulic Structures: Locks.* Delft, Technical University of Delft.

Mosallam, A.S., 2011. *Design Guide for FRP Composite Connections*. Virginia, ASCE.

Nijhof, A.H.J., 1981. *Ontwerpen in vezelversterkte kunststoffen*. Delft, Technical University of Delft.

Nijhof, A.H.J., 2004. V*ezelversterkte kunststoffen: Mechanica en Ontwerp*. Delft, DUP Blue Print.

CUR, 2003. *CUR-Aanbeveling 96*. Gouda, CUR.

CUR, 2003. *Vezelsterkte kunststoffen in civiel draagconstructies: Achtergrondrapport bij CUR-Aanbeveling 96*. Gouda, Stichting CUR.

Vrijburcht, A. & Kranenburg, D., 2000. Gates, operating mechanisms and sluices. In: Vrijburcht, A. & Glerum, A., 2000. *Design of locks Part 1*. Utrecht, Bouwdienst Rijkswaterstaat, [Pages: 7-1 to 7-146].

Weatherhead, R.G., 1980. *FRP Technology*. London, Applied Science Publishers LTD.

Zenkert, D., 1995, *An Introduction to Sandwich Construction*. Engineering Materials Advisory Services.

Theses

Chlosta, M., 2012. *Feasibility study on fiber reinforced polymer cylindrical truss bridges for heavy traffic*. MSc thesis, Technical University of Delft.

Doeksen, J.W., 2012. *Gate Design for Large, High Head Locks. “The development of an innovative lock gate”.* MSc thesis, Technical University of Delft.

Kok, L., 2013. *Feasibility study for fiber reinforced polymer in large hydraulic structures*. MSc thesis, Technical University of Delft.

Potyrala, P.B., 2011. *Use of Fibre Reinforced Polymer Composites in Bridge Construction. State of the Art in Hybrid and All-Composite Structures*. Universitat Politècnica de Catalunya.

Tuin, H., 2013. *New canalization of the Nederrijn and Lek-Design of a weir equipped with fibre reinforced polymer gates which is designed using a structured design methodology based on Systems Engineering*. MSc Thesis, Technical University of Delft.

Van Straten, R.W., 2013. *Feasibility study on fiber reinforced polymer slides in the Eastern Scheldt storm surge barrier*. MSc thesis, Technical University of Delft.

Reports/Papers/Articles

Committee on Durability and Life Prediction of Polymer Matrix Composites in Extreme Environments, National Research Council, 2005. *Meeting the Emerging Demand for Durable Polymer Matrix Composites*, the National Academy of Sciences, Washington, D.C. In: Going to Extreme, Washington D.C., THE NATIONAL ACADEMIES PRESS [http://www.nap.edu/openbook.php?record_id=11424&page=12], 16 Dec. 2013

Cripps, D. (Gurit Group Company), 2013. *Guide to Composites.* [http://www.gurit.com/default.aspx], 4 Dec. 2013.

©FAO(Food and Agriculture Organization of the United Nations), 2009. *Natural fibres , Ancient fabrics, high-tech geotextiles, Profiles of 15 of the world's major plant and animal fibres - many of them fundamental to human society since the dawn of civilization*. [http://www.naturalfibres2009.org/en/fibres], 10 Dec. 2013

FiberCore (1), s.d. *Sluisdeuren vaartverbinding Erica ter Apel*. [http://www.fibercore-europe.com/index.php?option=com_k2&view=item&id=362:sluisdeuren-vaartverbinding-erica-ter-apel&Itemid=183&highlight=WyJlcmljYSIsInRlciIsImFwZWwiLCJzbHVpcyIsImRldXJlbiIsImVyaWNhIHRlciIsImVyaWNhIHRlciBhcGVsIiwidGVyIGFwZWwiXQ==&lang=nl], 15 Jan. 2014

FiberCore (2), nov. 2013. *'s Werelds grootste composiet sluisdeuren in Tilburg*. 15 Jan. 2014 [http://www.fibercore-europe.com/index.php?option=com_content&view=article&id=215:wereldprimeur-sluisdeuren&catid=21:nieuws&lang=nl&Itemid=208&highlight=WyJzbHVpcyIsImRldXJlbiIsInRpbGJ1cmciXQ==]

Fiberline Composites S/A, 2003. *FiberLine Design manual*, [http://www.fiberline.com/sites/default/files/mediafiles/190107_dm_uk.pdf], 10 Dec. 2013

Groh, R., 2012.Composites manufacturing. In composite materials, Manufacturing Aerospace Engineering blog. [http://aerospaceengineeringblog.com/composite-manufacturing/], 8 Jan. 2014

InCom Working Group 106, 2009. *Innovation in navigation lock design*. Brussels, PIANC General Secretariat.

Karbhari, V.M., Chin, J.W., Hunston, D., Benmokrane, B. Juska, T., Morgan, R., Lesko, J.J., Sorathia, U. & Reynaud, D., 2003. Durability Gap Analysis for Fiber-Reinforced Polymer Composites in Civil Infrastructure. In: Bakis, C.E. *Journal of Composites for Construction*, ASCE, 238-247.

Honselaar, C.H., Kolstein, M.H., Van Leeuwen, W.M., Muller, H.D., Nagtegaal, G., Van der Weijde, G.D., De Winter, S.E.E, 1999. *Vezelversterkte kunststoffenin constructieve toepassingen.* Vereniging FME-CWE & Federatie NRK.

Nagtegaal, G, 2001.*Kunststof Puntdeuren voor de Spieringsluis*. From: PIB (product Innovatieblad) Spieringsluis, Vakgroep innovatief ontwerp en onderhoud, Bouwdienst Rijkswaterstaat.

Schumacher, A, 2009. *Design of FRP-Profiles and All-FRP-Structures.* Lecture Fibre Composite (FS09), EMPA.

USACE [1] (US Army Corps of Engineers), 2013. Manual No. 1110-2-2610, Mechanical and Electrical Design for Lock and Dam Operating Equipment.

USACE [2] (US Army Corps of Engineers), 1997. Manual No. 1110-2-2701, Design and Engineering, Vertical Lift Gates.

Visscher, 2012. *Sluisdeuren van composiet*. In: Technische Weekblad. [http://www.technischweekblad.nl/sluisdeuren-van-composiet.246491.lynkx], 24 Dec. 2013

Walter, E & Ashbee, K.H.G, 1982. *Osmosis in Composite Materials*. Bristol, Elsevier.

Internet sites

AIT (Advanced Infrastructure Technologies):
http://www.aitbridges.com/compositebridgesystem/

Bord à Bord asbl: http://bordabord.org/news/ecluse-de-laneuveville-devant-nancy-indisponible-1

Fiberline [1]: http://www.fiberline.dk/

Fiberline [2]: http://www.fiberline.com/structures/profiles-and-decks-bridges/profiles-footbridges-and-cycle-bridges/case-stories-footbridge/fiberline-bridge-kolding

Fibrex*:* http://www.fibrex.com/industries-served/other-frp-pipe-production/

GCE (Gardeners Construction Enterprises):
http://gardnerconstructionenterprises.com/composite.asp

Hollands Composites: http://www.hollandcomposites.nl/

Nedcam: http://www.nedcam.com/index.php

Poly Products: http://www.polyproducts.nl/bijzondere_bouwelementen/busstation-hoofddorp.htm

Solico: http://www.solico.nl/

University of Maine, The Advanced Structures and Composite Center:
http://www2.umaine.edu/aewc/content/view/185/71/

ZCT: http://zct.ru/en/katalog