Master of Science Thesis

# Saving weight and increasing performance by introducing a composite gangway for the Ampelmann system

## Creating a producible and certifiable composite design

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Confidential

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For obtaining the degree of Master of Science in Aerospace Engineering
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# Abstract

With the launch of the first Ampelmann system a revolution started for Walk2Work systems, replacing transfer methods like swingroping and helicopter transfers. Almost a decade later competition is picking up and client requirements become challenging. In order to be a step in front of the competition new developments are required. A gangway re-design using lightweight materials will open a new range of possibilities. The complete system weight can be decreased reducing power consumption. A longer gangway can be used on the current systems with the same mass as the current 25 meter Gangway XL (GXL).

Using lightweight materials, in this case the focus is on Fiber Reinforced Polymer (FRP), a gangway re-design will be performed. As there are no regulations for the use of composites in the offshore industry these need to be created in co-operation with the certifying authorities.

The feasibility of replacing the current 25 meter GXL by a composite gangway is determined in this thesis. The emphasis during the design is on the producability, certifiability and life cycle costs of the design. These three aspects will determine is the investments for further development are worthwhile.

Three concepts have been created and Key Performance Indicators (KPI's) were defined to find the most suitable design. A sandwich panel deck with a load carrying railing was found to be the most effective in the eigenfrequency, deflection, twist and production. On certification, the required connections are a challenge. The gangway re-design is stiffness based, the required eigenfrequency is the main driver of the design. Connections of the railing framework and between the booms and the transfer deck to the boom are other critical areas in the re-design.

A basic design has been created which fulfills all structural requirements from both Ampelmann and the certifying authorities. It consist of a sandwich deck made of different Gurit SE 84LV prepregs and a Gurit M130 core. The top railing is made using the same carbon prepreg to get the required bending stiffness needed for the eigenfrequency. Vertical and diagonal members in the railing framework are made from Exel Composites glass fiber pultrusions profiles. Except the most highly loaded ones which will be made from carbon fiber prepreg just like the railing in order to carry all the loads. The connections of the railing framework will be made using Computer Numerical Control (CNC) machining from (carbon

filled) Polyetheretherketone (PEEK). The telescoping, luffing and hinge point connections will be made from stainless steel.

A basic gangway design has been created with a weight of 1168 kg, a decrease of 65% from the current steel GXL. The design can be produced as been verified by third parties. The expected Life Cycle Costs (LCC) for the composite gangway is 40% less than the steel design over a life time of 20 years. This excludes initial investments for engineering and certification. In order to certify the gangway a prototype needs to be made and tested. The extend of this testing is undetermined at this point. Next to testing of the gangway the number of connections needs to be minimized according to the wishes of the certifying agency. Extra tests proving the effectiveness of the provided connecting solution will be needed.

Before a composite gangway can be implemented on the Ampelmann system a tip needs to be designed to introduce all loads into the gangway, the required smoke, fire and toxicity needs to be determined and a detailed design is needed from a specialized composite engineering firm. These aspect were out of the scope of this project.

# Table of Contents

# Acronyms

**Biax** Bi-axial.

**BVID** Barely Visible Impact Damage.

**c.o.g.** Center of Gravity.

**CFRP** Carbon Fiber Reinforced Polymer.

**CLAME** Code for Lifting Appliances in a Marine Environment.

**CNC** Computer Numerical Control.

**DNV GL** Det Norske Veritas Germanischer Lloyd.

**EC-CT** Emergency Case - Cargo Transfer.

**ETW** Elevated Temperature Wet.

**FBD** Free Body Diagram.

**FEM** Finite Element Method.

**FPF** First-Ply-Failure.

**FRP** Fiber Reinforced Polymer.

**GXL** Gangway XL.

**HEC** High Elongation Carbon.

**HMC** High Modulus Carbon.

**i.e.** id est.

**KPI's** Key Performance Indicators.

**LCC** Life Cycle Costs.

**LR** Lloyd's Register.

**MS** Margin of Safety.

**NDT** Non-Destructive Testing.

**NO-PT** Normal Operation - People Transfer.

**OOA** Out-of-Autoclave.

**PEEK** Polyetheretherketone.

**PVC** Polyvinylcloride.

**RTM** Resin Transfer Molding.

**SAN** Styrene acrylonitrile.

**T-boom** Telescoping Boom.

**UD** Unidirectional.

# List of symbols

| Sign | Description | Unit |
|---|---|---|
| $A$ | Area | $[m^2]$ |
| $AR$ | Aspect ratio | $[-]$ |
| $A_{railing}$ | Area of the railing profile | $[mm^2]$ |
| $D_{ij}$ | Bending stiffness matrix | $[Nmm]$ |
| $EI$ | Bending stiffness | $[Nm^2]$ |
| $E_{11}$ | Young's modulus in 0° direction | $[GPa]$ |
| $E_{22}$ | Young's modulus in 90° direction | $[GPa]$ |
| $FF_{luffing}$ | Free-float luffing force | $[kN]$ |
| $FF_{slew}$ | Free-float slewing force | $[kN]$ |
| $FF_{telescope}$ | Free-float telescoping force | $[kN]$ |
| $F_d$ | Duty factor | $[-]$ |
| $F_h$ | Hoisting factor | $[-]$ |
| $F_x$ | Force in x-direction | $[N]$ |
| $G$ | Shear modulus | $[GPa]$ |
| $GJ$ | Torsional rigidity | $[Nm^2]$ |
| $Gc$ | Core shear modulus | $[N/mm^2]$ |
| $L$ | Flow length | $[m]$ |
| $L_{gw}$ | Gangway length | $[mm]$ |
| $M_x$ | Moment around y-axis | $[Nmm]$ |
| $P$ | Point load | $[N]$ |
| $S$ | Material shear failure limit | $[N/mm^2]$ |
| $SC$ | Shear center location | $[mm]$ |
| $SWL$ | Safe working load | $[kN]$ |
| $T$ | Torque | $[Nm]$ |
| $T_g$ | Glass transition temperature | $[°C]$ |
| $Xc$ | Material compression failure limit in 0° direction | $[N/mm^2]$ |
| $Xt$ | Material tension failure limit in 0° direction | $[N/mm^2]$ |

| **Sign** | **Description** | **Unit** |
|---|---|---|
| $Yc$ | Material compression failure limit in 90° direction | $[N/mm^2]$ |
| $Yt$ | Material tension failure limit in 90° direction | $[N/mm^2]$ |
| $\alpha_{luffing}$ | Luffing angle | $[°]$ |
| $\kappa$ | Preform permeability | $[m^2]$ |
| $\rho$ | Density | $[kg/m^3]$ |
| $\sigma_y$ | Yield strength | $[MPa]$ |
| $\tau_{steel}$ | Shear strength on steel | $[MPa]$ |
| $\tau_{xy}$ | Shear strength | $[GPa]$ |
| $a$ | Length of the section | $[mm]$ |
| $acc_x$ | Acceleration in x-direction | $[m/s]$ |
| $acc_y$ | Acceleration in y-direction | $[m/s]$ |
| $acc_z$ | Acceleration in z-direction | $[m/s]$ |
| $h_{bar}$ | Railing profile height | $[mm]$ |
| $h_{deck}$ | Deck height | $[mm]$ |
| $h_{railing}$ | Railing height from deck | $[mm]$ |
| $q$ | Distributed load | $[N/m]$ |
| $q_{gw}$ | Distributed load due to dead weight | $[N/mm]$ |
| $r_{tube}$ | Tube radius | $[mm]$ |
| $t_c$ | Core thickness | $[mm]$ |
| $t_{ply}$ | Ply thickness | $[mm]$ |
| $v_f$ | Fiber volume fraction | $[-]$ |
| $v_{wind}$ | Wind velocity | $[m/s]$ |
| $w_{bar}$ | Railing profile width | $[mm]$ |
| $w_{deck}$ | Deck width | $[mm]$ |
| $w_{side}$ | Side panel width | $[mm]$ |
| $y_{gw}$ | Location on gangway from hinge point | $[mm]$ |

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# Chapter 1

# Ampelmann & the current systems

This chapter contains an introduction to Ampelmann. It briefly describes how the system works followed by the selection of systems of interest for this thesis. With this knowledge the problems of the steel gangway design are defined. From these the research questions and sub-questions follow. The project outline concludes this chapter.

## 1.1 Ampelmann

Ampelmann has created a motion compensating system for the save transfer of personnel and cargo to offshore structures like oil rigs, wind turbines or other vessels. Previously these transfers were done by small boats which were limited to calm seas, by means of swingroping or by helicopter transfers. These methods are either expensive or create an unsafe working situation, both of which are undesired. With the current oil crisis other markets become more important. One of the more important markets is that of crew changes, where fast crew vessels are used as an alternative for helicopters for mid range offshore platforms. The problem with these fast vessels is that the current Ampelmann system is to heavy and thereby influences the stability of the vessel in a negative way. Decreasing the mass of the system will result in a better product for these light and fast vessels. By investigating the possibilities of using composites, the gangway mass will decrease and so will the counterweight.

### 1.1.1 How does the Ampelmann system work

The Ampelmann system is a hexapod base frame with a transfer deck on top of it. The gangway is mounted to the transfer deck. The six cylinders of the hexapod result in the compensation of six degrees of freedom. These are used to compensate the ship motions.

The gangway motions can be seen in Figure 1.1. Telescoping changes the length of the gangway to stay in contact with the structure, this creates a compression force in the structure when in operation. Luffing changes the inclination of the gangway to reach higher or lower parts. Lastly slewing is used to align the gangway with the structure depending on the heading of the ship.


**Figure 1.1:** Ampelmann A-type gangway motions (Courtesy of Ampelmann)

What the hexapod does is measure the motions of the ship and in real time calculate the motions the hexapod needs to make in order to compensate the motions of the vessel. This compensation results in a non moving transfer deck with respect to the structure the gangway is attached to, facilitating a safe and easy crossing. Because of the length of the cylinders the Ampelmann system also has its limits regarding operational wave heights. These limits are significantly higher than conventional boat transfers.

## 1.2 Ampelmann's systems

Ampelmann has developed multiple system in the nearly 10 years of operation. Two of these systems are of importance for this thesis as these are used on fast crew vessels. Firstly there is the A-type, the first walk2work (transferring people from ship to structure by means of a gangway system) gangway system ever build. The A-type uses a 25 meter gangway, the Gangway XL (GXL). This system is displayed in Figures 1.1 & 1.2.

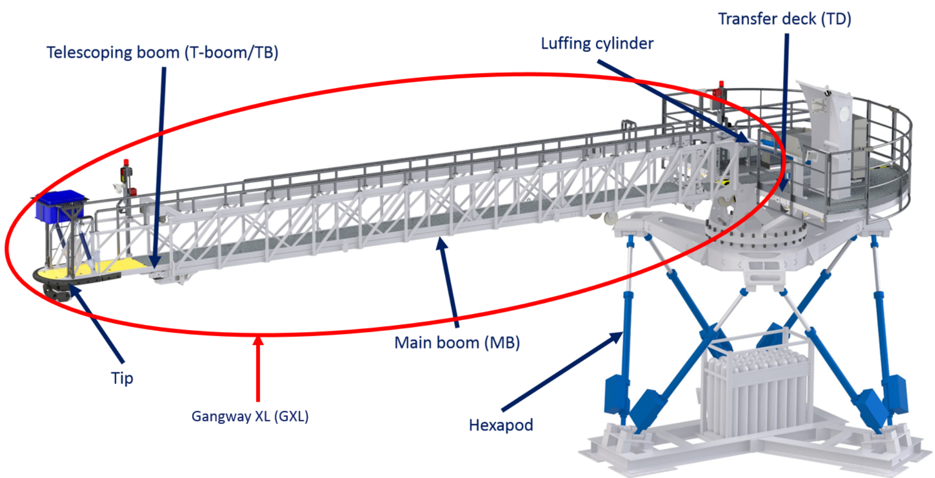



**Figure 1.2:** Different parts of the Ampelmann A-type system (Courtesy of Ampelmann)

Recently the S-type concept has been released, a lightweight system designed for fast crew vessels. The S-type does not use a hexapod with cylinders. The compensation is done in a different way. The current design of the S-type can be seen in Figure 1.3. Next to the removed hexapod, the luffing cylinders are pushing the gangway up instead of pulling on the railing as is done on the A-type. This might be beneficial for a composite gangway. The gangway of the S-type is the same length as the Gangway XL (GXL).


**Figure 1.3:** Ampelmann S-type gangway system (Courtesy of Ampelmann)

The current A-type gangway parameters can been seen in Table 1.1. The gangway consists of three parts. The main boom is the part connected to the platform, the Telescoping Boom (T-boom) is the part which extends to stay in contact with the structure. The tip is the final piece which actually makes contact with the structure. All parts can be seen in Figure 1.2. Regarding the axis of the Center of Gravity (c.o.g.), these can be seen in the bottom right of Figure 1.1.

**Table 1.1:** Gangway XL properties and center of gravity

| | Symbol | Unit | Main boom | Telescoping boom | Tip |
|---|---|---|---|---|---|
| **Mass** | $m$ | $[kg]$ | 1851 | 1365 | 182 |
| **Length** | $L$ | $[m]$ | 12.8 | 13.2 | 1.1 |
| **Height railing** | $h_{railing}$ | $[m]$ | 1 | 0.9 | 0.9 |
| **Walkway width** | $w_{walkway}$ | $[m]$ | 0.7 | 0.6 | 0.6 |
| **Center of gravity, retracted (x,y,z)** | | $[m]$ | (6.51,0.01,1.34) | (7.61,0.02,1.42) | (15.32,0.15,1.08) |

## 1.3 Issues of steel gangway design

The current systems are still competitive in the market, but with increasing competitors innovations need to be made in order to increase the market of Ampelmann. The steel gangway has reached its limits, by changing the material gangway specifications can be changed to increase the suitability of the gangway. The benefits of a composite gangway are listed below.

- Longer gangway at equal weight, removing the need for a pedestal and increasing possible landing heights.

- Wider gangway for increased passenger flow, shorter connections times will result in more transfers per day.
- More cargo load on the tip for transferring supplies, fewer moves for the same amount of payload.
- Less energy consumption by decreasing the weight of the moving parts of the system, possibility to go to an electric system.
- Lightweight system to minimize the influence on the ships behavior during transits, higher vessel speed for increased customer efficiency.

## 1.4 Composite design challenge

The current Ampelmann GXL meets all stated requirements. But since competition in arising new developments need to be made. One of the main points of the current system that it adds a lot of weight to the vessel. This reduces the maximum speed which is especially important on crew change vessels. Apart from this speed penalty, the high mass requires a lot of power to operate. Reducing the mass of the gangway would work its way down, reducing the weight of the complete system. That is the challenge of a composite gangway design.

### 1.4.1 Research questions

The main question which needs to be answered can be formulated as follows: *Can a composite gangway be designed which can be produced and certified while being lighter at equal performance compared to the current steel gangway*

1. Can a composite gangway be designed to replace the current GXL?
    - What are the critical load cases for a composite gangway?
    - Which locations are failure critical?
    - How would a basic design look like?
    - How will the design be produced?
2. How can joints be made to connect the different parts of the structure as well as to connect the gangway to the transfer deck?
    - Which connections are critical?
    - How would the connections look like?
    - Can these connection be certified?
3. What are the life cycle costs of a composite gangway?
    - What are the engineering and production costs?
    - What maintenance and inspections are needed?

### 1.4.2 Project outline

In Figure 1.4 the work flow of this master thesis is presented. The project starts with the literature study. From this a basis is formed the rest of the project. Requirements are defined, both from Ampelmann and the certifying authorities. Due to the absence of composite specific regulations the certifying agencies are contacted to see which steps will be needed to create regulations and/or certify a design. Materials and production processes are selected which suit the design philosophy. Three concepts will be created and analyzed using simplified equations to determine their performance. The chosen concept will be developed into a basic design, the connections are sized and the costs determined. Manual iterations follow if required. As a final step the limits of the basic design are tested, in other words, what is the maximum length given the design or the maximum cargo capacity on the tip.

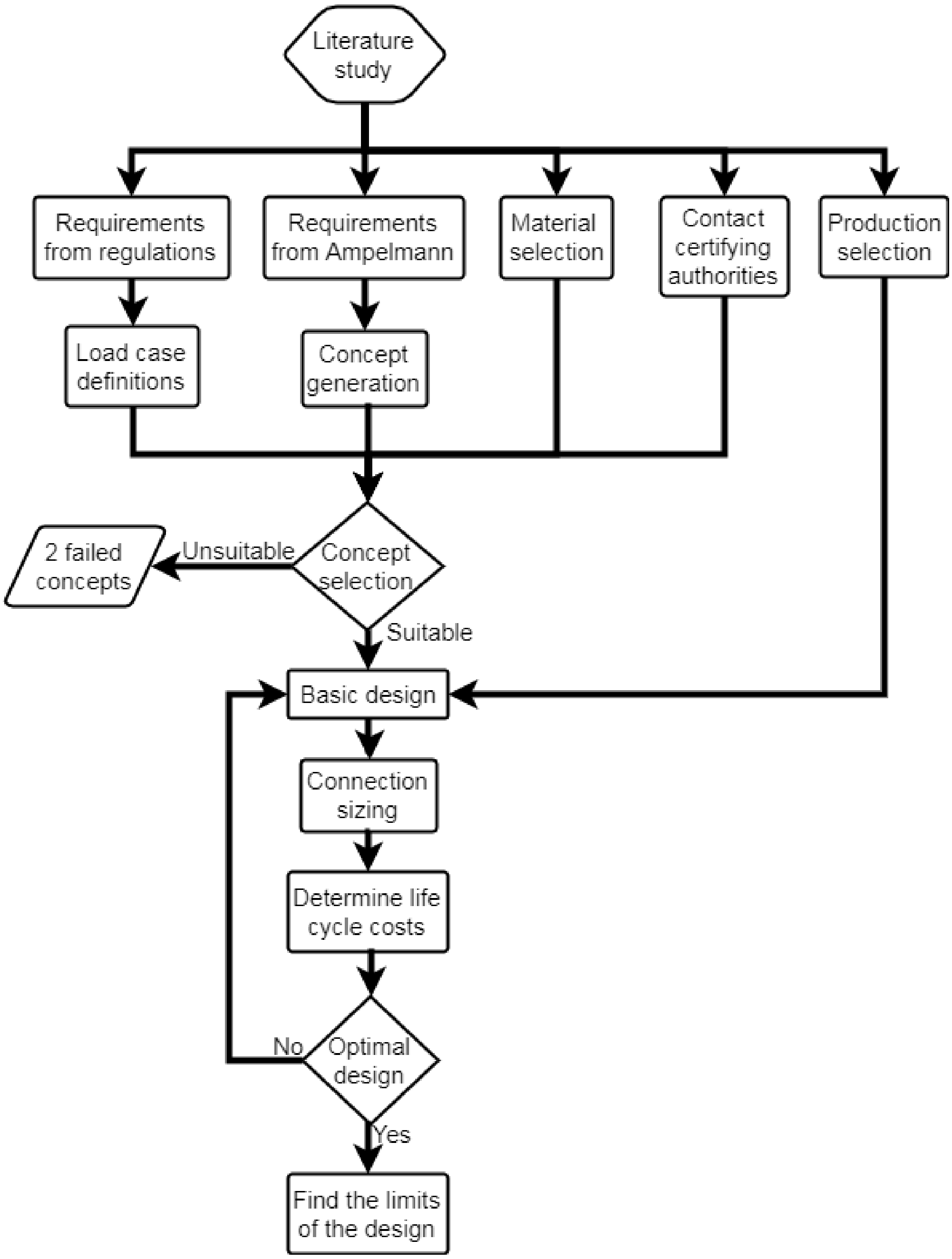



**Figure 1.4:** Composite gangway design project work flow

# Chapter 2

# Regulations & requirements

In order to be able to provide Ampelmann Operations with a product fulfilling their wishes, requirements need to be defined. These will state the minimal performance parameter a design needs to fulfill. Next to customer requirements, the certifying authorities have stated requirements as well, divided in two parts. Firstly the requirements for a motion compensated gangway and secondly regarding composite materials. Due to the, up to today, limited use of composite materials in the offshore industry the later is limited. This chapter starts with the regulations from which the load cases are obtained. It is concluded with the requirements stated by Ampelmann.

## 2.1 Regulations

The track record of Ampelmann is partly due to the certification of its systems. Two main certifying agencies are operating in the area where Ampelmann's systems are used, Lloyd's Register (LR) and Det Norske Veritas Germanischer Lloyd (DNV GL). Current systems are certified by LR but there is some discussion to switch the certification to be performed by DNV GL.

The certification can be split up in two parts. First there are the regulations for an offshore Walk2Work system. These define the loads and requirements for the complete system. Secondly there are the, although very limited, regulations regarding composite components for marine and offshore use.

### 2.1.1 Offshore Walk2Work system

The regulations for Walk2Work systems are available from both LR and DNV GL. LR was first with the Code for Lifting Appliances in a Marine Environment (CLAME). The regulations from DNV GL are largely based on the CLAME with some small differences. The most important difference is the maximum wind speed requirement which is lower in the DNV GL regulations.

As the current Gangway XL (GXL) is certified under the CLAME from LR this guideline will be used for the composite design as well. The most important requirements following from the CLAME are stated below:

- Minimal walkway width should be 600 mm
- Minimal railing height should be at least 1000 mm
- Spacing between stanchions should be less than 1500 mm
- At least three horizontal members should be present in the railing
- Gangway deflection in people transfer mode should be $\leq$ L/100 mm
- Gangway deflection in cargo transfer mode should be $\leq$ L/30 mm
- Gangway walking surface should not be slippery, also when wet

### 2.1.2 Composite for offshore

Next to the system, the composite gangway will need to be certified. Due to the limited use of composites in the offshore industry there are no clear regulations. DNV GL has more regulations for composite components, the list of certified materials like resin, fibers and cores is also more extensive compared to LR. The different guidelines and documents with certified materials are stated in Table 2.1.

**Table 2.1:** Certification rules and guidelines

| | **Lloyd's Register** | **Det Norske Veritas Germanischer Lloyd** |
|---|---|---|
| Gangway | Code for Lifting Appliances in a Marine Environment (CLAME) [1] | Certification of offshore gangways for personnel transfer (DNVGL-ST-0358) [2] |
| Composites | Rules for the Manufacture, Testing and Certification of Materials (MTCM) [3] | Composite Components [4] |
| Materials | Carbon and para-aramid fibre reinforcements [5]<br>Core materials for sandwich construction [6]<br>Thermosettign marine resins [7]<br>Adhesive/bonding pastes/resin topcoats [8] | DNV approval finder [9] |

Both DNV GL and LR were approached during the basic design phase to determine the critical points in the introduction of a composite gangway. DNV GL was unwilling to provide assistance in the process, LR did provide useful information about how the see the implementation of a composite gangway for Ampelmann. The main points stated by Maro Hartmann, from LR, for the possible certification are:

- Depending if the structure is used as an evacuation system, specific fire and heat resistance might be required.
- A specialized composite engineering firm will help to speed up the certification. The will need to provide a composite specific Finite Element Method (FEM) analysis.
- The production and assembly needs to be audited.
- Testing of a prototype or prototype parts, depending on the design, is needed.
- Yearly inspection of the gangway is needed to detect damage at an early stage.
- Ideally there are no connections, if there is no other way the peel stresses need to be minimized.
- Damages and their repairs need to be submitted for approval.

## 2.2 Load cases

For a successful design the forces and moment acting on the gangway during different operations are needed. These follow from load factors and accelerations, defined per operational mode, as described in the CLAME from LR.

The gangway operational modes can be divided in two cases. The first is as a cantilever been, as can be seen in Figure 2.1. There is the dead weight of the main boom and the Telescoping Boom (T-boom), they are combined at the overlapping section.

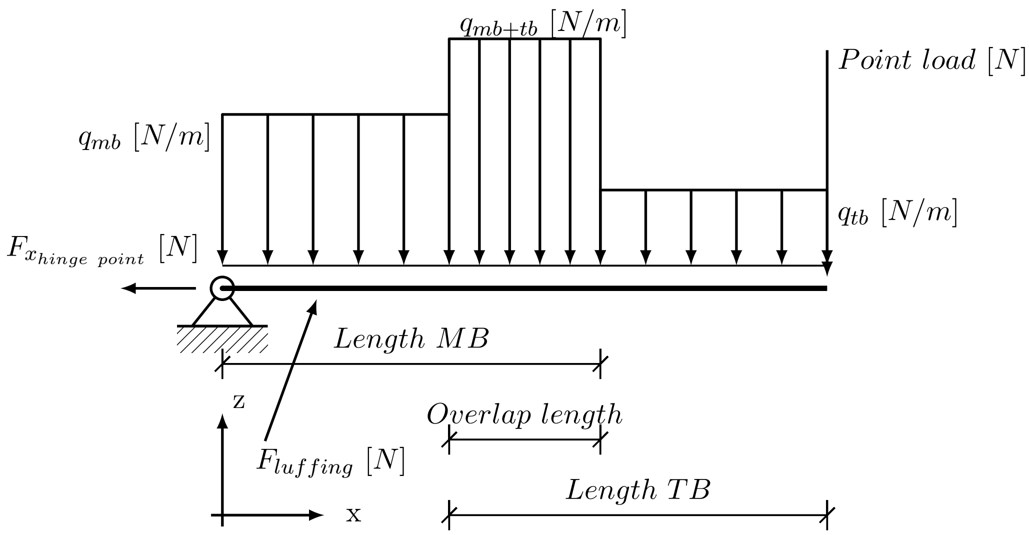



**Figure 2.1:** Free body diagram of the gangway in cantilever mode (x-z plane)

When the gangway is landed against the structure the situation changes partly. The weight of the gangway itself is still behaving as a cantilever beam but the point load is removed. The other loads are on a structure which can be described as simply-supported, see Figure 2.2. The point load is moved to the center of the gangway and an extra force is introduced. The telescoping force is the way to have a firm connection between the gangway and the platform.

The different operational modes correspond to load cases as described below. Load factors, accelerations and forces corresponding to these load cases can be found in Table 2.2.

#### Load case 1: Normal operation - cargo transfer (NO-CT)

If cargo is transferred, it is placed on the tip while the gangway rests on the deck. The system is activated and the gangway is directed to the platform. The cargo is thereby supported by the gangway in cantilever mode.

#### Load case 2: Normal operation - people transfer (NO-PT)

The main operating mode is people transfer. In this case the gangway will be in its nominal length in calm weather. There are residual accelerations and reaction forces due to the landed tip. Only one transferee is assumed to be on the gangway at any moment in time.

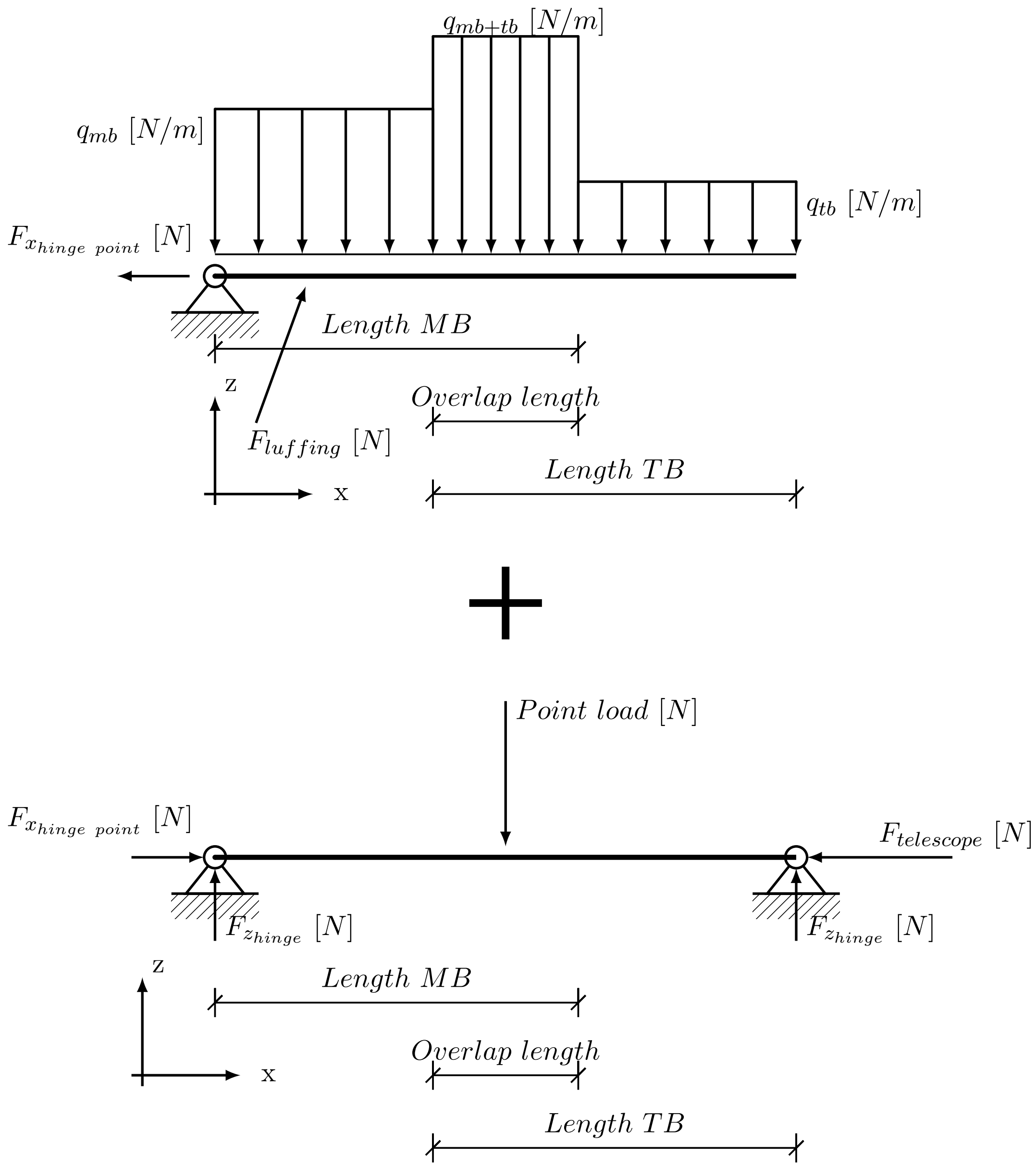



**Figure 2.2:** Free body diagram of the gangway in landed mode (x-z plane)

#### Load case 3: Emergency case - extra long gangway (EC-EL)

The gangway is extended to the maximal length and not landed. A tip load is present and wind is acting on the gangway. The luffing angle is zero degrees and no heel and trim are present.

#### Load case 4: Emergency case - 3 people transfer (EC-3P)

If there is an emergency and a person needs to be transferred by means of a stretcher the live load on the gangway increases. At least three people, two walking and one on the stretcher, will be on the gangway close to each other. It has to withstand these loads in rough conditions with high winds and residual accelerations.

#### Load case 5: Emergency case - cargo transfer (EC-CT)

When a cargo transfer is being performed at rough conditions the EC-CT parameters are reached. This most challenging case is the most critical one in the design.

#### Load case 6: Stowed condition (SC)

The final load case is when the gangway is stored on deck. The complete gangway is assumed to be simply supported. During Atlantic transfers wind speeds can go up drastically. The stowed load case is not taken into account in this research as the exceptional loads will have a large influence on the outcome.

**Table 2.2:** Load case parameters based on CLAME by Lloyd's Register [1]

| Parameter | Symbol | Unit | NO-CT | NO-PT | EC-EL | EC-3P | EC-CT |
|---|---|---|---|---|---|---|---|
| Safe working load | $SWL$ | [kN] | 0 | 1 | 1 | 3 | 0 |
| Duty factor | $F_d$ | [-] | 1.2 | 1.2 | 1.0 | 1.0 | 1.0 |
| Hoisting factor | $F_h$ | [-] | 1.15 | 1.15 | 1.15 | 1.15 | 1.1 |
| Wind velocity | $v_{wind}$ | [m/s] | 0 | 0 | 20 | 20 | 20 |
| Acceleration x | $acc_x$ | [m/s$^2$] | 0.5 | 0.5 | 0.5 | 0.5 | 2.0 |
| Acceleration y | $acc_y$ | [m/s$^2$] | -0.5 | -0.5 | -0.5 | -0.5 | -2.0 |
| Acceleration z | $acc_z$ | [m/s$^2$] | 0.5 | 1.0 | 1.0 | 1.0 | 2.0 |
| Free-float slew | $FF_{slew}$ | [kN] | 1 | 1 | 0 | 1 | 0 |
| Free-float luffing | $FF_{luffing}$ | [kN] | 1 | 1 | 0 | 1 | 0 |
| Free-float telescope | $FF_{telescope}$ | [kN] | 10 | 10 | 0 | 10 | 0 |
| Max heel | | [°] | 0 | 0 | 0 | 0 | -5 |
| Max trim | | [°] | 0 | 0 | 0 | 0 | 2 |
| Luffing angle | $\alpha_{luffing}$ | [°] | 0 | 10 | 0 | 0 | 10 |
| Operational mode | | [-] | Landed | Landed | Cantilever | Landed | Cantilever |

Based on Table 2.2 and outcomes of the design script the Emergency Case - Cargo Transfer (EC-CT) is found to be the worst load case. The combination of the cantilever mode, luffing angle, heel, trim, wind speed and accelerations creates the highest loads on the gangway.

## 2.3 Requirements by Ampelmann

Next to the requirements needed for certification, Ampelmann has extra requirements for the gangway. These are split up in operational, structural, Life Cycle Costs (LCC), production and certification requirements.

### 2.3.1 Operational

Next to the minimal dimensions as stated in section 2.1, Ampelmann has extra requirements for the gangway, such that it fulfills the demands of the market.

- Nominal gangway length should be 21 m
- Maximal gangway length should be 25 m
- Deck space used when stored should be minimal
- Railing height should be 1100 mm
- Gangway should be compatible with current of future systems
- Design temperature is between -20 °C & 50 °C

### 2.3.2 Structural

To secure safe operation of the gangway and transfers the structure has to be designed fulfilling the following requirements:

- Eigenfrequency in cantilever mode should be $\geq$ 1.50 Hz
- Gangway deflection in people transfer mode should be $\leq$ L/100 mm
- Gangway deflection in cargo transfer mode should be $\leq$ L/30 mm
- Twist of the gangway in people transfer mode should be $\leq$ L/10 °
- Twist of the gangway in cargo transfer mode should be $\leq$ L/3 °
- Appropriate (composite) material knockdowns need to be used
- Use of metals should be minimal to decrease the impact of corrosion
- Failure should not occur during the life time of the gangway during normal use

### 2.3.3 Life time & life cycle costs

Saving weight or increasing the capacity of the gangway could create value. As the extend of the business potential is not known the requirements are stated as follows:

- Gangway shall have a life time of at least 20 years
- Gangway should not deteriorate in offshore conditions
- Life cycle cost should be less than the GXL
- Required maintenance costs/intervals should be estimated

### 2.3.4 Production

To make the introduction of a composite gangway feasible, the initial investment costs should be kept to a minimum.

- The gangway should be producible at minimal costs
- Repair/replacement of parts can be performed, ideally offshore

### 2.3.5 Certification

- Certified materials should be used where possible to minimize costs of testing
- The gangway should be safe to operate offshore
- The design should be convincing to create a process for certifying a composite gangway

# Chapter 3

# Concept design phase

In this chapter different gangway concepts are defined and compared, but first the basics of composites are described. Comparing these concepts is done based on Key Performance Indicators (KPI's) which are defined. Based on the outcome of the comparison, critical areas will be defined and a concept will be chosen. This design will be developed further in Chapter 5.

## 3.1 Introduction to composites

A short introduction to composites is described which is followed by stating the main advantages and disadvantages of using composites as a structural material for offshore applications.

### 3.1.1 Components inside a composite

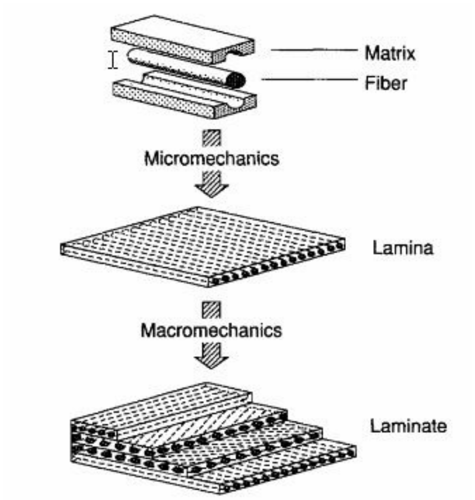
Fiber Reinforced Polymers (FRPs) are a composite material, consisting of two materials with different properties. On the one hand there is the fiber, strong and stiff in the lengthwise direction but weak in the perpendicular direction. These can be glass fibers, carbon fibers, Boron, Kevlar and many more. On the other hand there is the resin, also called matrix, isotropic but not strong, nor stiff. The resin is needed to introduce the forces into the fibers and to keep the fibers together. The combination of fibers and resin and curing them result in the formation of the actual composite material. As the fiber are only strong in a single direction different fiber angles are used to for a laminate. This process is depicted in Figure 3.1a. [10] Four principle angles are defined, [0°, 90°, +45°, -45°], these are most frequently used in laminates.

To minimize side effective of composites the laminate is preferably symmetric and balanced. Symmetric means that the ply angles are symmetric around the laminate mid plane. Balanced is that for a $+\theta$ ply there is a -$\theta$ ply, So for a +45° there needs to be a -45° ply. These plies need to be close to another, preferable directly on top, to minimize bending-twisting couplings as follows from the B-matrix.

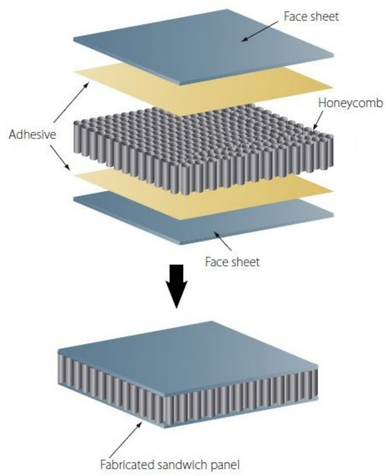
Due to each ply having different stiffness, different angle and other distance to the mid-plane a representation of the laminate needs to be made. Classical laminate theory is used to calculate the ABD matrix, a 6x6 matrix, where the A matrix is the top left 3x3 representing the laminate stiffness, the D-matrix is the bottom right 3x3 representing the laminate bending stiffness and the remaing two blocks are both the same B-matrix, which determines the membrane/bending coupling. A balanced and symmetric laminate simplifies the ABD matrix as the B-matrix is zero in this case. More information about the ABD matrix and the calculation can be found in *Design and Analysis of Composite Structures* by Christos Kassapoglou. [11]

Another important parameter of a composite is the fiber volume fraction, $v_f$, this ranges between 0.3 for lower quality composites to 0.7 for high end space applications. The higher the fiber volume fraction the better the performance of the laminate. A values close to 0.7 the toughness is reduced and the laminate becomes brittle. An ideal fiber volume fraction for the gangway would be around 0.6. Next to the fiber volume there is the matrix volume fraction and void fraction, the latter is important as this is a measure of the quality of the laminate. The void volume fraction should be below 0.02 for the gangway application. [10]

When extra bending stiffness is needed two laminates can be placed on a core to create a sandwich panel as can be seen in Figure 3.1b. Adding this distance between the two laminates has a large effect on the bending stiffness with a minimal increase in weight. Different core materials can be used with a scale of densities and other properties as will be discussed in Section 4.1. As the core is lightweight its properties are low. The core is a weak parts of the design and precautions are needed to prevent failures associated with the core, more is explained in Section 4.3.




**(a)** Creating a laminate from matrix and fibers (Adapted from Isaac M. Daniel [10])




**(b)** Creating a sandwich panel (Adapted from Admatis [12])

**Figure 3.1:** Different phases of composites from individual fibers and resin to a sandwich panel

### 3.1.2 Advantages & disadvantages of composites

Using composites as a replacement of steel will have advantages as well as disadvantages. The most important advantages are stated first and are followed by the disadvantages and possible solutions to minimize the effect of those.

#### Advantages

- Composites do not corrode when in contact with salt water.
- Fibers used in composites are isotropic, material is only placed in the direction where it is needed, resulting in extra weight savings for structures mainly loaded in one direction.
- Composites require little to no maintenance.
- Composites have good fatigue behavior compared to steel.
- The expected life time of a composite (bridge) structure is 50-100 years.

#### Disadvantages

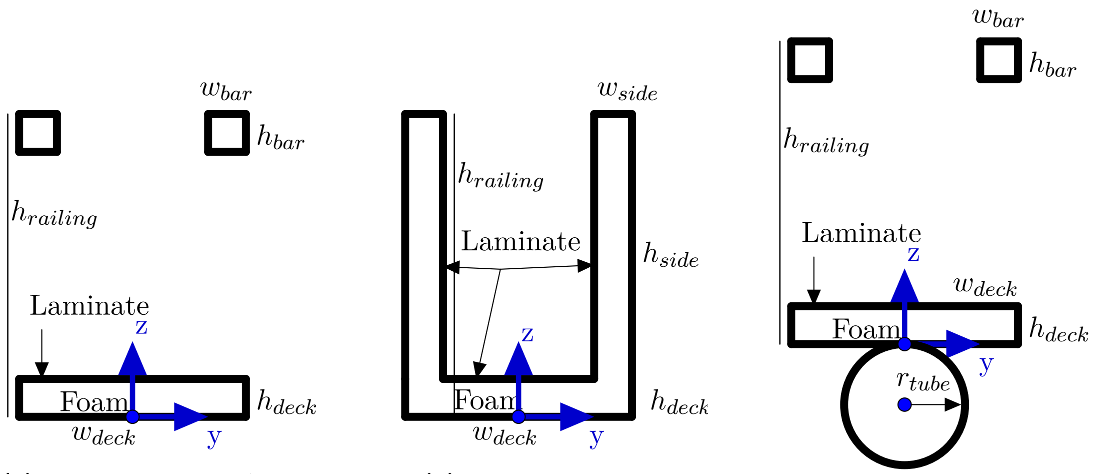
- Carbon fiber and steel are not directly compatible, galvanic corrosion will occur. Using stainless steel and/or using a layer of glass fiber will isolate the materials and prevent the galvanic corrosion.
- Damage (impact) cannot be seen from the outside while serious damage might be present on the inside of the laminate. To monitor the "health" of the gangway it is possible to embed sensors into the laminate to measure the deformations and loads encountered by the gangway. Sending a warning when stated thresholds are exceeded.
- Composites do not yield, they are elastic until failure. This means that if it fails, it is suddenly and most likely critical failure. Multiple design factors are taken into account to remove uncertainties and create an overdesigned structure.
- The production of the structure is, at the same time, also the production of the material. Taking care of the production is critical to minimize flaws in the product.
- No regulations for using composites for offshore applications like the Ampelmann system exists at this moment. This creates a possibility to define regulations in a combined effort.
- In general using carbon fiber composites to replace steel will increase the costs. Carbon Fiber Reinforced Polymer (CFRP) costs are about 20-50 €/kg, [13] depending on the type of fiber used. Fewer material is needed as the gangway mass is decreased. Furthermore no welding is required, reducing both time during welding as the checks performed on every weld. It is not possible to state up front if a composite gangway will be more expensive compared to the steel Gangway XL (GXL).

## 3.2 Concept introduction

In order to find a good concept for a composite re-design of the gangway different concepts were created. The main focus points for these configurations were producability and certifiability. The ultimate composite design is less important. Due to the time frame of this thesis three concepts have been defined, these are displayed in Figure 3.2.

The first concept consists of a sandwich deck with a railing attached to it, Figure 3.2a. The railing and the deck are carrying the bending loads. Below the railing there will be a framework consisting of stanchions, diagonals and extra horizontal members in order to create rigidity.

The second concept is shown in Figure 3.2b, a one-piece U-shaped boom, completely made using sandwich panels is a new concept for Ampelmann. The closed sides will provide a feeling of safety and increase the bending stiffness. The extra side area might cause a problem in high wind operations.




**(a)** Concept 1: Deck & railing

**(b)** Concept 2: U-shape

**(c)** Concept 3: Deck, railing & tube

**Figure 3.2:** Graphical representation of the load carrying structures for the three different concepts

The third concept looks similar to concept 1 but with the addition of an extra tube mounted below the deck, Figure 3.2c. Adding this tube increases the torsional rigidity of the structure. Telescoping of the gangway can be done using the tube as well.

## 3.3 Assumptions made for concept calculations

To speed up the calculations needed to select a concept, assumptions are made for each concept. These assumptions simplify calculations but still result in a good comparison between the different options. Some of these assumption hold for all concepts where others are concept specific. The used assumptions are stated per concept.

### Concept 1: Sandwich deck with loaded railing

1. All sides of the sandwich deck have the same balanced and symmetric lay-up
2. The Center of Gravity (c.o.g.) location is defined from the bottom of the deck
3. The core is weak and has therefore no influence on bending stiffness and torsional rigidity. It only creates distance between the skins
4. The ABD and inverse ABD (abd) matrices are calculated using Equation (3.1) [11]
5. The foam, both mass and physical properties, are neglected
6. The railing will only carry bending moments and no torsional loads

$$D_{ij} = 2D_{ij_f} + 2A_{ij_f}\left(\frac{t_c + t_f}{2}^2\right) \tag{3.1}$$

In which $D_{ij_f}$ and $A_{ij_f}$ are the A & D matrix terms of the facesheet and $t_c$ and $t_f$ are the core and facesheet thickness's.

#### Concept 2: Sandwich panel U-shape

1. All laminates have the same balanced and symmetric lay-up
2. The structure is modeled as three panels forming a U, plies going around the corner and the required radius are neglected
3. The ABD and inverse ABD (abd) matrices are calculated using Equation (3.1) [11]
4. The c.o.g. location is defined from the top of the railing
5. The core is weak and has therefore no influence on bending stiffness and torsional rigidity.It only creates distance between the skins
6. The foam, both mass and properties, are neglected

#### Concept 3: Sandwich deck with loaded railing and tube

1. All sides of the sandwich deck have the same balanced and symmetric lay-up
2. The connection of the tube to the deck is neglected
3. The c.o.g. location is defined from the bottom of the deck
4. The ABD and inverse ABD (abd) matrices are calculated using Equation (3.1) [11]
5. The core is weak and has therefore no influence on bending stiffness and torsional rigidity. It only creates distance between the skins
6. The foam, both mass and properties, are neglected
7. The railing will only take bending moments and no torsional loads

## 3.4 Key performance indicators

In order to compare the options, Key Performance Indicators (KPI's) are defined to which all are tested. These KPI's are defined such that important requirements are covered. The main performance parameters are the deflection and twisting of the gangway in cantilever mode and the eigenfrequency when operating the gangway from lifting from deck until landed against the structure.

### 3.4.1 Bending stiffness and deflection

The maximal deflection of the gangway in operation is defined by the regulations and is set to $L/100$. The tip deflection of the gangway, in cantilever mode, is calculated using Equation (3.2). A low bending stiffness will results in excess deflection, also the motions of the gangway when trying to land increase with a decrease in stiffness.

$$\delta_{tip} = \frac{PL^3}{3EI} + \frac{qL^4}{8EI} \tag{3.2}$$

In which $P$ is the point load on the tip in $N$, $L$ is the length of the gangway in $m$, $EI$ is the average bending stiffness of the gangway in $Nm^2$ and $q$ is the distributed load due to the gangway mass in $N/m$.

In order to calculate the deflection of the gangway the distributed load $q$ is needed, which is the dead weight of the gangway. The mass calculation for the different concepts can be found in Appendix A.3. The bending stiffness, $EI$, is calculated as shown in Appendix A.1. The final calculation of the gangway deflection can be found in Appendix A.4.

### 3.4.2 Torsional rigidity and twist

Next to deflection of the gangway, twisting will result in discomfort and dangerous situations. Therefore the twist, in degrees, is calculated using Equation (3.3).

$$\phi' = \frac{T}{GJ}\frac{180}{\pi} \tag{3.3}$$

In which $T$ is the torque in $Nm$ and $GJ$ is the torsional rigidity of the gangway in $Nm^2$.

The torsional rigidity is different for each concept, the calculations can be found in Appendix A.2. Torsion of the gangway is mostly created by wind. It is a function of wind speed and side area, as can be seen in Appendix A.5.

### 3.4.3 Eigenfrequency

The eigenfrequency requirement of the gangway is set such that the system will not be dynamically unstable, furthermore it assures the system to be able to connect to the platform efficiently. An initial and simplified estimation is made using an analytical approach as stated in Equation (3.4), from Young, et al. [14].

$$f = \frac{1.732}{2 \cdot \pi}\sqrt{\frac{EI \cdot g \cdot 1000}{P \cdot g \cdot L_{gw}^3 + 0.236 \cdot q_{gw} \cdot L_{gw}^4}} \tag{3.4}$$

In which $EI$ is the average bending stiffness of both booms in $Nmm^2$, $P$ is the point load on the tip in $kg$, $L_{gw}$ is the total gangway length in $mm$ and $q_{gw}$ is the gangway weight in $N/mm$.

### 3.4.4 Producability

An optimal gangway design which cannot be produced is useless for Ampelmann. Due to the fact that quantifying the produceability is not possible, an engineering judgment will be used to determine which concept shows the most potential considering production. This engineering judgment is based on personal experience with building FRP pedestrian bridges.

### 3.4.5 Certifiability

Certification is a difficult KPI to quantify, especially since there are no rules yet regarding the use of a composite offshore gangway. Based on the different regulations regarding composites in an offshore/marine environment from both Lloyd's Register (LR) and Det Norske Veritas Germanischer Lloyd (DNV GL) it was found that connections will cause concerns at the authorities.

Hence, the main criteria for certification will be the number and difficulty of the needed connections. Next to this, the design needs to withstand all loads. Due to the generic laminates used, this will not result in differences between the concepts and is therefore not taken into account in this study.

## 3.5 Results

In this section the results of the concept phase are discussed. Before the results can be obtained, the input parameters need to be defined. A sensitivity analysis is made to determine the most effective parameters to tweak. The results follow thereafter.

### 3.5.1 Input parameters

Two sets of inputs are needed. First geometrical parameters can be found in Table 3.1. These are based on the current GXL and prior FRP bridge building experience. Second, material properties are defined in Table 3.2. The used materials are carbon fiber prepreg and Polyvinylcloride (PVC) foam.

**Table 3.1:** Initial geometric parameters for parametric study

| Parameter | Symbol | Unit | Value |
|---|---|---|---|
| Width of deck | $w_{deck}$ | [mm] | 800 |
| Height of deck | $h_{deck}$ | [mm] | 80 |
| Width of railing bar | $w_{bar}$ | [mm] | 50 |
| Height of railing bar | $h_{bar}$ | [mm] | 50 |
| Width of the side panel | $w_{side}$ | [mm] | 50 |
| Height of the railing | $h_{railing}$ | [mm] | 1000 |
| Radius of the tube | $r_{tube}$ | [mm] | 100 |
| Plystack | | [°] | 45/-45/0/0/90/0/0/-45/45 |

**Table 3.2:** Material properties used for parametric study

| Prepreg | | | | Foam | | | |
|---|---|---|---|---|---|---|---|
| **Parameter** | **Symbol** | **Unit** | **Value** | **Parameter** | **Symbol** | **Unit** | **Value** |
| Fiber volume fraction | $v_f$ | [%] | 60 | Density | $\rho$ | [kg/m$^3$] | 250 |
| Density | $\rho$ | [kg/m$^3$] | 1,530 | Shear strength | $\tau_{xy}$ | [MPa] | 4.5 |
| Young's modulus (0°) | $E_{11}$ | [GPa] | 130 | Shear modulus | $G$ | [MPa] | 97 |
| Young's modulus (90°) | $E_{22}$ | [GPa] | 8 | | | | |
| Shear modulus | $G$ | [GPa] | 4.8 | | | | |
| Ply thickness | $t_{ply}$ | [mm] | 0.5 | | | | |

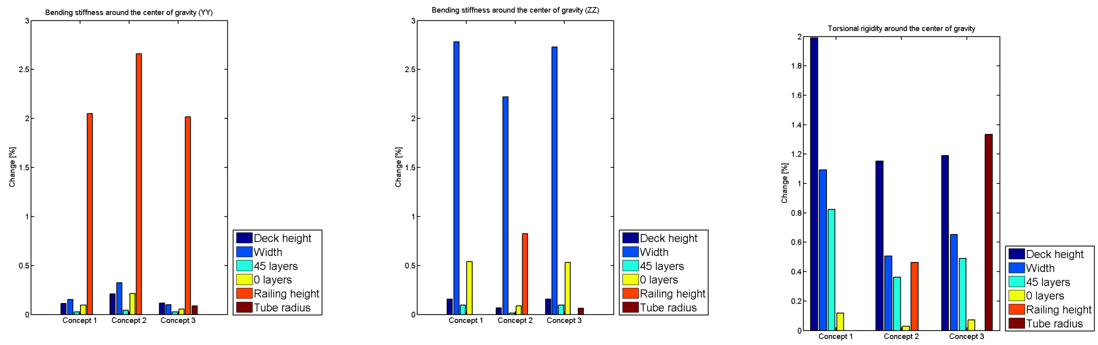
### 3.5.2 Sensitivity analysis of bending stiffness and torsional rigidity

Bending stiffness and torsional rigidity are, together with the eigenfrequency, the most important KPI's. To get a better understanding on the influence of changing geometric parameters, a sensitivity analysis is done.

Bending stiffness is calculated about the gangway y- and z-axis. The y-axis is important for the deflection and the luffing stability whereas the z-axis is important for slewing stability. The results of the sensitivity analysis can be seen in Figure 3.3a for the y-axis and Figure 3.3b for the z-axis.

Looking closer at Figure 3.3a it can be concluded that increasing the railing height has the largest influence on the bending stiffness. This is due to the parallel axis theorem, the area of a member times the distance to the structure's c.o.g. squared. Placing the load carrying members further away from the c.o.g. is the best way to increase the bending moment.

For the bending stiffness around the z-axis, Figure 3.3b, the same conclusion can be drawn. An increase in the width of the gangway places the sides of the deck and the railings further away from the c.o.g., resulting in an $EI_{zz}$ increase of at least 2% per % change.




**(a)** Bending stiffness around y-axis **(b)** Bending stiffness around z-axis **(c)** Torsional rigidity

**Figure 3.3:** Sensitivity analysis of the gangway stiffness's with a 1% increase in parameter value

The sensitivity of the torsional rigidity is depicted in Figure 3.3c. Differences can be seen between the different concepts. For concept 1, increasing the deck height has the most influence due to the increase of the closed area of the deck. For concept 2 the influence is less due to the open structure. Concept 3 will benefit the most from an increase in tube radius and increase in deck height. The effect of only deck height increase is less than for concept 1 because the total torsional rigidity of concept 3 is higher resulting in the same absolute increase but a lower relative one.

### 3.5.3 Masses and displacements

Before the deflection can be calculated the mass needs to be determined. Figure 3.4 shows the change in gangway mass with increasing length. Concept 1 is the lightest, while 2 is the heaviest due to the constant laminate thickness at all facesheets. This could be further optimized in an eventual design but is out of the scope of this concept phase.

The mass, together with the bending stiffness around the y-axis can be used to calculate the deflection as in Figure 3.5. A tip load of 100 $kg$ is placed on the tip, simulating a person is standing on the tip when the gangway disconnects. In red the threshold limited from the requirements, $L/100$ is displayed. All concepts fail the requirement below the desired length of 25 meter, meaning the lay-up used is insufficient for the loads. More plies are needed to increase the stiffness resulting in less deflection.

Wind loads can be high in offshore operating conditions. This wind will introduce a torsional load resulting in twist of the gangway. The twist of the concepts can be seen in Figure 3.6. In red once again the threshold value, $L/10$ [°] in this case. Concept 2 is, by far, the worst performing design. The closed railing with the open, U-shaped, design results in a large wind force and a shear center below the structure. It is difficult to see in Figure 3.6, but concept

3 experiences less twist compared to concept 2. The effect of the torsion tube is present but the effect is minimal. The tube also increases the side area resulting in more torsion.

### 3.5.4 Eigenfrequency

The last parameter to check is the eigenfrequency. Figure 3.7 shows the eigenfrequencies of the three concepts and the one of the current GXL.

Concept 1 is close to the GXL, as is concept 3. The U-shaped concept 2 is well below the others. Ideally the new gangway will have an eigenfrequency well above the GXL. Changing the lay-up will increase the eigenfrequency.

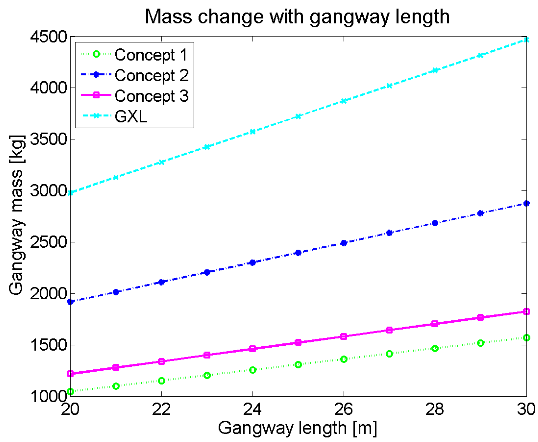



**Figure 3.4:** Gangway mass estimation of the concepts

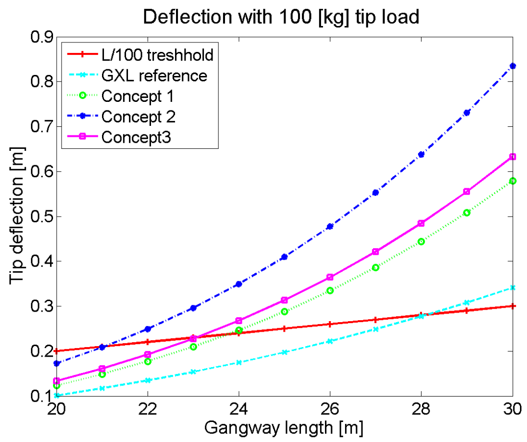



**Figure 3.5:** Deflection in cantilever mode with a tip load of 100 [kg]

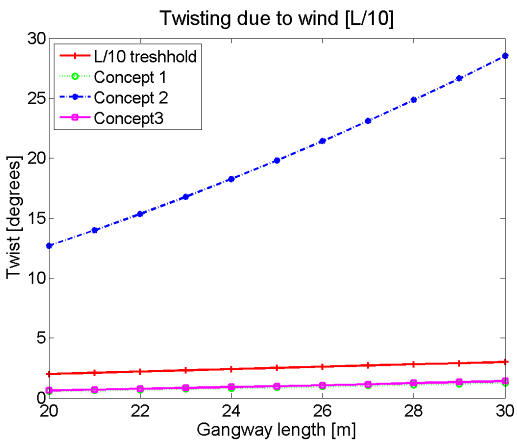



**Figure 3.6:** Twisting of the gangway in cantilever mode due to wind load

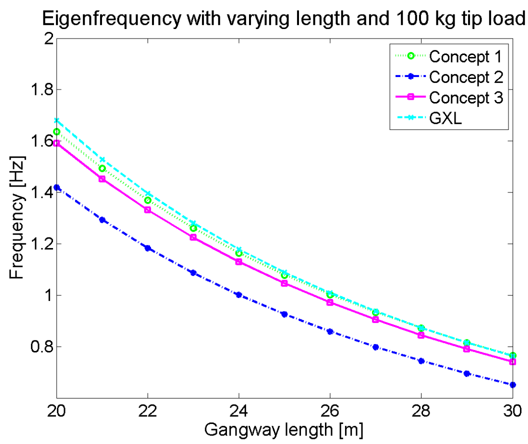



**Figure 3.7:** Eigenfrequencies for the different concepts at different lengths

## 3.6 Critical areas

From the results of the concept phase three critical areas can be defined:

- Eigenfrequency
- Railing connections
- Other connections

The eigenfrequency is the driver of the design. The calculation of the eigenfrequency is based on the assumption that the top part of the railing will carry bending loads. In order transfer loads from and to the railing the connections of the railing framework are highly important. The same holds for the other connections. A gangway which is unable to luff, slew and telescope in a safe way will not finds its way onto an Ampelmann system.

## 3.7 Trade-off

For a comparison of the different concepts the obtained results are used. An estimate of producability and certifiability is added. The trade-off table can be seen in Table 3.3. For each of the KPI's a weight factor has been defined.

The concepts are rated from 1 to 3, where 1 equals the best performing and 3 is the worst. Multiplying the weight with the rating and then summing all results in a total number of point, fewer points means a better concept.

**Table 3.3:** Gangway concept trade-off results

| **KPI** | **Weight** | **Concept 1** | **Concept 2** | **Concept3** |
|---|---|---|---|---|
| Deflection | 1 | 1 | 3 | 2 |
| Twist | 1 | 2 | 3 | 1 |
| Eigenfrequency | 1 | 1 | 3 | 2 |
| Production | 2 | 1 | 2 | 3 |
| Certification | 2 | 2 | 1 | 3 |
| **Total** | | 10 | 15 | 17 |

The trade-off results in **Concept 1** being the best option. It scores a second place on twist and certification. Twist is just a few percent below concept 3, still well below the stated threshold. At certification it scores a second place as well. Based on the amount of connections needed it performs less than concept 2, as concept 1 will have multiple connection in the railing compared to none for concept 2.

# Chapter 4

# Designing a composite structure

This chapter describes the process of creating composite structures focusing on the composite gangway. It starts with defining the materials considered in the composite re-design of the Ampelmann gangway. Different production methods for the parts of the gangway are stated next. Failure of composites is different compared to metals, how and why it fails is described in Section 4.3. Specific design rules for composites are described and how these influence the design of the gangway.

## 4.1 Materials

When designing a gangway made form Fiber Reinforced Polymer (FRP) there are a lot of different materials which are being used, especially when you compare this to a steel design. Each material needs to be certified to be part of the load carrying structure. Lloyd's Register (LR) has list of certified composite base materials in different categories, as discussed in Chapter 2. Using those materials will save both time and costs in the realization of a composite gangway.

### 4.1.1 Fibers and resin

Carbon fiber prepreg is selected as the material to use in the composite gangway design. Prepreg is short for pre-impregnated, meaning the resin is applied to the fibers after weaving/stitching. It needs to be stored inside a freezer to prevent curing. The SE 84LV prepreg series by Gurit is selected, different fibers are used for this prepreg, all of which are certified by LR. [5]

Prepreg will be used because it has a high fiber volume fraction of about 0.6, resulting in an efficient gangway. The properties are equal at every location as there is no risk of resin rich or poor areas as can be the case when using infusion processes. The resin rich or poor areas are weak points in the structure and should be avoided. The higher costs of prepreg, compared to dry fibers and resin are minimal as the amount of scrap materials are lower. Quality and safety of the structure are more important than costs.

Three different prepregs will be used in the design. High Elongation Carbon (HEC) and High Modulus Carbon (HMC) Unidirectional (UD) plies are used and a HEC ±45° Bi-axial (Biax). The most important properties are stated in Table 4.1 and the complete datasheet can be found in Appendix B The UD HEC is used for the 90° layers and lower loaded areas whereas the UD HMC is used in the 0° direction to increase the bending stiffness. The Biax layers are used to reduce the time to place these fibers.

**Table 4.1:** Gurit SE 84LV prepreg properties

| Parameter | Symbol | Unit | UD HEC | UD HMC |
|---|---|---|---|---|
| Young's modulus 0° | $E_{11}$ | [GPa] | 134 | 222 |
| Young's modulus 90° | $E_{22}$ | [GPa] | 8.3 | 7.1 |
| Tensile strength | $Xt$ | [MPa] | 2458 | 2658 |
| Compression strength | $Xc$ | [MPa] | 39.2 | 30.1 |

### 4.1.2 Core materials

A core is used between the two deck laminates to increase the bending stiffness of the gangway resulting in the desired eigenfrequency. A core has three specific requirements, first it needs to have a good connection to the facesheet to prevent debonding, second it needs to withstand the forces acting on it and thirdly it needs to be certified.

A foam core is selected for the gangway, it has sufficient mechanical properties, low moisture absorption and relatively inexpensive. The properties of foam core are depending on the type of foam and the density. The higher the density the better the core properties are.

The Gurit Styrene acrylonitrile (SAN) M-Corecell is selected as it has the good properties and is used in marine applications. Multiple densities are certified and the interphase between the laminate and core is good as both are from Gurit. Properties of the two suitable densities are stated in Table 4.2, depending on the loads either of them can be used.

**Table 4.2:** Gurit PVC and M-Corecell properties

| Parameter | Symbol | Unit | M60 | M130 |
|---|---|---|---|---|
| Density | $\rho$ | [kg/m$^3$] | 65 | 140 |
| Shear strength | $\tau_{xy}$ | [MPa] | 0.68 | 1.98 |
| Compression strength | $Xc$ | [MPa] | 0.55 | 2.31 |
| Tensile strength | $Xt$ | [MPa] | 0.81 | 2.85 |

### 4.1.3 Adhesives

Adhesives are needed at multiple locations in the gangway. First of all there is an adhesive layer between the core and the laminate to increase the core to facesheet bonding. Secondly connection in the railing framework and connection for the gangway motions are bonded to the deck.

To maximize the compatibility of the adhesive to the laminates the Gurit SA 80 adhesive is used. This bonding system is designed to work with the SE 84LV prepreg system and is certified to use.

**Table 4.3:** Gurit SA 80 adhesive properties

| Parameter | Symbol | Unit | SA 80 |
|---|---|---|---|
| Tensile strength | $Xt$ | [MPa] | 48 |
| Tensile modulus | $E_{11}$ | [GPa] | 2.5 |
| Glass transition temperature | $T_g$ | [°C] | 99 |
| Shear strength on steel | $\tau_{steel}$ | [MPa] | 36 |

### 4.1.4 Connectors

Two type of connectors can be distinguished, first there are the connections in the railing framework, secondly there are the connections for the hinge point, luffing cylinders and telescoping supports.

#### Railing connections

The railing connectors will be made from Polyetheretherketone (PEEK), a high performance thermoplastic. For the higher loaded connections the PEEK can be filled with glass or carbon fiber to enhance its performance. The properties of different types of PEEK can be found in Table 4.4. If the use of PEEK turns out to be impossible due to regulations, alternative solution can be made using the same carbon fiber prepreg as used in the deck.

**Table 4.4:** Properties of different grades of PEEK

| | Glass filled PEEK (LATI Larpeek 10 G/30) [15] | Carbon filled PEEK (LATI Larpeek 10 K/30) [16] | PEEK (LATI Larpeek 10) [17] |
|---|---|---|---|
| Tensile strength [MPa] | 175 | 240 | 90 |
| Filler content [%] | 30 | 30 | - |
| Density [kg/m$^3$] | 1500 | 1410 | 1300 |
| Tensile modulus [GPa] | 11.5 | 24.0 | 3.7 |

#### Luffing, telescoping and hinge point connections

These brackets will experience more complex loads, an isotropic material is used for these brackets. The combination of carbon fiber and metal can be tricky due to galvanic corrosion. Stainless steel is used to minimize the difference in potential. To further eliminate the galvanic corrosion an insulating layer of glass fiber is placed at the locations where brackets are placed. Typical values for stainless steel are stated in Table 4.5, these parameters are used in the design of the brackets.

**Table 4.5:** General stainless steel properties

| Parameter | Symbol | Unit | Stainless steel [18] |
|---|---|---|---|
| Tensile strength | $Xt$ | [MPa] | 620 |
| Yield strength | $\sigma_y$ | [MPa] | 310 |
| Tensile modulus | $E_{11}$ | [GPa] | 203 |
| Density | $\rho$ | [kg/m$^3$] | 8000 |

## 4.2 Production of composite structures

Different parts of the gangway will be produced in different ways. The main division of parts can be made in deck, railing and connections.

### 4.2.1 Prepreg lay-up for the deck & top railing

Due to the small number of gangways being build and the design not being weight critical hand lay-up is the process to go for. During this process employees place the prepreg inside a mold and apply a vacuum bag before the material is cured.

#### Placing the fibers in the mold

The mold is prepared by applying release agent to it. This will assure that the product can be removed from the mold after curing. Once the release agent is dry the prepreg will be placed inside the mold according to the lay-up drawings. The foam is placed in the mold and the prepreg is folded back over the foam. When the complete structure is laminated, peel-ply and breeder fabric are placed on top. The peel-ply acts as the release agent but now on top of the laminate. It prevents the bleeder fabric, used to remove excess resin in the prepreg, to stick to the deck. An advantage of the peel-ply is that, after removing it, it leaves a rough surface which is ideal for applying the grip layer. On top of the bleeder fabric the vacuum bag is placed. Air tightness is secured by applying tacky tape around the edges. Ones the vacuum has been tested the product is ready for curing.

#### Curing

The Gurit SE 84LV prepreg is an Out-of-Autoclave (OOA) prepreg, meaning only heat and vacuum is needed to cure the resin. No external pressure is required. An oven will be build around the mold, a simple tent can be used to contain the heat in a enclosed area. Heaters will be placed to increase the temperature whilst vacuum is applied to the mold. Depending on the temperature a certain curing times is needed. These times and temperatures can be found in Table 4.6. After curing the structure needs to cool down before it can be removed from the mold. The mold is cleaned and the process can start again.

**Table 4.6:** Cure times and corresponding propreties Gurit SE 84LV prepreg

| **Cure temperature** | **Cure time** | **Cure pressure** | **Dry Tg** |
|---|---|---|---|
| 80° C | 12 hours | -1 bar | 98° C |
| 120° C | 1 hour | -1 bar | 115° C |

### 4.2.2 Pultrusion for the railing framework

A cost effective process to produce large quantities of FRP is pultrusion. A process where dry fibers are pulled through a resin bath and run through a die. This die forms and heats the resin and fibers such that, ones it exits the die, the product is cured. Pultrusion is schematically presented in Figure 4.1.

Pultrusion can be done with both glass- and carbon fiber. In industry glass fiber is used almost always due to cost considerations. All thermosetting resin can be used, polyester or vinylester is used most from a cost perspective.

Custom profile designs are possible, just like carbon fiber pultrusion. Due to the start-up costs and the design and production of the mold this is feasible for production series of at least 1000 m according to Gert de Roover from Exel Composites. [19]

Exel Composites produces glass fiber pultrusions in different standard sizes. The fire, smoke and toxicity properties of Exel Composites are DIN1402 B2 certified [19], which should be sufficient for the operations of the system. Pultrusion profiles are used because it is a cheap process which produces constant quality, the main properties of some standard profiles are stated in Table 4.7. [20]

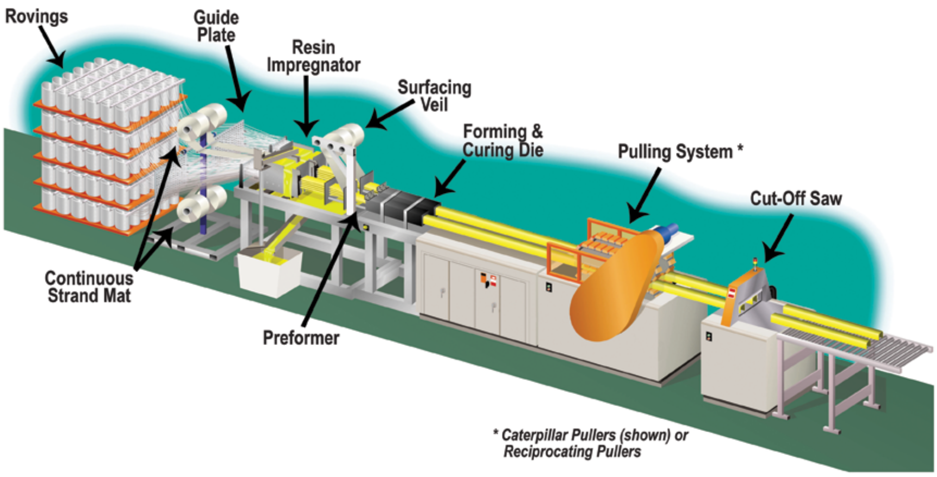



**Figure 4.1:** Schematic of pultrusion of composite profiles (Courtesy of Pultrusion Industry [21])

**Table 4.7:** Exel Composites glass fiber pultrusion profile properties

| Parameter | Symbol | Unit | 38x38x3 profile | 38x38x5 profile |
|---|---|---|---|---|
| Young's modulus 0° | $E_{11}$ | [GPa] | 23 | 23 |
| Young's modulus 90° | $E_{22}$ | [GPa] | 7 | 7 |
| Tensile strength | $Xt$ | [MPa] | 240 | 240 |
| Heat distortion temperature | | [° C] | >150 | >150 |

### 4.2.3 Railing connections

The brackets will be made using a Computer Numerical Control (CNC) machine using block of (filled) PEEK. The machine mills away the undesired material from the block. Depending on the amount of material and the tolerance required this process taken between minutes and a couple of hours. The advantage of CNC is that every bracket can be designed according to the loads acting on them. Furthermore, the process leaves a rough surface, which is ideal for the bonding of the profiles. Another main advantage is that the angle of the diagonal profile can be changed without the need for a new mold, making a change of boom length easier.

The downside of the process is the extra engineering time needed. If the product is successful and multiple gangways need to be built other production methods become cheaper. Suitable processes would be Resin Transfer Molding (RTM) or compression molding. These have no flexibility in the part thickness and geometry as they are made inside a mold.

### 4.2.4 Luffing, telescope and hinge point Connections

The metal brackets will be made by a forming or casting, depending on the bracket and the required radii of the corners. When forming is used, welding is required to combine the different parts. Each weld needs to be checked if the quality is sufficient. For casting production, investment casting is, due to the amount of brackets, most suitable. Both these processes are labor intensive, raising the costs of the brackets and the gangway.

## 4.3 Composite failure modes

Composites can fail in many different ways. All the possible failure modes need to be checked in order to determine the safety of the design. Most of the failure modes specific for a sandwich panel can be seen in Figure 4.2. This section does not contain formula's. However it will give an overview of failure modes and loads and described. More information about the calculations can be found in Chapter 5.

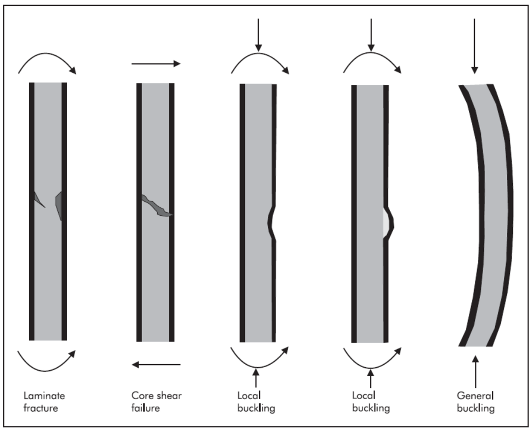



**Figure 4.2:** Different failure modes for sandwich panels (Courtesy of Strong [22])

The most important failure modes for the composite gangway design using a sandwich panel deck are listed below.

- First-ply-failure → Tsai-Wu criterion
- Laminate fracture
- Global buckling
- Local buckling
- Wrinkling
- Core shear failure
- Matrix cracking
- Facesheet debonding from the core

The first-ply-failure is the most important structural failure mode to check. Different theories have been developed over the years. [11]. Depending on the load case the most appropriate one can be chosen. Due to the combination of loads in the gangway in cantilever mode the Tsai-Wu failure criterion (Equation (5.10)) is used in the design.

## 4.4 Composite design rules

The composite industry has created guidelines and estimation methods to efficiently design laminates which will stand the test of time. First general laminate guidelines will be discussed followed by material knockdown factors.

### 4.4.1 Laminate design guidelines

For the design of a successful laminate guidelines exist. The rules stated below are taken from chapter 12 of the book of Christos Kassapoglou, *Design and Analysis of Composite Structures*. [11] Other authors have stated slightly different numbers, for example Joyce states a 12.5% rule [23] instead of the 10% by Kassapoglou [11]. These differences are small, for consistency all values are based on Kassapoglou's statements.

**Lay-up guidelines** When the lay-up is determined several guidelines are commonly used. These are defined over time and are used industry wide for the design of laminates. [11, p. 343-344]

- The lay-up should be symmetric and balanced, resulting in a B matrix which is zero and terms $A_{16} = A_{26} = 0$
- Bending/twisting couplings should be avoided by using fabrics if possible
- The 10% rule, minimal 10% of plies in all of the four principal directions
- No more than 4-5 UD plies in the same direction on top of each other or 0.6-0.8 mm
- Place ±45° plies on the outside to improve damage resistance, this also helps against buckling and crippling

### 4.4.2 Knockdown factors

When designing composite structures certain safety margins are build in to take certain physical effects into account. Knockdown factors are introduced to account for the degradation of both the strength and the stiffness of the material over time. Different knockdowns are defined for physical effects which will be elaborated on. The eventual knockdown factors which will be used in the design are stated in Table 4.8.

**Material scatter** Not every fiber will have the exact same properties. Material tests are needed to determine the properties of the material combination used. For the design of the composite the gangway the so called A-basis will be used. The A-basis is defined as "*The A-Basis value is the one percentile of the population: 99% of the tests performed will have strength greater than or equal to the A-Basis value.*" [11, p. 77]. In other words, the reduction of the properties with the knockdown of 0.8 will make sure that 99% of all material used will have at least the strength used in the calculations.

**Environmental influences** Using FRPs in offshore environments all over the world, as is the case with the systems of Ampelmann, will result in lots of different environmental conditions. From cold and wet to dry and hot and everything in between. These environmental conditions will have an influence on the properties of the composite. Since the exact operating conditions are unsure for the system some conservative estimate needs to be made. Elevated Temperature

Wet (ETW) is the most influencing case. Subramanian did research towards the decrease of properties when carbon/epoxy was exposed to 55° C and a relative humidity of 90% for a period of eight weeks. [24] The results show that using a knockdown factor of 0.8, as suggested by Kassapoglou, is valid. [11].

**Fatigue** Although the fatigue of composites is limited a slight knockdown factor of 0.9 is introduced to create a conservative design. Due to the life time requirement of only 20 years this values is used. Increasing the life time of the gangway will introduce more load cycles and the design will become less conservative.

**Impact** The damage done by an impact is hard to predict. It depends on the shape and energy of the object hitting the laminate. To account for the damage done after an impact resulting in Barely Visible Impact Damage (BVID) a knockdown factor of 0.65 will be used. [11] The design outcome will be conservative. The level of conservatism will increase with a thicker laminate as a thicker laminate can withstand higher energies without severe damage.

**Stiffness degradation** Not only the strength is decreasing over time. The stiffness of the laminate is degraded as well. A knockdown factor of 0.9 is used, based on the regulations of Det Norske Veritas Germanischer Lloyd (DNV GL). [4]

**Table 4.8:** Knockdown factors used in the design process

| Cause | Knockdown factor |
|---|---|
| Material scatter | 0.8 |
| Environmental | 0.8 |
| Fatigue | 0.9 |
| Impact | 0.65 |
| Stiffness degradation | 0.9 |

# Chapter 5

# Basic design composite gangway

This chapter describes the process of creating the basic design of the gangway. It consists of three parts. First the design process is discussed, the way the design is done. Secondly the sizing of the gangway is described, this includes both the process and formula's used as well as the reasons why and validation of the code. Thirdly the joints needed in the gangway are sized.

## 5.1 Gangway design process

The process of creating a basic design for a composite Ampelmann gangway can be divided in:

- A computational step (structural design)
- A semi-computational step (joint sizing)
- The definition of production and certification steps/milestones

The part of the design calculation which are performed in MATLAB[1], is visualized in the flow chart in Figure 5.1. Several intermediate checks are built in. This checks if the outcome is in line with the requirements as stated in Section 2.3, if this is not true the program is terminated and parameters can be manually adapted.

[1]version R2013a (8.1.0.604)

The program is split up in five sections. Where the sections 1 & 2 can be combined as these calculate the most critical parts for the stiffness based composite gangway design.

Sections 1 & 2 can be seen as the preconditioning, this step takes less than a second to compute and is a fast measure of the effectiveness of the design. Due to the design being stiffness based the eigenfrequency and deflection are, most likely, the critical parameters.

Section 3 is the failure of the gangway, if the outcome is either negative, id est (i.e.) it does not pass the requirements or the margin of safety is to high the design can be changed manually before a new run is initiated.

Section 4 estimates the costs of the gangway. This includes all costs from engineering of both the gangway and the required molds, production, certification and maintenance during the life time.

Section 5 calculates the forces in both the connections and in the railing. Stresses for the critical locations follow and the global picture of the connection is created.

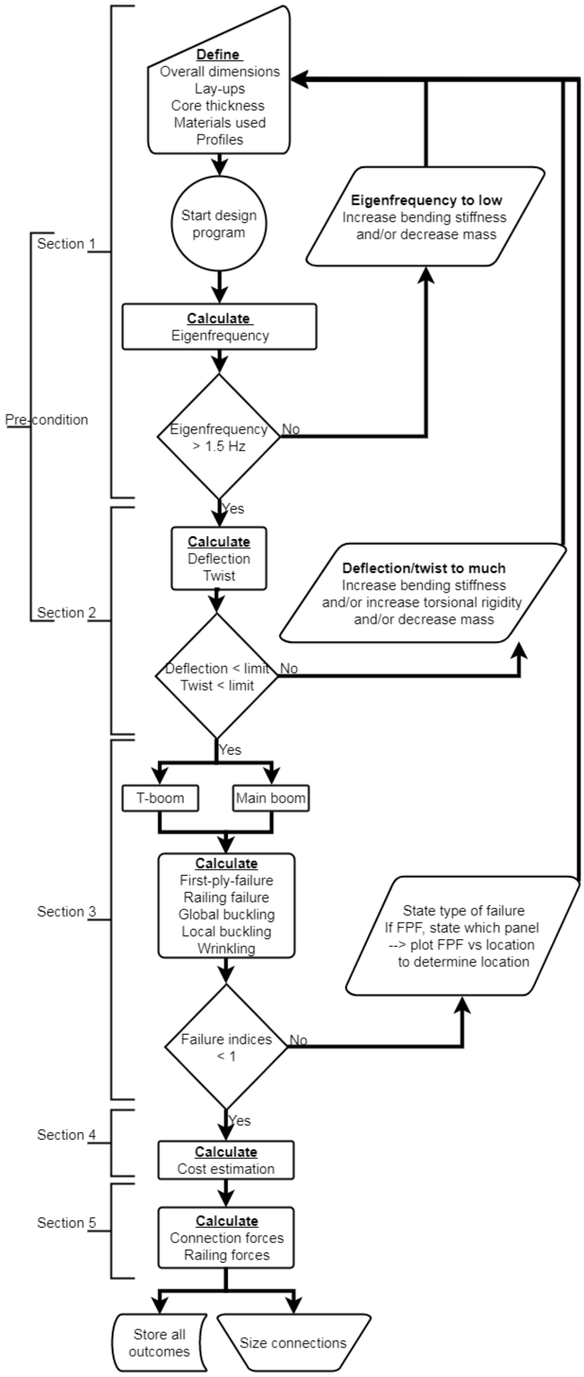



**Figure 5.1:** Flow chart of the composite gangway structural design code

## 5.2 Gangway sizing procedure

The sizing of the gangway is a non-automated iterative process. A design is created and then tested. This section describes the sectional flowcharts from the overview as in Figure 5.1. The charts of the individual sections can be found in Appendix C.

### 5.2.1 Section 1: Eigenfrequency

The first section of the code is about determining the eigenfrequency of the gangway in cantilever mode. Before the eigenfrequency can be calculated intermediate steps need to be performed. The required steps are displayed in Figure C.1 in Appendix C.1.

#### Initial run parameters

Before the analysis can start key parameters need to be entered. These variable inputs include, but are not limited to, width and length of main boom and Telescoping Boom (T-boom), height of the railing, types of profile used for the railing and the railing framework.

**Variable inputs** The initial gangway dimensions are entered in the code which can be seen in Appendix D.1. All other required, hard coded, values can be entered in the class Parameter.m as is displayed in Appendix D.2.

**Rules for inputs** Certain assumptions have been made in the code, putting requirements on the input parameters. The main requirement for the input are:

- The plystacks need to be symmetric and balanced.
- All vertical and diagonal members are made using the same profile,
- The main boom and T-boom railings are equal in size and thickness.
- The core material is the same for main boom and T-boom, thickness can differ.

#### Eigenfrequency determination

The eigenfrequency is of great importance for the dynamic stability of the system when trying to land the gangway to the platform. Before the eigenfrequency can be calculated the bending stiffness is needed. The stiffness of the gangway is calculated as stated in Appendix A.1. An important parameter is the ABD matrix as the stiffness of the laminate is depending on the inverse of this matrix. To verify the calculations performed in the design code multiple checks have been performed, these can be found in Appendix E.1.

The frequency of the steel Gangway XL (GXL) is calculated using Equation (3.4), the same is used for the composite re-design. Looking closer at Equation (3.4) one can see that the eigenfrequency can be increased by increasing the bending stiffness ($EI$), decreasing the tip load ($P$), decreasing the mass of the gangway ($q_{gw}$) or decreasing the length of the gangway ($L_{gw}$). Decreasing the tip load or the gangway length are not an option, the opposite is what is desired. What remains is to increase the bending stiffness or decrease the mass in order to fulfill the set requirement.

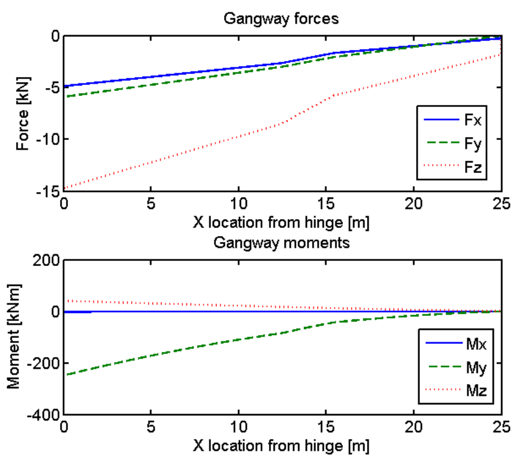
### 5.2.2 Section 2: Deflection & twist

When the eigenfrequency criteria is passed the requirements deflection and twist of the gangway need to be checked. In order to determine these, the gangway forces and moments need to be determined first. This is done in section 2 of the code as can be seen in Figure C.2 of Appendix C.2.

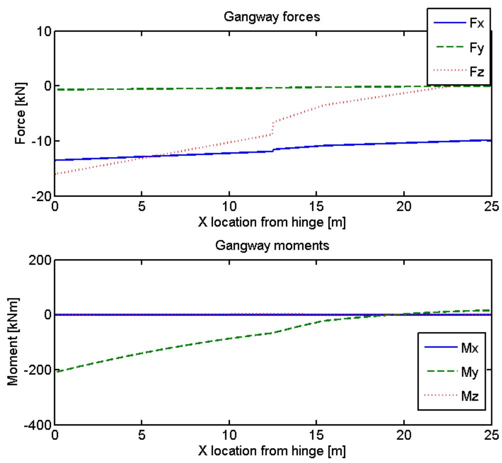
#### Forces and moments

Depending on the load case an analysis for a cantilever or simply supported beam is performed. Based on the parameters associated with the load case like the accelerations, luffing angle, heel and trim and the design parameter like width an ply stack resulting in a gangway mass. The forces $F_x$, $F_y$ and $F_z$ are calculated for the main boom and T-boom using the principle of superposition of static calculations. These are added to get the picture of the complete gangway. The same is done for the moments $M_x$, $M_y$ and $M_z$. Figure 5.2a shows the result of a Emergency Case - Cargo Transfer (EC-CT) load case analysis, Figure 5.2b shows those of the Normal Operation - People Transfer (NO-PT) case. The verification of the the force and moment calculations can be found in Appendix E.2.

The bending moment around the y-axis is about equal in both cases, This is due to the assumption that the bending moment is always in cantilever mode. In case of a sudden disconnection the gangways luffing angle will be restored by the system. A difference between the two operational modes is the force in x-direction, $F_x$. In the landed case this force is higher due to the constant force pushing the gangway to the platform to keep the gangway connected.




**(a)** Cantilever gangway in EC-CT mode




**(b)** Landed gangway in NO-PT mode

**Figure 5.2:** Forces and moment for different operational modes and load cases

Depending on the mode of operation the deflection and twist of the gangway can be determined. Both these parameters are more critical in cantilever mode compared to the landed mode.

**Deflection** In cantilever mode the deflection in z-direction is determined by summing the deflections due to the dead load, tip mass and live load. The calculation is performed using Equations (5.1). [25]

$$\begin{aligned}
\delta_{z_{Deadload_{cantilever}}} &= \frac{q_{gw} y_{gw}^2}{24EI_{gw}} \left(6L_{gw}^2 - 4L_{gw}y_{gw} + y_{gw}^2\right) \\
\delta_{z_{Tipmass_{cantilever}}} &= \frac{P_{tip}g}{6EI_{gw}} \left(2L_{gw} - 3L_{gw}y_{gw} + y_{gw}^2\right) \\
\delta_{z_{Liveload_{cantilever}}} &= \frac{P_{Liveload}g}{6EI_{gw}} \left(2L_{gw} - 3L_{gw}y_{gw} + y_{gw}^2\right) \\
\delta_{gw_{Cantilever_{cantilever}}} &= \delta_{z_{Deadload_{cantilever}}} + \delta_{z_{Tipmass_{cantilever}}} + \delta_{z_{Liveload_{cantilever}}}
\end{aligned} \tag{5.1}$$

In which $q_{gw}$ is the distributed load of the dead weight in $N/mm$, $EI$ is the bending stiffness of the gangway in $Nmm^2$, $y_{gw}$ the location from the hinge point in $mm$, $L_{gw}$ the gangway length in $mm$ and $P_{tip}$ and $P_{Liveload}$ are the external masses in $kg$.

When the gangway is landed against the structure the deflection with a person standing in the middle is calculated using Equations (5.2). [25]

$$\begin{aligned}
\delta_{z_{Deadload_{landed}}} &= \frac{q_{gw} y_{gw}}{24EI_{gw}} \left(L_{gw}^3 - 2L_{gw}y_{gw}^2 + y_{gw}^3\right) \\
\delta_{z_{Liveload_{landed}}} &= \frac{P_{Liveload}gL_{gw}^3}{48EI_{mb}} \\
\delta_{gw_{Cantilever_{landed}}} &= \delta_{z_{Deadload_{landed}}} + \delta_{z_{Liveload_{landed}}}
\end{aligned} \tag{5.2}$$

In which $q_{gw}$ is the distributed load of the dead weight in $N/mm$, $EI$ is the bending stiffness of the gangway in $Nmm^2$, $y_{gw}$ the location from the hinge point in $mm$, $L_{gw}$ the gangway length in $mm$ and $P_{Liveload}$ is the external mass in $kg$.

**Twist** Twisting of the gangway is most important in cantilever mode. Too much twist and it will be difficult to successfully land the gangway, walking on a twisted gangway is more difficult and creates a feeling of discomfort for the transferee. Therefore the twist of the gangway is calculated using Equation (5.3).

$$\begin{aligned}
\theta_{mb} &= \frac{T_{mb}}{GJ_{mb}} \frac{180}{\pi} \\
\theta_{tb} &= \frac{T_{tb}}{GJ_{tb}} \frac{180}{\pi} \\
\theta_{gw} &= \theta_{mb} + \theta_{tb}
\end{aligned} \tag{5.3}$$

In which $T = M_x$ is the torsion in $Nmm$ and $GJ_i$ is the torsional rigidity of the main boom/T-boom in $Nmm^2$.

### 5.2.3 Section 3: Failure modes

If the pre-conditioning is passed the failure modes for the gangway need to be checked. The steps in the process of checking the different failure modes is stated in Figure C.3 in Appendix C.3. Before the failure modes can be calculated the forces and moments acting on the gangway need to be divided over the load carrying parts of the structure.

#### Dividing the forces and moments over the load carrying parts

In order to divide the forces over the railing and the deck some assumptions are made these are listed below.

- Vertical and diagonal members of the railing are not carrying bending loads.
- $F_x$, is only taken by the deck, the result of the force acting on the gangway when landed.
- $F_y$, is carried by the horizontal deck laminates (top and bottom of deck).
- $F_z$, is carried by the core as well as by the sides of the deck.
- $M_x$, the torsion, is carried by the deck only.
- $M_y$, is carried by all horizontal parts of the structure (top and bottom of deck and railing).
- $M_z$, is carried by all vertical parts of the structure (sides of deck and railing).

As a result of the assumptions the division of forces and moments over the different parts of the structure is presented in Table 5.1. This is purely which part will carry the force and has no value regarding the actual force taken by the member.

**Table 5.1:** Force and moment distribution between different parts of the gangway

| | Top railing | Side railing | Bottom railing | Top deck | Side deck | Bottom deck | Foam |
|---|---|---|---|---|---|---|---|
| $F_x$ | | | | ✓ | ✓ | ✓ | |
| $F_y$ | | | | ✓ | | ✓ | |
| $F_z$ | | | | | ✓ | | ✓ |
| $M_x$ | | | | ✓ | ✓ | ✓ | |
| $M_y$ | ✓ | | ✓ | ✓ | | ✓ | |
| $M_z$ | | ✓ | | | ✓ | | |

**Force distribution($F_x$)** Depending on the force a division is made between the different laminates. Taking the force in x-direction as an example, $F_x$. The force in x-direction is taken by the four edge of the deck. The force on a laminate is depending on the length of that part in comparison with the total laminate length and can be calculated using Equation (5.4).

$$F_{deck_i} = N_x l_i = \frac{F_x}{2\left(w_{deck} + h_{deck}\right)} l_i \tag{5.4}$$

In which $l_i$ is the width of the deck or the side. To get from the force on a part to the running load we simply remove the $l_i$ in Equation (5.4), leving the running load $N_x$.

**Moment distribution($M_y$)** Assuming the gangway deforms as a single structure, i.e. the cross section remains perpendicular to the centerline, Euler-Bernoulli's beam theory can be applied. Now, the stress in a certain part $i$ can be calculated using Equation (5.5).

$$\sigma_i = E_i \epsilon_i \tag{5.5}$$

In which $E$ is the Young's modulus of the laminate and $\epsilon_i$, the local strain, can be calculated with Equation (5.6).

$$\epsilon_i = z_i \kappa = z_i \frac{M}{EI} \tag{5.6}$$

In which $\kappa$, the radius of curvature of the deflected gangway, depending on the moment and corresponding bending stiffness.

Combining Equations (5.5) and (5.6) result in the force acting on a member $F_i$, Equation (5.7).

$$F_i = \sigma_i A_i = E_i \epsilon_i A_i \tag{5.7}$$

Using Equation (5.7) and the corresponding width of a section the running load $N_i$ can be calculated as in Equation (5.8). This running load is needed for the determination of the First-Ply-Failure (FPF)

$$N_i = \frac{F_i}{w_i} = \frac{E_i \epsilon_i w_i h_i}{w_i} = E_i z_i t_i \frac{M}{EI} \tag{5.8}$$

So, the load per unit width is depending on the local laminate stiffness $E_i$, the distance from the neutral axis $z_i$, the thickness of the laminate $t_i$ and the curvature $\kappa = \left(\frac{M}{EI}\right)$. In Equation (5.8) $z_i$ can be replaced by $y_i$ for the moment around the z-axis.

### Failure modes

With the running forces determined the different failure modes can be calculated. The knock-down factors as stated in Section 4.4 will be used in the calculations.

**Railing failure** The railing can fail in tension. A profile made from prepregs is used as a pultrusions profile made from carbon fiber is economically unfeasible. A simple lay-up was used for the profile. The unity check [2] of the railing is calculated using Equation (5.9).

$$UC_{Railing} = \frac{\frac{F_x}{A_{railing}}}{Xt_{railing}} \tag{5.9}$$

In which $F_x$ is the force in the railing in $N$, $A_{railing}$ is the area of the railing profile in $mm^2$ and $Xt$ is the tension failure limit of the material in $N/mm^2$.

[2] A calculation of the applied load divided by the failure load, meaning a value smaller than 1 means that no failure will occur

**Tsai-Wu first-ply-failure** The first ply failure is calculated using the Tsai-Wu criterion. [11] Tsai-wu is used over the stated Puck criterion by the regulations of Det Norske Veritas Germanischer Lloyd (DNV GL) due to the combined loading on the gangway. Tsai-Wu will result higher values and therefore a better representation of the real world performance. The Tsai-Wu criterion is stated in Equation (5.10). The verification of the Tsai-Wu calculation in the design code can be found in Appendix E.3, where a comparison has been made with a case from literature. [26]

$$TW = \frac{\sigma_x^2}{XtXc} + \frac{\sigma_y^2}{YtYc} - \sqrt{\frac{1}{XtXc}\frac{1}{YtYc}}\left(\sigma_x\sigma_y\right) + \left(\frac{1}{Xt} - \frac{1}{Xc}\right)\sigma_x + \left(\frac{1}{Yt} - \frac{1}{Yc}\right)\sigma_y + \frac{\tau_{xy}^2}{S^2} \quad (5.10)$$

In which $Xt$ is the reduced material tension limit in 0° direction in $N/mm^2$, $Xc$ is the reduced material compression limit in 0° direction in $N/mm^2$, $Yt$ is the reduced material tension limit in 90° direction in $N/mm^2$, $Yc$ is the reduced material compression limit in 90° direction in $N/mm^2$, $S$ is the reduced material shear limit in $N/mm^2$, $\sigma_x$, $\sigma_y$ and $\tau_{xy}$ are the stresses acting in each individual ply in the laminate.

**Global & local buckling** Both local and global buckling are calculated for the deck using Equations (5.11) and (5.12), respectively. [11] First the critical load is calculated using Equation (5.11) then a correction is made as the facesheets no longer stay perpendicular to the mid-plane of the core. [11]

$$N_{E_{crit}} = \frac{\pi^2}{a^2}\left[D_{11}m^2 + 2\left(D_{12} + 2D_{66}\right)AR^2 + D_{22}\frac{AR^4}{m^2}\right] \quad (5.11)$$

In which $a$ is the length of the section in $mm$, $D_{ij}$ are the D-matrix terms in $Nmm$, $AR$ is the aspect ration and defined as length over width and $m$ is the number of half-waves in the panel and is varied from 1 to 50 to find the minimal value. Using the minimal value from Equation (5.11) the unity check is calculated using Equation (5.12).

$$UC_{Buckling} = \frac{Nx_{deck}}{Nx_{crit}} = \frac{Nx_{deck}}{\frac{N_{E_{crit}}}{1+\frac{kN_{E_{crit}}}{t_cG_c}}} \quad (5.12)$$

In which $\kappa$, the shear correction factor, is set to 5/6 due to the fact that the core has a high shear strength for a foam core [11], $t_c$ is the core thickness in $mm$ and $Gc$ is the shear modulus of the core in $N/mm^2$.

**Wrinkling** The unity check for wrinkling failure of the core is calculated using Equation (5.13). [11]

$$UC_{Wrinkling} = \frac{Nx_{deck}}{0.91t_{deck}\left(E_{deck}E_{core}G_{xz}\right)^{\frac{1}{3}}} \quad (5.13)$$

In which $Nx$ is the force per unit width in $N/mm$, $t_{deck}$ the thickness of the deck in $mm$, $E_i$ the Young's modules of the deck and core in $MPa$ and $G_{xz}$ the shear stiffness of the core in $MPa$.

### 5.2.4 Section 4: Cost estimation

The costs of the gangway are split up in two components. Firstly there are the non-recurring costs. These are independent off the actual gangway parameters like the dimensions and lay-ups and are only made once. Secondly there are the recurring costs, these are dependent on the gangway parameters and are most important for the Life Cycle Costs (LCC) estimation of the composite gangway, these costs are made for each gangway.

The calculation of the costs associated with the design is presented in Figure C.4 in Appendix C.4. It is a combination of fixed costs, estimates independent on the design and recurring costs which are depending on the design.

#### Non-recurring costs

The costs are made once per design or once per multiple gangways as is the case for molds. Investments will be discounted over the gangway produced if multiple will be made. It is assumed that only a single composite gangway will be made so all the costs are associated to this single gangway.

**Engineering** This thesis provides a basic design to determine the feasibility of a composite gangway from a production and certification point. A specialized firm will do the final engineering of the gangway for two reasons. Firstly, the required knowledge is not available within Ampelmann and secondly, the certifying authorities would like to see a design made by a respectable company in composite engineering to secure the quality of the required calculations.

Estimating the costs of outsourcing the design of the gangway is done based on quotations from multiple parties, including InfraCore company and Solico. Expected costs are between €35,000 and €100,000. These estimates include the design of the structure and the mold. Furthermore basic material tests are included in order to have the right calculation values for the selected material. The upper limit is used to present a worst case scenario.

**Molds** As stated in Section 4.2 a mold is required for the creation of a composite structure. This mold is made specifically for the product. Designing the structure such that an easy mold can be used decreases the investment costs. A sandwich panel without radical changes in dimensions can be seen as simple construction. Furthermore the railing will be designed such that simple tooling is needed for the production and assembly. All is done to limit the investments for the first couple of gangways. For a simple sandwich deck as is the case in the design the molds costs are estimated to be between €15,000 and €35,000, according to KVE Composites and InfraCore company.

**Certification** The process of certifying the gangway is unclear at this moment. Initial contact with Lloyd's Register (LR) resulted in a global view on how to certify the new gangway. Testing of a prototype is required and, depending on the material used, material tests need to be performed. As the definition of testing a prototype is unclear the assumption is made that the prototype will be tested until failure. The first operational gangway will therefore be the second one build. Certification costs are estimated, based on this assumption, to be the cost of a single gangway plus 20% costs for the presence of the authorities.

### Recurring costs

Each gangway being build will use materials and man hours. These are the recurring costs. A learning curve can be expected in the fabrication of gangways. The first gangway will require more time to produce compared to later ones. The first gangway is therefore more expensive. The learning effect is neglected in the cost determination as the gangway will, most likely, be made in very small numbers. Doing so will result in a conservative price estimate for the gangway.

**Materials** The material costs can be split up in different parts:

- Prepreg
- Core material
- Railings
- Production consumables
- Brackets

The costs for the railing are the materials used for the production of the carbon railing and the costs associated with the purchase of the pultrusion profiles. The production consumables are all materials needed for the production which will not end up in the structure. These are, for example, the vacuum bag, peel-ply and bleeder fabric.

When building with composites there is always excess material which cannot be used, a scrap rate is used to account for the material which will be waste. Using Bi-axial (Biax) fabrics for the ±45° limits the carbon waste. The scrap rates used in the determination of the gangway costs are stated in Table 5.2.

The amount of material is now known when the design is created and with the prices as stated in Table 5.3 and the scrap rates the material costs are calculated. Two values need some extra explanation. First the bracket price. This is an assumed average price. The highly loaded brackets will be more expensive whereas the intermediate brackets will be cheaper. The vacuum consumables are also an estimate. Included in this estimate are materials like the vacuum bag, release agent, peel-ply, tacky tape, bleeder fabric, etc.

**Table 5.2:** Material scrap rates

| Scrap rate | Percentage |
|---|---|
| Foam | 20% |
| Carbon fiber prepreg | 30% |
| Glass fiber profile | 10% |
| Adhesive | 10% |

**Table 5.3:** Material prices used for cost estimation

| Materials | Unit | Price [€] |
|---|---|---|
| HEC carbon prepreg | €/m$^2$ | 26.00 |
| HMC carbon prepreg | €/m$^2$ | 69.82 |
| Biax carbon prepreg | €/m$^2$ | 39.25 |
| Foam | €/m$^2$ | 91.54 |
| SA80 adhesive | €/m$^2$ | 15.84 |
| Glass fiber profiles | €/m | 11.00 |
| Price railing bracket | €/piece | 50.00 |
| Vacuum consumables | € | 5,000.00 |

**Metal connection brackets** The three metal connections, a total of seven metal parts are needed for the gangway. As the number of gangways is small the production will consist of mostly labor costs. Based on dimension, thickness and complexity estimates are made which are stated in Table 5.4.

**Table 5.4:** Bracket prices used for cost estimation

| Bracket | Price | Amount | Price |
|---|---|---|---|
| Hinge point bracket | €1000 | 1 | €1000 |
| Luffing cylinder bracket | €750 | 2 | €1500 |
| Telescoping support | €600 | 4 | €2400 |
| **Total** | | | €4900 |

**Labor** The labor costs are estimated based on information from the industry. InfraCore Company stated that building a bridge takes about four days, the amount of people or hours spent are not known. Maarten Labordus from KVE Composites [27] estimated the total production time of the gangway to be about two weeks with two people. A total of 160 hours are assumed to be needed for the production. At an estimated cost per hour of €100 the result is €16,000. Adding or removing layers in the deck laminate has a very small influence on the production time, this costs is independent on the design when the gangway length remains to be 25 meter.

### Maintenance and repair

*The gangway shall have a life time of at least 20 years* has been stated in Chapter 2.3. During this period maintenance will need to be executed as well as examining any occurring damage. A 5-yearly maintenance plan is currently used for the Ampelmann gangways. The same 5-year maintenance scheme will be used for a life cycle cost estimation.

Parts that will wear during operation of the gangway, requiring replacement, are:

- Telescoping wheels
- Abrasion layers at telescoping wheels
- Grip layer on the deck
- Coating/paint on the railings, deck sides and bottom

During these maintenance session the gangway needs to be checked for damages as well. A Non-Destructive Testing (NDT) method needs to be executed and analyzed by an expert. Contact with LR resulted in the requirement of scanning the gangway every year. Apart from this planned maintenance, sensors can be laminated into the structure to monitor the health of the gangway continuously. Such systems have been developed by MOCS and InfraCore Company and can be implemented in the design.

Repair costs are not estimated, the nature, location and extend of the damage influence the costs of repair. As these are not known prior to the creation of the damage estimation is useless. For the current steel GXL these costs are also not known, the comparison is still fair.

Maintenance costs will be mostly determined by labor. Removing the old coating and grip layer, preparing the surface and re-applying the coating/layer takes time. The same holds for scanning the gangway. This yearly scanning of the gangway and getting the data analyzed by an expert is assumed to be €5,000. The 5-yearly maintenance is assumed to be €25,000. The total maintenance costs, based on a 20 year lifetime is €170,000.

### 5.2.5 Section 5: Calculation of connection and railing forces

The calculation of the forces acting on the connection points and inside the railing are determined in section 5, this process is visualized in Figure C.5 of Appendix C.5. First the connection forces of the gangway are calculated using overall equilibrium, with these known the forces in the railing framework are calculated in a step by step process using multiple sections. All data is stored for the design of the joints.

#### Overall equilibrium

The luffing actuators used to move gangway create an equilibrium position such that the gangway can be landed against the structure. They exert the force required for the gangway to not move up nor down. The situation during this phase of the gangway being in cantilever mode is drawn in Figure[3] 5.3.

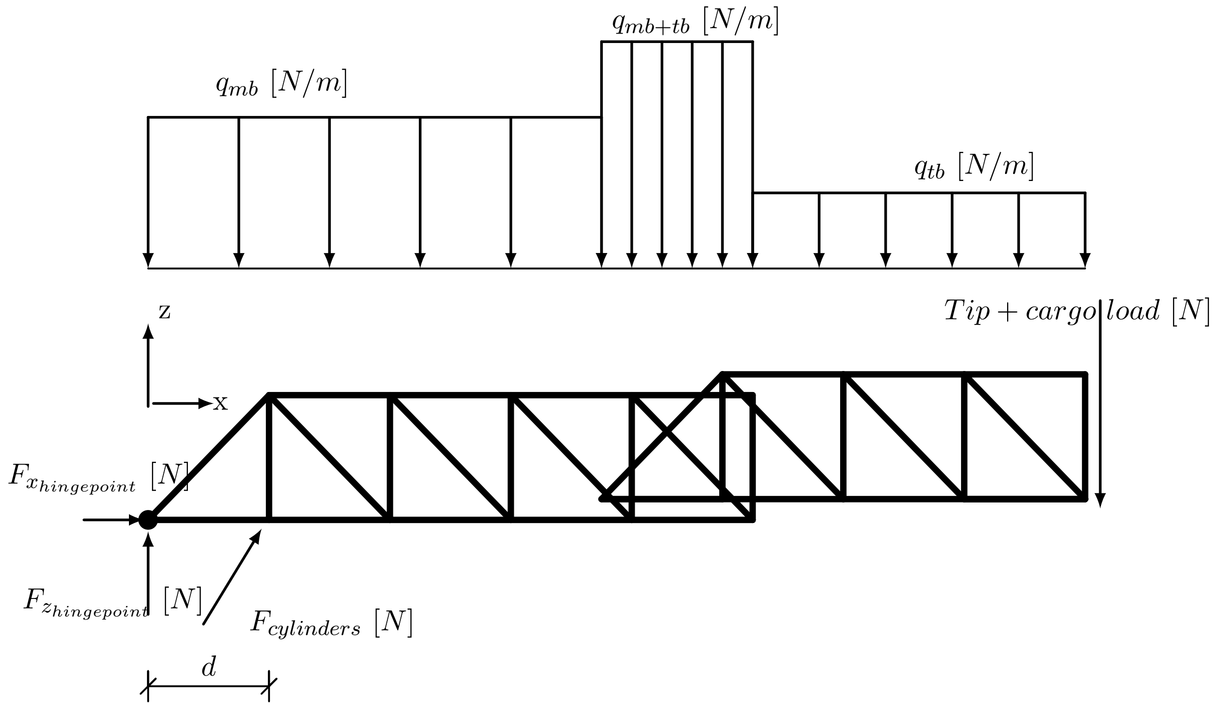



**Figure 5.3:** Free body diagram of the gangway system(number of vertical and diagonal members not as in the basic design)

The system as defined in Figure 5.3 has three unknowns, $F_{cylinder}$, $F_{x_{hingepoint}}$ & $F_{z_{hingepoint}}$. Three equations can be set-up, sum of forces in x- and z-direction ans moment equilibrium around the hinge point, the system is statically defined and can be solved using Equations (5.15),(5.14) and (5.16).

$$\sum M\ ccw+ : 0 = F_{cylinders_z} d - M_{y_{gw}} \rightarrow F_{cylinders_z} = \frac{M_{y_{gw}}}{d} \tag{5.14}$$

[3]Gangway is simplified and not all parts are drawn

Where $d$ $[mm]$ is the distance between the hinge point and the attachment of the luffing cylinder and $M_y$ is the moment acting on the gangway at the hinge point in $Nmm$.

$$\sum F_{z_{up}} + : 0 = F_{z_{hingepoint}} - F_{tip} - F_{cargo} - q_{total} + F_{cylinders_z} \rightarrow$$
$$F_{z_{hingepoint}} = F_{tip} + F_{cargo} + q_{total} - F_{cylinders_z} \quad (5.15)$$

$$\sum x \overset{+}{\rightarrow} : 0 = F_{x_{hingepoint}} + F_{cylinders_x} - F_{x_{q\ component\ luffing\ angle}} \rightarrow$$
$$F_{x_{hingepoint}} = F_{x_{q\ component\ luffing\ angle}} - F_{cylinders_x} \quad (5.16)$$

Calculations have been performed for the two load cases EC-CT and NO-PT. The results are stated in Table 5.5. There is a difference between cantilever (EC-CT) and landed (NO-PT) but not as big as expected. Again this is due to the assumptions that the dead weight is always in cantilever mode.

**Table 5.5:** Hinge point and cylinder forces for two load cases, combined cylinder forces

| | Unit | EC-CT | NO-PT | Difference |
|---|---|---|---|---|
| $F_{x_{hingepoint}}$ | [kN] | -119.0 | -100.2 | 18.8% |
| $F_{z_{hingepoint}}$ | [kN] | -196.3 | -169.8 | 15.6% |
| $F_{cylinders}$ | [kN] | 214.3 | 181.5 | 18.1% |
| $F_{cylinders_x}$ | [kN] | 114 | 96.6 | 18.0% |
| $F_{cylinders_z}$ | [kN] | 181.4 | 153.7 | 18.0% |

With the external forces known a cut is made just after the first bracket in order to calculate the forces in the railing, deck and second diagonal member. The gangway is in equilibrium, meaning the unknown forces can be calculated as the section is statically determined. The situation is displayed in Figure 5.4.

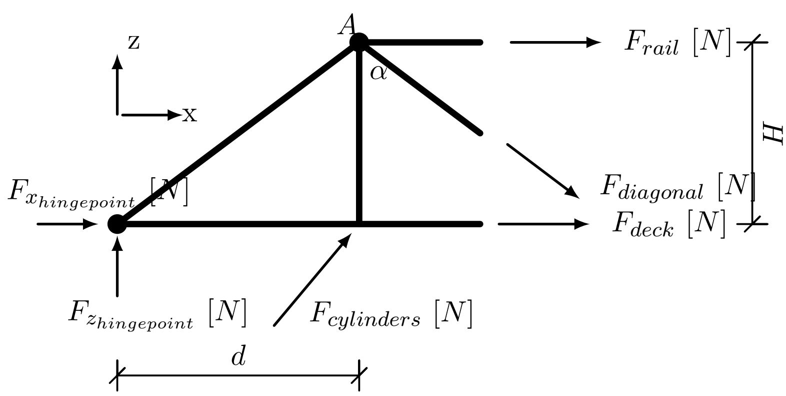



**Figure 5.4:** Free body diagram to determine internal forces in the gangway railing, deck and diagonal member

The system as defined in Figure 5.4 has three unknowns, $F_{rail}$, $F_{diagonal}$ & $F_{deck}$. Three equations can be set-up, sum of forces in x- and z-direction ans moment equilibrium around point $A$, the system is statically defined and can be solved using Equations (5.17),(5.18) and (5.19).

$$\sum z\ up+ : 0 = F_{z_{hingepoint}} + F_{cylinders_z} - F_{diagonal} cos(\alpha) \rightarrow F_{diagonal} = \frac{F_{z_{hingepoint}} + F_{cylinders_z}}{cos(\alpha)} \tag{5.17}$$

$$\sum M_A\ ccw+ : 0 = (F_{deck} + F_{x_{hingepoint}} + F_{cylinder_x})H - F_{x_{hingepoint}} d \rightarrow \\ F_{deck} = \frac{F_{x_{hingepoint}} d}{H} - F_{x_{hingepoint}} - F_{cylinder_x} \tag{5.18}$$

$$\sum x \overset{+}{\rightarrow}: 0 = F_{x_{hingepoint}} + F_{cylinder_x} + F_{rail} + F_{deck} + F_{diagonal} sin(\alpha) \rightarrow \\ F_{rail} = -F_{x_{hingepoint}} - F_{cylinder_x} - F_{rail} - F_{deck} - F_{diagonal} sin(\alpha) \tag{5.19}$$

Different brackets can be distinguished in the structure. Looking at the loaded part of the main boom railing the first and last bracket are differently loaded compared to the in between ones.

**First bracket** The first bracket is the highest loaded one. All the force carried by the railing needs to be transferred back to the deck, through the hinge point into the transfer deck. The free body diagram of the first railing bracket for both the main boom and the T-boom can be seen in Figure 5.5.

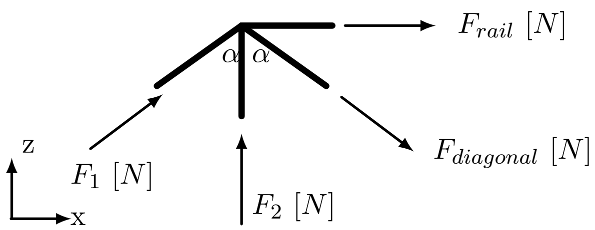



**Figure 5.5:** Free body diagram of the members connected to the first bracket

$$\sum x \overset{+}{\rightarrow}: 0 = F_{rail} + F_{diagonal} sin(\alpha) + F_1 sin(\alpha) \rightarrow F_1 = \frac{-F_{rail} - F_{diagonal} sin(\alpha)}{sin(\alpha)} \tag{5.20}$$

$$\sum z\ up+ : 0 = F_2 + F_1 cos(\alpha) - F_{diagonal} cos(\alpha) \rightarrow F_2 = F_{diagonal} cos(\alpha) - F_1 cos(\alpha) \tag{5.21}$$

Using the equations stated above and the data from Table 5.5 the forces in the different members of the bracket can be calculated. The results for the load cases EC-CT and NO-PT can be found in Table 5.6. Again the difference between landed and cantilever is small.

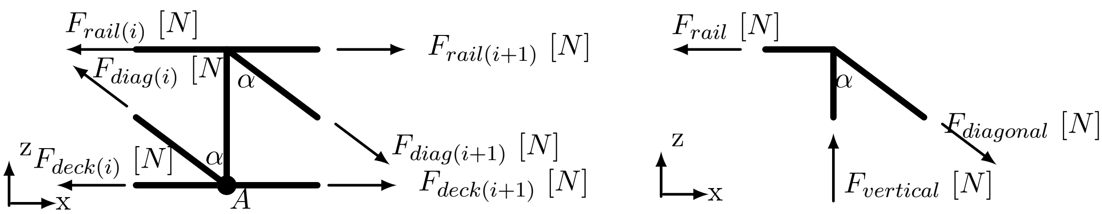
**Table 5.6:** Bracket forces results for two load cases, one side of the railings

| | Unit | EC-CT | NO-PT | Difference |
|---|---|---|---|---|
| $F_{rail}$ | [kN] | 115.5 | 97.8 | 18.1% |
| $F_{diagonal}$ | [kN] | 12.0 | 13.1 | -8.4% |
| $F_1$ | [kN] | -158.8 | -137.4 | 15.6% |
| $F_2$ | [kN] | 90.7 | 76.8 | 18.1% |

**Intermediate brackets** With the first bracket known he next section can be analyzed, Figure 5.6a. In order to have force equilibrium in z-direction each diagonal member will be loaded equally. The force in the railing will decrease when moving away from the hinge point. Its decrease is calculated using Equation (5.22).

$$F_{rail_{decrease}} = F_{diag(i+1)} sin(\alpha) \tag{5.22}$$

**Last bracket** The last bracket is special, see Figure 5.6b, on the right side of the bracket no force is going through the railing anymore. The result is a higher loaded diagonal member compared to the intermediate ones.




**(a)** Free body diagram of the intermediate brackets **(b)** Free body diagram of the last bracket

**Figure 5.6:** Free body diagrams of intermediate and final load carrying brackets

The force in the last diagonal member can be calculated using Equation (5.23).

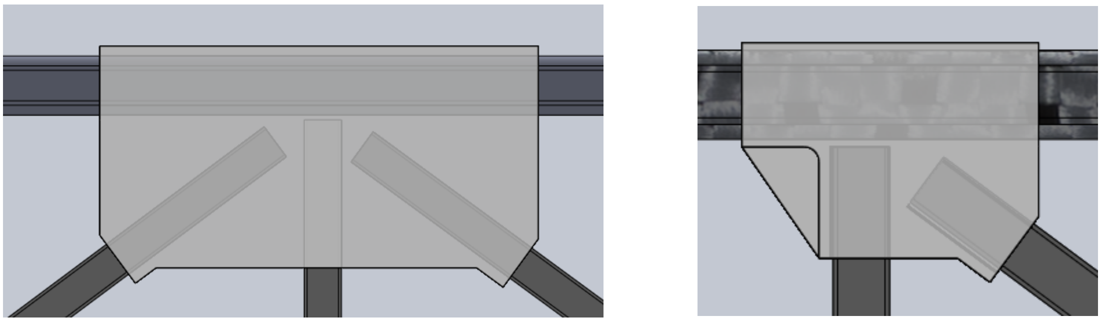
$$F_{diagonal_{last}} = \frac{F_{rail}}{sin(\alpha)} \tag{5.23}$$

## 5.3 Joint design

Different connections can be defined in the gangway, connections in the railing framework, telescoping supports, luffing cylinder attachments and the hinge point connection. Each of the connections will be reviewed and discussed.

### 5.3.1 Railing framework joints

The load carrying railing is connected to the deck by means of a framework with vertical and diagonal members as can be seen in Figure 5.3. Not every connection is loaded equally. The first loaded bracket on the railing experiences the most loads as can be concluded from Table 5.6. A design for this bracket is stated in Figure 5.7a. If this bracket will hold the remaining brackets can be designed as is shown in Figure 5.7b.



**(a)** Highly loaded connection **(b)** Remaining connections

**Figure 5.7:** Railing connections for different locations

The proposed design is machined from a block of (filled) Polyetheretherketone (PEEK). The sizing of the bracket can be split in two. First, the adhesive area needs to be sufficient to transfer the load from the profiles into the bracket and back into a profile. Second, the material of the bracket needs to be strong enough to withstand the forces passing through the bracket.

**Adhesive stress** The average stress in the adhesive layer needs to sufficient low to assure the bond to hold. There will be some weaker spot in a bond line so extra care has to be taken in both the design and the assembly of the brackets. The average adhesive stress is calculated using Equation (5.24).

$$\sigma_{adhesive_{average}} = \frac{F}{A_{adhesive}} \tag{5.24}$$

In which $F$ is the force in the member which is bonded to the bracket and $A_{adhesive}$ is the total area of the adhesive. Increasing the area for the adhesive lowers the stresses in the adhesive. At the same time it increases the length of the bracket, associated with an increase of material costs and production time. An optimum needs to be found between the Margin of Safety (MS), Equation (5.25) and the weight and cost of the bracket

$$MS_{adhesive} = \frac{\sigma_{adhesive_{ultimate}}}{\sigma_{adhesive_{average}}} - 1 \tag{5.25}$$

**Materials stress** The stress in the bracket material is a function of the amount of material as can be seen in Equation (5.26). No stress concentrations are taken into account here. For an analysis of the stress concentrations a Finite Element Method (FEM) analysis is required. This has not been performed due to the limited time available. To prevent failure a sufficient MS is needed, which is calculated using Equations (5.26) & (5.27).

$$\sigma_{material_{average}} = \frac{F}{A_{material}} \tag{5.26}$$

In which $A_{material}$ is the material surrounding the profile in $mm^2$.

$$MS_{material} = \frac{\sigma_{material_{ultimate}}}{\sigma_{material_{average}}} - 1 \tag{5.27}$$

### 5.3.2 Telescoping supports

As the T-boom will move almost constantly when the gangway is operated the design of both the support as well as the wheels and the interface of the wheels and the deck are important. The forces acting in z- and y-direction are determined as stated in Section 5.2.5. Both the bracket is designed and required reinforcements for the deck discussed.

#### Telescoping bracket design

The current design of the telescoping support bracket can be seen in Figure 5.8. It is a stainless steel bracket with attachments for the guidance wheels in z- and y-direction. Four of these brackets will be placed on the gangway, two on each side. The spacing between them is 2800 mm or equal to twice the distance between two vertical members as the core is already reinforced at these locations for the railing bracket.

The bracket is placed around the main boom deck for sufficient area for the load transfer. As the bracket is made from stainless steel a protective glass fiber layer is placed between the bracket and the deck to minimize the change of galvanic corrosion.

#### Local deck reinforcements

The wheels introduce a local force perpendicular to the face sheets. A part of this load will be carried by the core. The Gurit M130 foam is not sufficiently strong so reinforcements need to be made. At the location where the wheels will be on the T-boom the core will be cut and shear webs will be made using multiple plies of $\pm 45^c irc$ layers to carry the shear force introduced by the wheels. These webs are made by wrapping the foam with Biax fabrics before it is placed inside the mold, the amount of plies is depending on the eventual design. This can be done with either glass- or carbon fiber, where glass fiber will save costs at a minimal weight increase, while having sufficient strength.

The core itself needs to be reinforced as well to prevent core crushing. To spread the load over a larger area a metal plate can be placed inside the laminate where the wheels will act. This plate needs to be isolated from the carbon fiber by a layer of glass fiber.

Next to the internal reinforcements, external reinforcements will be needed as well. The wheels will cause wear of the laminate. Extra layers of glass fiber are placed on the deck which will act as abrasion layer. The sides of both the main boom and T-boom will be reinforced as well. Carbon Biax prepreg will be used. The main boom needs to be reinforced to have sufficient material to deal with the shear forces. For the T-boom, the extra layers are needed to support the wheel forces in y-direction. As this force is only 25% of the force in z-direction in the worst load case no extra internal reinforcement is needed.

### 5.3.3 Luffing cylinder attachments

The luffing cylinders are attached to the bottom of the main boom using two stainless steel brackets as can be seen in Figure 5.9. This is different compared to the GXL where the luffing is done at the beginning of the railing. Pushing on the deck instead of pulling on the railing is preferred in the composite design as this eliminates the changes of debonding the facesheet from the core.

Ideally these brackets will be bonded to the deck with a layer of glass fiber in between. However due to regulations, bolting will need to be used as well. In order to have a secure bolting connection reinforced blocks will replace the core foam locally. Placing these brackets and bolting them to the reinforcements with insert and applying an adhesive layer will result in a redundant connection, if either of them fail the other will be able to carry all the loads.

The location of the luffing cylinder attachment will be at the same location as the second vertical member. In the basic design this is at 1400 mm. This assures efficient use of the reinforcement of the core as this location is the highest loaded one on the gangway.

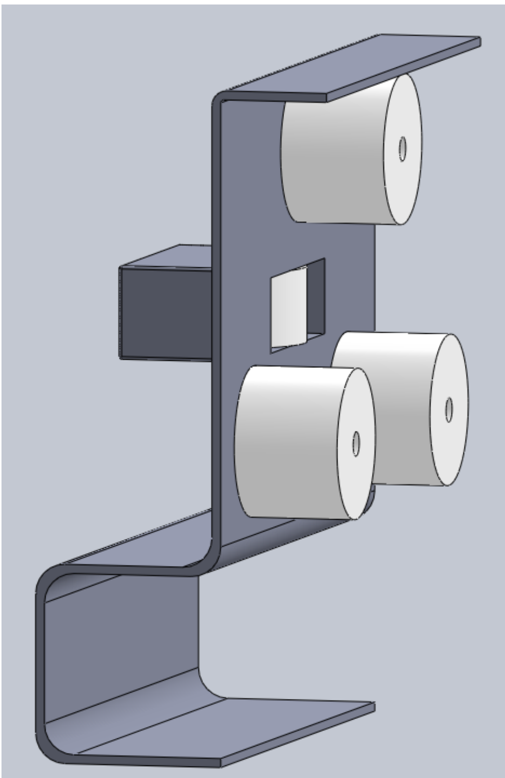


**Figure 5.8:** Telescoping support closest to the hinge point

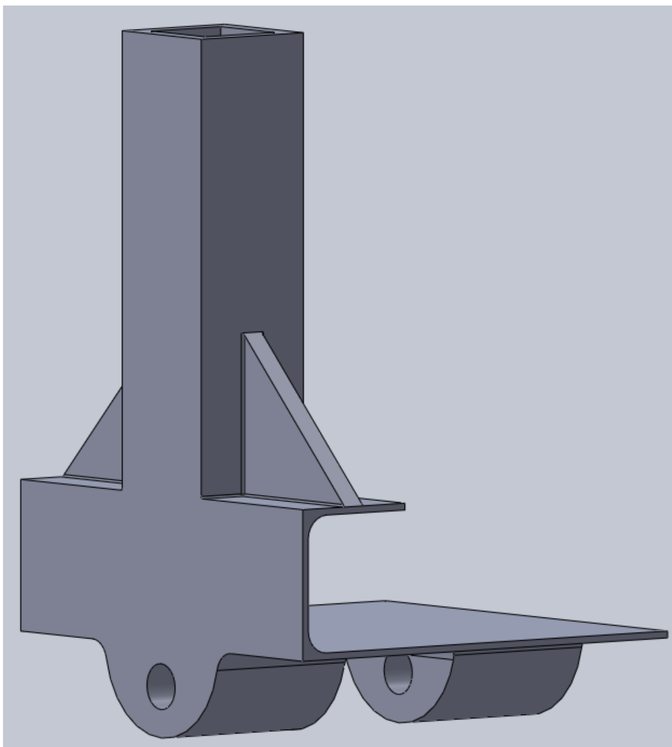


**Figure 5.9:** Luffing cylinder attachment bracket

### 5.3.4 Hinge point connection

To allow luffing of the gangway the main boom needs to be connected to the transfer deck, the hinge point connection design can be seen in Figure 5.10. A pinned connection is used to connect the gangway and the transfer deck. The dimensions of the connection are equal to the current one such that the gangway is compatible with these systems.

As all the loads from the gangway need to be introduced into the transfer deck through this bracket it needs to be redundant. The same procedure as for the luffing cylinder attachments will be used. The core will be replaced and tapered into the foam creating a gradual changing foam reducing stress concentrations. Using a strong core allows for bolting completely through the deck. The stainless steel bracket will be isolated from the deck by a layer of glass fiber. Adhesive will be applied as well, creating a redundant connection. Both the bolts as the adhesive is capable of carrying all applied load.

In Figure 5.10 one can see that the connection of the railing framework to the deck is at the same location. It is a combination of the connection to the transfer deck and the connection for the railing framework. The carbon diagonal profile with an outer layer of glass fiber and the vertical glass fiber profile, will be bonded into the metal bracket, as is done for the other railing framework members.

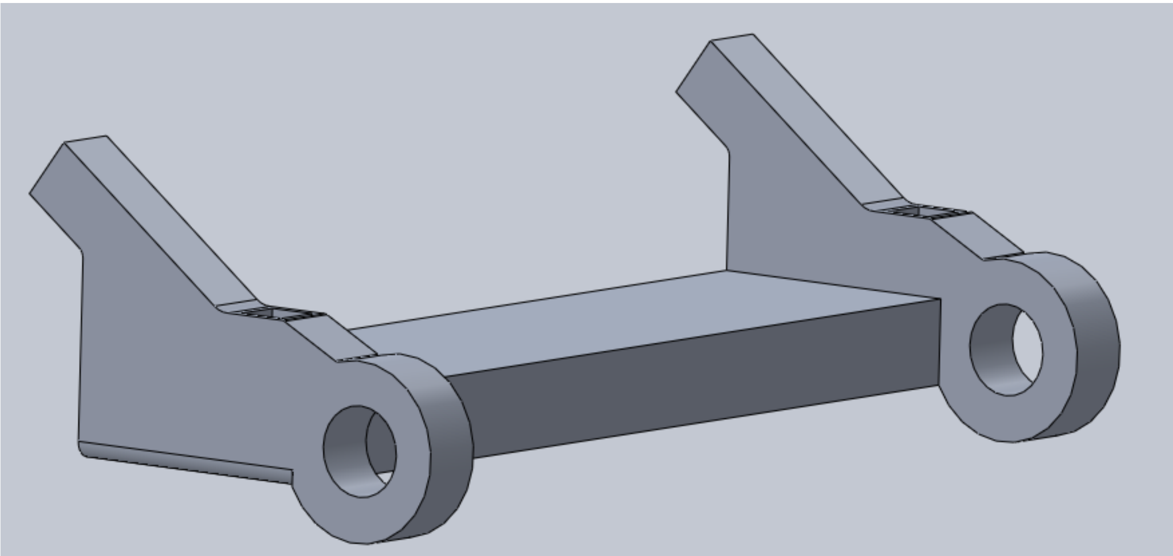


**Figure 5.10:** Hing point bracket design

# Chapter 6

# Basic design results

The results of the design process are described in this chapter which results in a basic design. First an overview of the gangway is presented after which details of the deck, weight and railing profiles are given. The design and sizing of the joints is described next. The gangway failure modes and effects are described next. Production and certification are defined and a cost estimation is presented. This chapter concludes with a Life Cycle Costs (LCC) and determining the limits of the design.

## 6.1 Gangway overview

The outcome of the basic design of the composite gangway can be seen in Figures 6.1, for the main boom and 6.2 for the Telescoping Boom (T-boom).

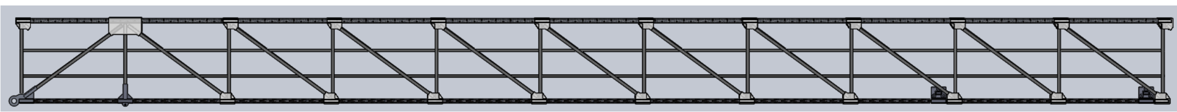


**Figure 6.1:** Overview main boom basic design with the hinge point connection on the left

The main boom in Figure 6.1 has the hinge point connection on the left. The first diagonal member is mounted different compared to the remaining members, the reason is that placing it this way it is loaded in tension. The forces in the railing need to be transfer to the transfer deck through the hinge point bracket. One vertical member to the right the luffing cylinder connection can be seen. At the top of the second vertical the Polyetheretherketone (PEEK) bracket can be seen. All the way to the right the telescoping supports are placed.

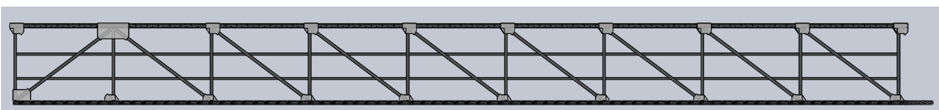


**Figure 6.2:** Overview telescoping boom basic design with the tip on the right

On the left side of the T-boom the first diagonal member is inverted as well. This is done to divert the forces in the railing back to the deck in the case the T-boom is fully extended. When the T-boom is moving the forces in the T-boom change and the diagonal become loaded differently. With a less than fully extended T-boom the forces in the gangway decrease and some diagonals in the T-boom will be loaded in less tension or even compression. The forces are small so the pulltrusion profiles will be able to carry the compressional load.

## 6.2 Deck lay-out

The important deck dimensions and parameters from the basic design are stated in Table 6.1. These are also stated in the drawing in Appendix F.1. The core thickness is set to 50 mm as this is the maximum thickness produced for this type of core. A thicker core could be made by adding an extra layer of foam with an adhesive layer in between. Increasing the core thickness will reduce the twist. The presented basic design fulfills the requirements so the extra complexity of adding a layer of foam is not desired.

**Table 6.1:** Main boom and T-boom deck design

| | **Main boom** | **T-boom** |
|---|---|---|
| Length [mm] | 15400 | 12600 |
| Width [mm] | 850 | 750 |
| Core thickness [mm] | 50 | 50 |
| Core material [-] | Gurit Corecell M130 | Gurit Corecell M130 |
| Lay-up [°] | $[0/0/\pm45/0/0/90]_s$ | $[\pm45/0/0/\bar{90}]_s$ |

Next to the properties as stated above, a weight is dedicated to a grip layer. The weight estimate is based on the POLYAC® from Resiplast. [28] Such grip layer has been succesfully applied on Fiber Reinforced Polymer (FRP) bridge decks. Due to the limited use and load the lightest option is sufficient. The weight of the package, the grip layer and a top coat, is approximately 3.5 kg/m$^2$. [28]

## 6.3 Gangway weight

One of the main objectives was to reduce the weight of the gangway. This would create the possibility to further develop a lightweight system, longer or wider gangway. The gangway weight of the basic design is estimated to be 1168 kg. A division of the individual components is made in Figure 6.3. The deck accounts for 64% of the weight, excluding the grip layer of another 10%. The railing, all profiles and brackets combined accounts for 26% of the weight. These masses include a 30% contingency which is taken into account for dealing with the required local reinforcements. Next to that the masses of the metal brackets are included in this percentage as they will scale with the forces acting on the gangway. At last an amount of mass for secondary systems is included in this margin.

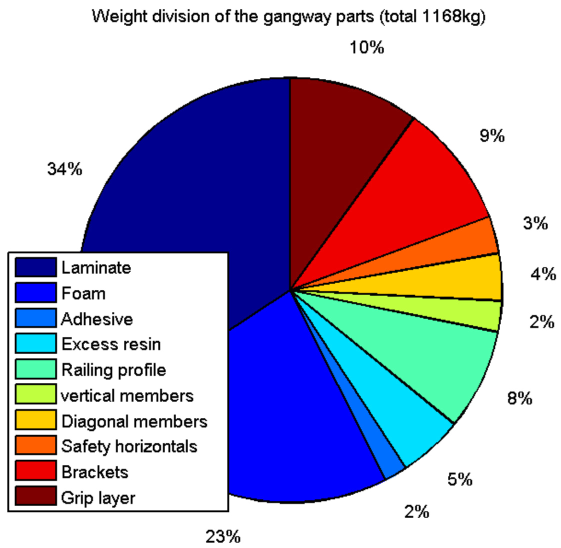



**Figure 6.3:** Weight division of individual gangway parts

## 6.4 Railing profiles

The railing profile sizing can be split up in two parts. The carbon top railing is designed to have a sufficient bending stiffness to fulfill the eigenfrequency requirement. The other, glass fiber pultrusions are sized to be sufficiently strong to support the railing and to protect the transferee in case this is needed. The dimensions and materials are stated in Table 6.2. The glass fiber pultrusions are standard and are bought off-the-shelve.

**Table 6.2:** Railing framework profile dimensions and materials

| | **Booms** |
|---|---|
| Railing (w x h x t) [mm] | 60x60x4.5 |
| Material railing | Gurit HEC Carbon fiber |
| Vertical members (w x h x t) [mm] | 38x38x3 |
| Material vertical | Exel glass fiber |
| Diagonal members (w x h x t) [mm] | 38x38x3 |
| Material diagonals | Exel glass fiber |

If we look at the force in the first diagonal member in Figure 6.4 one can see that 159 [kN] is to much for the glass fiber profile. The resulting stress is 379 MPa whereas the limit for the profile is only 240 MPa. Therefore this first diagonal member will be made from carbon fiber, just like the railing will be. The second vertical member has the same problem and will be made using carbon fiber. The dimensions of the profile be roughly the same as the glass fiber pultrusion as the strength of the carbon profile is roughly 2500 MPa for pure Unidirectional (UD) profiles.

## 6.5 Joints

All joints are analyzed to determine their effectiveness. As the joint are bonded the stress in the adhesive is checked for all joints as well. Due to time constraints and complexity stress concentrations of the joints were not taken into account. Some joint, with stresses close to the critical material properties, will require more extensive analysis before a firm conclusion can be drawn.

### 6.5.1 Connection and railing forces

Before the connections sizing can be checked the forces need to be known. First the connection forces are calculated followed by the determination of the internal forces in the railing framework.

**Connection forces** The forces in the connections were calculated as defined in Section 5.2.5. The outcome of these calculation for the worst load case, Emergency Case - Cargo Transfer (EC-CT), can be found in Table 6.3.

**Table 6.3:** Connection forces for the worst load case (EC-CT)

| Parameter | Unit | Value |
|---|---|---|
| Fx hinge point | [kN] | -59 |
| Fz hinge point | [kN] | -97 |
| Fx luffing cylinder (per cylinder) | [kN] | 57 |
| Fz luffing cylinder (per cylinder) | [kN] | 90 |
| Fy telescoping support (per support) | [kN[ | 3 |
| Fz telescoping support (per support) | [kN] | -11 |

**Main boom railing forces** The forces in the main boom are calculated as stated in Section 5.2.5. Next to these forces the main boom is loaded by the T-boom through the two supports on the main boom. These points introduce a load into the framework. These are added at their nodes, namely at 12.8 m and 15.6 m from the hinge point. At the first location an internal force in the negative z-direction is introduced, at the tip this is in the positive z-direction. This has an influence of the internal framework forces. The internal forces in the railing framework can be seen in Figure 6.4.

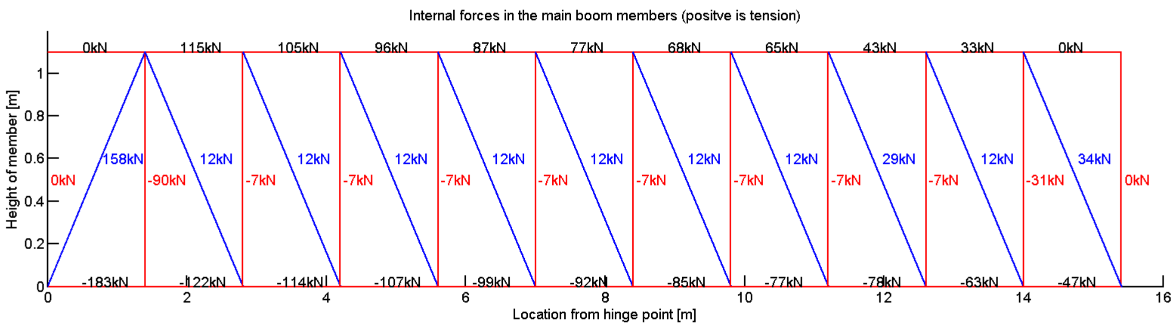



**Figure 6.4:** Internal forces in the main boom railing members for EC-CT load case (positive is tension)

Looking at the connections between the railing and the vertical/diagonal members, the second and second to last are highly loaded. The ones in between experience loads of less than 10% of the second bracket. The design of these brackets will therefore need to be different to prevent excess weight by over designed brackets at the in between locations.

**Telescoping boom railing forces** The T-boom experiences only the load on the tip and its dead weight. Due to theses lower forces on the system the internal forces in the framework are lower as well. These are displayed in Figure 6.5. These forces are when the T-boom is fully extended and the telescoping supports are at the railing brackets.

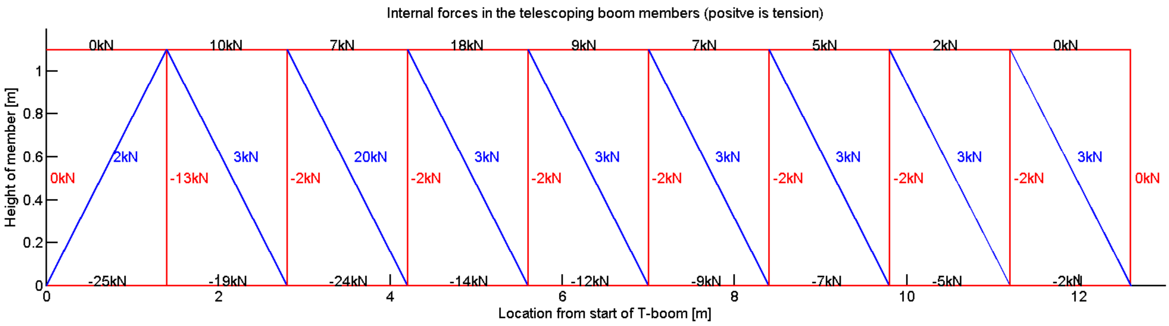



**Figure 6.5:** Internal forces in the telescoping boom railing members for EC-CT load case (positive is tension)

When the T-boom is moving the telescoping supports act on different locations of the T-boom deck. At these points the telescoping force, which keeps the T-boom inside the main boom, acts solely on the deck. The applied shear webs and metal plate are used to deal with these loads. As the deflection of the T-boom is downward due to the mass, the two wheels of the bracket are placed on the contact side of the deck when deflected.

## 6.5.2 Railing connections

Only the highly loaded railing connection at the railing is analyzed. It is assumed that if this connection can be designed, the rest can be done as well.

Different areas of the bracket need to be checked. First, there is the required area for the adhesive to transfer all the load to and from the profiles. Secondly, the bracket needs to withstand the stresses due to the forces in the profiles. Ideally a Finite Element Method (FEM) analysis needs to be done to check for stress concentrations, due to time constraints this has not been performed. Simple stress calculations can be done to see if the thickness's are sufficient for the loads.

Tables 6.4 and 6.5 show the results for the bracket with the forces as shown in Figure 5.5. The dimensions of the bracket can be found in Appendix F.2. The second column shows the force as indicated by the arrows, the third column shows the adhesive stress, all well below the design limit of 32 MPa. The fourth column states the stress in the material. Normal and glass filled PEEK is not strong enough, 30% carbon filled PEEK will be strong enough as the Margin of Safety (MS) is 1.2. A detailed FEM analysis is desired to convince the certifying authorities.

**Table 6.4:** Adhesive stresses in the railing connection

| | Force [kN] | Adhesive area [mm$^2$] | Adhesive stress [MPa] | Margin of safety [-] |
|---|---|---|---|---|
| Railing ($F_{rail}$) | 116 | (446x60)x3 = 80,280 | 1.4 | 33.3 |
| Diagonal 1 ($F_1$) | -159 | (200x38)x4 = 30,400 | 5.2 | 8.2 |
| Vertical ($F_2$) | 91 | (150x38)x4 = 22,800 | 4.0 | 11.0 |
| Diagonal 2 ($F_{diagonal}$) | 12 | (200x38)x4 = 30,400 | 0.4 | 119 |

**Table 6.5:** Material stresses in the railing connection

| | Force [kN] | Material area [mm$^2$] | Material stress [MPa] | Margin of safety [-] |
|---|---|---|---|---|
| Railing ($F_{rail}$) | 116 | 3x(60x10) = 1800 | 64.2 | 1.5 |
| Diagonal 1 ($F_1$) | -159 | (60x60)-(38x38) = 2156 | 73.7 | 1.2 |
| Vertical ($F_2$) | 91 | (60x60)-(38x38) = 2156 | 42.2 | 2.8 |
| Diagonal 2 ($F_{diagonal}$) | 12 | (60x60)-(38x38) = 2156 | 5.7 | 27.2 |

### 6.5.3 Telescoping supports

The bracket as can be seen in Figure 5.8 has been sized. The dimensions of the bracket can be found in Appendix F.3.

The forces are determined at the level of the wheels, this is approximately 70 mm from the middle of the deck. The force in y-direction creates a moment of 175 Nm. Which can be converted to a force couple of 3 kN with the deck thickness of 58 mm. The resulting forces in the bracket and in the adhesive layer are displayed in Table 6.6. The stresses in the adhesive are well below the limit of the adhesive. The stresses in the bracket, with the neglecting of stress concentrations, are also below critical limits.

**Table 6.6:** Stresses associated with the telescoping support connection in the EC-CT load case

| | Force [kN] | Adhesive stress [MPa] | Bracket material stress [MPa] |
|---|---|---|---|
| Top brackets | 6 | 0.6 (200x50) | 10.0 (200x3) |
| Bottom bracket | 1 | 0.1 (200x50) | 1.7 (200x3) |
| Side of deck | 11 | 0.8 (200x66) | 55.6 (66x3) |

### 6.5.4 Luffing cylinder attachment

The bracket as can be seen in Figure 5.9 has been sized. The dimensions of the bracket can be found in Appendix F.4.

The stresses in the adhesive are, again, well below the critical value. The side of the bracket is a point of concern. The stress in the side of the bracket is close to the allowable limit. Three options are left. Increase the properties of the stainless steel by heat treatments or increasing the thickness, adding extra weight, the last option is to done a detailed analysis to see if the peak stresses remain below the required limits.

**Table 6.7:** Stresses associated with the luffing cylinder connection in the EC-CT load case

| | **Force [kN]** | **Adhesive stress [MPa]** | **Bracket material stress [MPa]** |
|---|---|---|---|
| Bottom of deck | 57 | 1.4 (200x200) | 95.0 (200x3) |
| Side of deck | 90 | 6.8 (200x66) | 150.0 (200x3) |

### 6.5.5 Hinge point connection

The bracket as can be seen in Figure 5.10 has been sized. The dimensions of the bracket can be found in Appendix F.5.

Due to width of the gangway and the length of the bracket both the adhesive stress and the material stress for the top and bottom of the bracket are low. However, the same does not hold for the sides. Not only the force is higher, the area is much lower as well. The result is that the adhesive will be strong enough but the material is very close to the allowable design value. Increasing the thickness of the sides will reduce the stress at the cost of complexity in the production and extra weight.

**Table 6.8:** Stresses associated with the hinge point connection in the EC-CT load case

| | **Force [kN]** | **Adhesive stress [MPa]** | **Bracket material stress [MPa]** |
|---|---|---|---|
| Top & bottom | 59 | 0.2 ((200x858)x2) | 11.5 ((858x3)x2) |
| Sides | 97 | 3.7 ((200x66)x2) | 245.0 ((66x3)x2) |

## 6.6 Gangway failure mode and effects analysis

Gangway failure is divided in the determination of the unity checks for the different failure modes and in the consequences of

### 6.6.1 Failure mode unity checks

The determination of the gangway failure is split up in three figures. Figure 6.6 shows the eigenfrequency (1.78 Hz), deflection (-163 mm) and twist (-7.12°) for the worst load case (EC-CT). All unity checks are below one, meaning all stated requirements are met.

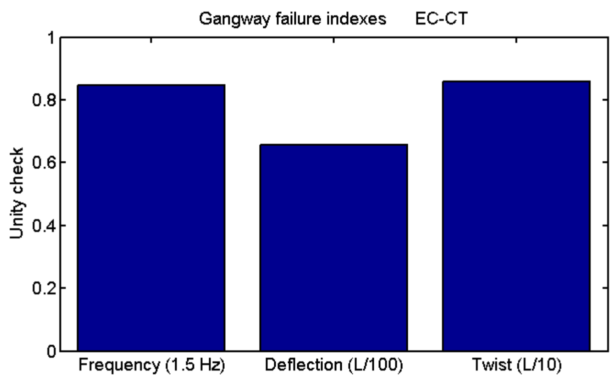



**Figure 6.6:** Unity check of eigenfrequency, deflection and twist (EC-CT load case)

In Figure 6.7 the Tsai-Wu failure criteria is plotted for each ply in the laminate. The top is for the first millimeter of the main boom and the bottom is the first millimeter of the T-boom, stated differently, these are the worst case scenarios, with all the material knockdown factors, the heaviest load case and the worst location. The sides of the deck are the locations closest to failure. This is due to the small width of the laminate in comparison to the load acting on it. The same reasoning is true for the top and bottom of the deck. Duo to the large width the load per unit length is low, failure will not occur.

Another interesting fact is that the +45° and -45° layer are not equal. The reason is that the deck is loaded with torsion. Depending on the direction of the torsion, from which side is the wind blowing, the +45° or -45° layer is carrying more load. In Figure 6.7, the wind is blowing in y-direction as is stated in Figure 1.1.

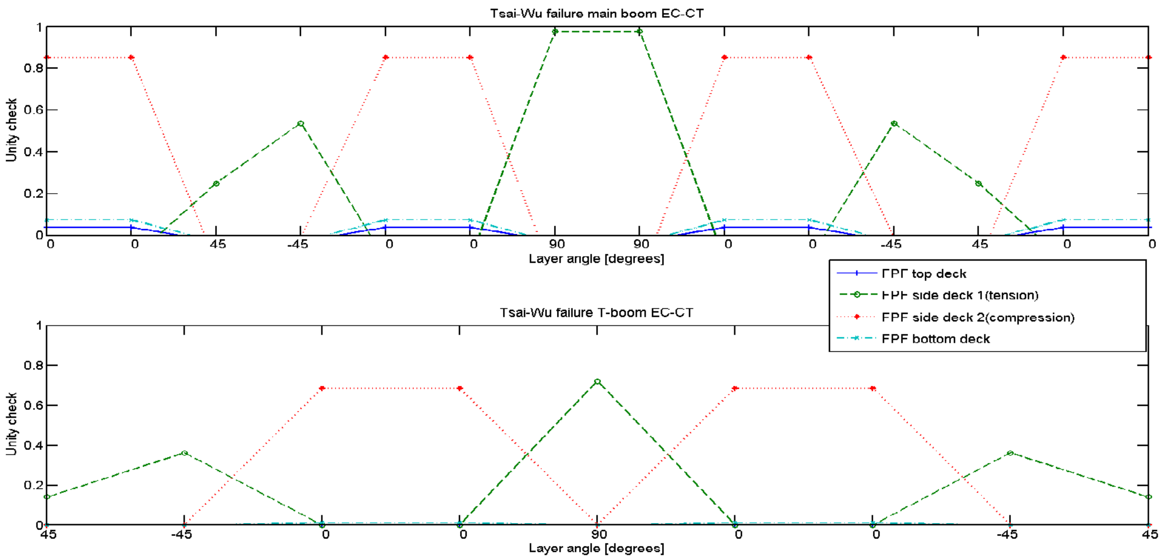



**Figure 6.7:** Tsai-Wu first-ply-failure maximal values (EC-CT load case)

Other failure modes are depicted in Figure 6.8. The railing failure is the most critical at less than 0.4 in the worst load case. The railing itself will not fail nor will the gangway buckle or wrinkle.

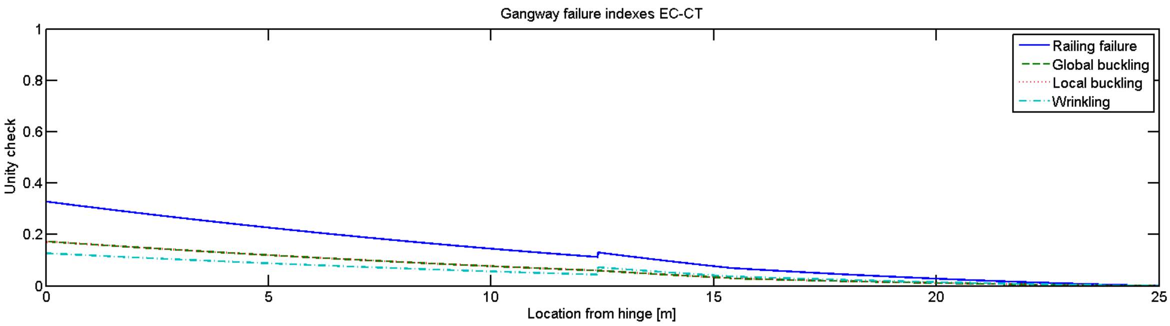



**Figure 6.8:** Gangway failure modes unity checks (EC-CT load case)

### 6.6.2 Failure effect analysis

The gangway consist of two booms, each made from a deck, a railing and a supporting framework. Due to fatigue, possibly in combination with impacts, parts of the gangway can fail. The extend of the consequence is dependent on which part will fail. To minimize the possibility of unexpected failure the gangway will be scanned completely once a year, however failures can never be completely excluded. An analysis is made of possible damages and the consequence of them

The risk matrix is a created by combining the severity of an accident and the likelihood of the incident to happen. Most of the failures can occur on either the main boom or T-boom. Due to the smaller forces acting on the T-boom the effect on the gangways capability to perform its task is, most of the times, smaller for the T-boom than for the main boom.

- One of the railings can fail completely, resulting in a railing which is not capable to carry any loads. This result in a decrease in bending stiffness, reducing the eigenfrequency. The deck will need to carry more loads as well. Depending on the operational mode and the wind at that time this will introduces extra bending and torsion into the deck. Bending around the y-axis will not be a problem as these fibers are not critically loaded, see Figure 6.7.
- Impact damage on the side of the T-boom. As the side carries the bending due to the wind and the torsion the severity of an impact is depending on the wind conditions and the extent of the damage. A possible impact on the side of the gangway will occur only in cantilever mode, meaning no people and possibly some cargo is on the gangway. The loads on the side of the deck are small a local failure is not going to be critical. This does not mean that it does not require a thorough check or repair.
- Impact damage on the side of the main boom. The same reasoning applies to the main boom as for the T-boom.
- Partly railing failure, i.e. one connecting bracket losing connection. A single connection failure, not the first or the last, will result in one vertical and one diagonal member not carrying load. The result is an increase in load for the member closer to the hinge point. The increase in force will not start a sequence of failure as the framework has sufficient MS to handle the extra load.
- Failure of a luffing cylinder bracket. There are two luffing cylinders, when one of the connections fails all load will go through the other bracket. The loads double and torsion is introduced. A detailed analysis needs to be performed to determine if the single bracket will be sufficiently strong to safely finish the transfer in progress and retract the gangway.
- Failure of a telescoping support. If a single support will fail, it will not be able to carry loads. The three remaining brackets will have to carry all loads. It will be difficult to telescope the T-boom but no catastrophic failure will occur.
- Failure of the hinge point bracket. This would be considered a catastrophic failure where lives will be at risk. To prevent the risk of the adhesive to fail bolts will be used for the connection as well. Both methods are capable of carrying all loads, so in the case of one failing the gangway is still fully operational.

## 6.7 Production

The production of the composite gangway is split up in three sections. The creation of the deck and railing from prepreg carbon fiber and foam. The brackets need to be produced, these include the one for the railing and those needed for the movement of the gangway.

**Deck and railing** The production of the railing and deck are done in a similar manner. Both consist of a foam core and prepreg. Firstly the molds are prepared and release agent is applied. The prepreg is placed inside the molds, a U-shaped mold for both cases, with the fiber hanging over the edge of the mold. When all required layers are placed inside the mold the core is placed. For the railing this is a simple beam with rounded edges. The core fore the deck consist of multiple blocks of foam. Local reinforcements for connection points and the telescoping wheels are placed. The fibers are now folded back onto the foam and additional layers are placed to have an equal thickness and to assure that load transfer between different plies is assured.

When all fibers are placed peel-ply and bleeder fabric is applied before a vacuum bag is put over. The vacuum bag needs to be tested for leaks before the oven can be put on. A oven will be build around the molds, the Out-of-Autoclave (OOA) prepreg needs to cure for 12 hours at 80° C or 1 hour at 120° C according to the datasheet by Gurit as stated in Appendix B. This can be achieved by building a isolated tent over the mold and use heaters. Multiple temperature sensors will be placed inside the mold to check if the required temperature is achieved.

The time needed to produce the two decks, four railings, two vertical and two diagonal members is dependent on the number of molds used. Assuming that there is one mold for the deck, main boom railing, T-boom railing, vertical and diagonal member, two runs are needed for the production. With the preparation, placing the fibers and sealing followed by curing assumed to take three days for two people, the production time for railing and deck will be six days.

**Brackets** The railing connectors are made using Computer Numerical Control (CNC) machining. The time needed is dependent on the amount of material which needs to be removed and the tolerances required for a proper fit. These bracket will be ordered up front and should be delivered before the production of the deck start to check the quality and tolerances.

The brackets for the hinge point, luffing cylinders and telescoping support will be produced by a certified producer from stainless steel. These also need be delivered prior to fabrications of the deck and railings.

**Assembly** The order in which the gangway is assembled is important. Every bracket can be bonded to the deck independent of other brackets allowing for proper preparation and alignment of the brackets without problems of adhesive curing before the complete railing is assembled. The assembly of the gangway as presented in this basic design is estimated to take about one week for two persons by Maarten Labordus from KVE Composites [27], this is an estimate based on general dimensions and without an detailed analysis.

## 6.8 Certification

As the process to obtaining a certification is both time and costs intensive a clear path is needed to limit both resources. Contact has been made with Lloyd's Register (LR) and their opinion regarding the implementation is stated below. This is followed by small tests which can be performed to get familiar with the materials used and the type of connections.

### 6.8.1 Current status of certification requirements

Contact with LR resulted in their opinion regarding this design and the creation of a composite gangway in general. Several points of concern were raised but overall they are open to investigate the option to start the process of certification of a composite gangway for the Ampelmann system. The main points of concern are:

1. A specialized firm in composite engineering doing the design will speed up the certification process, a good track record is required to create trust in the eventual design.
2. A composite specific FEM analysis will need to be provided, fulfilling the requirement stated in the Code for Lifting Appliances in a Marine Environment (CLAME) and based on general composite design philosophy.
3. During the production and assembly of the gangway an auditor from LR needs to be present.
4. A prototype or prototype parts need to be tested depending on the eventual design.
5. Depending on the actual use of the system certain fire and heat resistance requirements might be added. If the system is used as an evacuation system these will need to be met.
6. Their recommendation is not to use any connections, if bonded connections cannot be avoided peel stresses need to be minimized.

Points 1-3 are straight forward, Ampelmann never had the goal to design the gangway internally. Audits are also being performed during the production of the current Gangway XL (GXL). Number 4 is not specific, it is not clear if a working prototype needs to be tested and to what extent. If a gangway needs to be tested until failure the development costs increase significant. Point 5 is something that needs further investigation. Ampelmann, and their clients, need to find out if the system will have a function as evacuation solution. If this is true, the time required and temperature during such a procedure need to be determined in order to find a solution. Point 6 is a point of concern with the basic design as it is. This concepts is build around bonding. Most of the joints are completely fixed and have minimal peel stresses. The highly loaded first bracket can be made such that no adhesive joint is present at the costs of flexibility and ease of production. Other primary connections will be connected using adhesive and bolts to provide redundancy, these are the hinge point, luffing cylinder attachments and telescoping supports.

### 6.8.2 Tests for concept verification

In order to verify the basic design small test can be performed to see if the calculations are in line with the test results. Having these tests and showing these to the certification authority will create a solid basis without investing significant money.

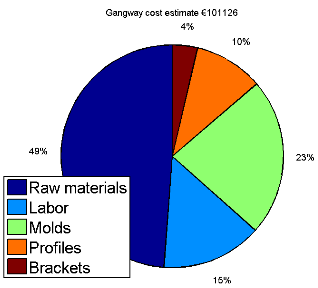
- Testing the connection between a CNC bracket and glass fiber profile. Both tension and compression can be tested. By changing the dimensions, especially the thickness, of the profile the stresses for different connections can be replicated. This eliminates the need for production of a carbon profile, reducing both costs and complexity. Failure of the profile is unlikely as the bracket material and adhesive are the weak areas in the connection.

- Impact tests of the railing connections. What happens to the adhesive layer when an impact has occurred. This impact is followed by cyclic loading to determine the fatigue properties of the connection.
- T-boom reinforced deck test to see if the shear web and reinforced core will carry all loads. This can be done in ultimate load or as a fatigue tests. During cyclic loading the wear of the deck can be analyzed as well.
- A section of the main boom deck can be build in order to perform a bending test, this test needs to be performed for both the bending around the y- and z-axis.
- A section of the T-boom can be build to test the possible core crushing of people walking. Furthermore, this section can be used to determine the effectiveness of the reinforced core to prevent core crushing from the telescoping wheels.

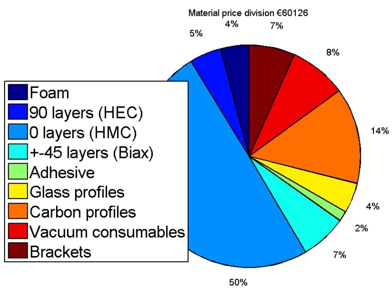
## 6.9 Cost estimation

An estimate of the production of the gangway can be made as can be seen in Figure 6.9a. In this case the molds used are depreciated for a single gangway, whereas they can be re-used for the production of new gangways. About half the costs are associated with materials.

A split up of the material costs is made in Figure 6.9b. Half of the costs are associated with the High Modulus Carbon (HMC) prepreg which is needed for the stiffness. All the costs associated to carbon fiber result in 76% of the material costs. Another interesting conclusion is the foam, it contributes only 4% to the costs while being 23% of the weight of the gangway.




(a) Composite gangway production




(b) Required materials

**Figure 6.9:** Gangway cost division

## 6.10 Life cycle costs

A fair comparison can only be made over the life-time of a gangway. Using the required life time of 20 years, conservative for the composite gangway, the comparison as stated in Table 6.9 can be made. If the costs are taken with a contingency of 10% and including the initial engineering costs, including an estimate for certification, an estimated 20 year LCC of €531,500 is found. Comparing this with the estimates of the costs of operating the steel GXL for 20 years, a cost of an estimated €500,000 a cost increase of €31,500 is made. Taking the engineering costs and initial certification of the gangway out of the equation results a cost saving over 20 year of €185,400.

**Table 6.9:** Costs comparison between the current steel GXL and a composite gangway of 25 meter over 20 years

| | Steel | Composite | Composite (contingency 10%) | Difference steel & (composite contingency) |
|---|---|---|---|---|
| Engineering costs [€] | n.a. | 100,000 | 110,000 | -110,000 |
| Mold costs [€] | n.a. | 35,000 | 38,500 | -38,500 |
| Gangway production costs [€] | 200,000 | 81,000 | 89,100 | 110,900 |
| Certification [€] | n.a. | 97,200 | 106,900 | -106,900 |
| Maintenance [€] | 300,000 | 170,000 | 187,000 | 113,000 |
| **Total LCC [€]** | 500,000 | 483,200 | 531,500 | -31,500 |

## 6.11 Maximizing gangway dimensions

One of the added benefits of a composite gangway is to increase the length of the gangway and/or to increase the tip load. Doing an analysis on the effect of changing the main boom length and the tip load can be seen in Figure 6.10. During this analysis the T-boom length was kept constant at 12000 mm and the lay-up, core thickness and other dimensional parameters were kept the same as the basic design. Only the eigenfrequency is done here as this is critical in the design.

From this figure we can see that if we want to have a maximum length of 25 meter the tip load can be 250 kg. Alternatively, keeping the tip load equal to a 100 kg, the gangway can have a maximal length of 27 meter. Removing the cargo transfer at the tip, only using the gangway for people transfer/cargo over the gangway, the length can be stretched to about 28.5 meter.

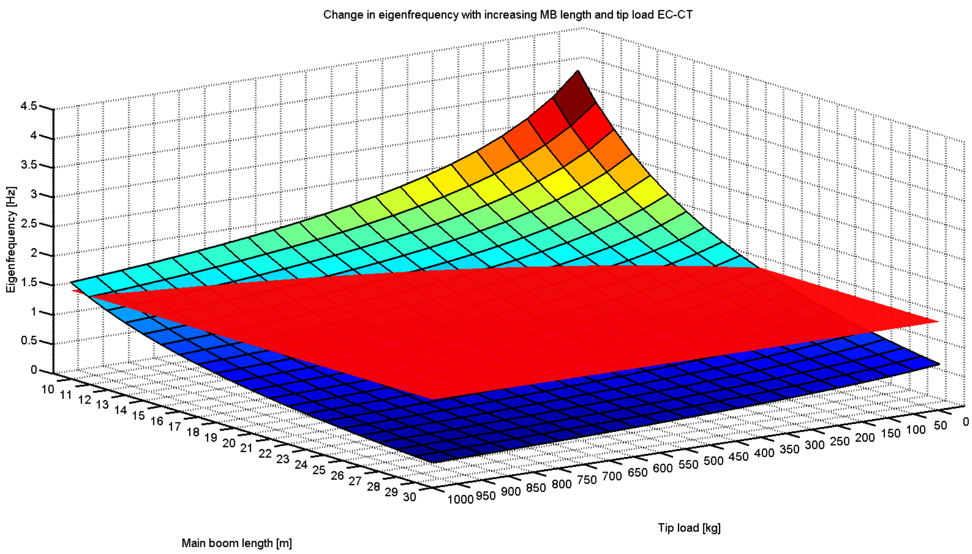



**Figure 6.10:** Eigenfrequency change with increasing main boom length and tip load, T-boom length is fixed to 12000 [mm]

# Chapter 7

# Conclusions

As competition is rising in the market of Walk2Work systems new developments are desired. The current system is heavy, thereby decreasing the speed of the vessel and consuming to much power. A weight saving composite gangway will start an overall decrease of the system weight. The goal of this thesis to define a composite gangway design which can be designed and produced which will have better performance as the current Gangway XL (GXL) while being lighter.

The project started with the design of three concepts which have been analyzed to find the most suitable solution for a composite re-design. The most suitable solution looks similar to the steel design. It consists of a sandwich deck with a load carrying railing to increase the bending stiffness. A framework is built to support the railing and to create a safety barrier for the transferee. A closed side design was taken into consideration as this would minimize the required joints. However it was not possible due to excess torque created by the wind load, resulting in excessive twist of the gangway.

Pre-certified materials are selected in order to speed up the certification process. Gurit is selected for the carbon fiber prepreg, foam and adhesive. All are certified and compatible with on another. The SE 84SE prepreg is selected, both the Unidirectional (UD) High Modulus Carbon (HMC), UD High Elongation Carbon (HEC) and Bi-axial (Biax) HEC are used in the design. The Corecell M130 core is used, as it has the desired properties such as minimal water ingress. The SA 80 adhesive is used as well. For most of the profiles in the railing framework pultrusion profiles from Exel Composites will be used.

Both the booms have an equal core thickness of 50 mm, the maximum standard thickness of the core as supplied by Gurit. The 0° layers are UD HMC for increased stiffness, the 90° layers use UD HEC. The main boom lay-up is $[0_2/\pm 45/0_2/90]_s$ and the Telescoping Boom (T-boom) deck consists of $[\pm 45/0_2/\overline{90}]_s$. The main boom length is 15400 mm and a width of 850 mm, the T-boom is 12600 mm long and 750 mm wide.

As the railing carries bending loads, the forces in the railing and the supporting framework, consisting of vertical and diagonal members need to be calculated. These forces are needed to size the brackets connecting these elements. The railing itself is a carbon fiber profile of 60 by

60 mm with a thickness of 4.5 mm. The first diagonal and second vertical member are made from carbon fiber as well as these experience more load as the forces from the railing need to be diverted back to the deck at the hinge point. The remainder of the diagonals (loaded in tension) and verticals (loaded in compression) use glass fiber 38 by 38 by 3 mm pultrusion profiles from Exel Composites. The connecting brackets are machined from (30% carbon filled) Polyetheretherketone (PEEK). The bracket which experiences the most sever loads is designed and using 30% carbon filled PEEK a Margin of Safety (MS) of 1.2 is achieved. Meaning all other railing joint are possible as well.

The connections required for the movements of the gangway are made from stainless steel. An isolating layer of glass fiber is used to prevent galvanic corrosion. The hinge point connection, connecting the gangway to the transfer deck, is the most critical but is able to withstand all forces when the core is locally replaced such that bolts can be used in combination with adhesive. The result is a redundant connection which is beneficial for certification. The luffing cylinder connections, located on the bottom of the deck require a local core reinforcement as well. This bracket is combined with the highly loaded vertical member. The lasts connections are those that facilitate the telescoping of T-boom. It secures the T-boom inside the main boom by having wheels guiding it in y- and z-direction. To deal with the shear forces the bracket creates, exta $\pm 45$ layers are locally placed on the side of the deck.

The basic design has an eigenfrequency of 1.78 Hz where 1.5 was the minimal. Deflection and twist are within specifications and all failure mode unity checks are below one, including all composite specific knockdown factors as well as the material knockdown from the regulations based on metals. The most critical areas are the side of the deck close to the hinge point in cantilever mode, due to the wind force acting on the side of the gangway.

The design is based around the philosophy of simple production. The deck is made by hand lay-up in a simple mold. The same is true for the railing. The pultrusion profiles are bought and the brackets of the railing are machined, resulting is design flexibility. The metal connections are made by a combination of forming and casting. The whole gangway is assembled by adhesive bonding and bolting in some critical locations. As this is needed for certification. Contact with the certifying authorities resulted in several steps before certification can be obtained. First of all the connections need to be reduced to a minimal number, the connections which are needed should have minimal peel stresses. A Finite Element Method (FEM) analysis will be needed as well as testing of a prototype. The extend of these tests are not known until now.

As a final step in this thesis the Life Cycle Costs (LCC) of the composite gangway are determined. The LCC of the gangway are estimated to be €314,600 excluding engineering and first gangway certification(€531,500 including), compared to the estimated costs of the current gangway of €500,000 this results in a saving of €185,400. Roughly the costs of the gangway production. Furthermore, the life time of the composite gangway could be well over 20 years, increasing the saving even further.

Based on the results of this thesis it can be said that a composite gangway can be designed for the Ampelmann system. It can be produced in a simple manor and certification can be obtained with minor changes to the current design. Even with the initial investment needed a composite gangway is only €30,000 more than a steel one. Further exploring the limits of the material can result in an longer and/or wider gangway increasing the market of the system.

# Chapter 8

# Recommendations

During the study to investigate if a producible and certifiable gangway can be designed some assumptions were made to stay within the set time-frame. Next to these assumptions, new aspects came up in the process. Before a composite gangway can be implemented on a Ampelmann system further research is desired for the following challenges.

- The required fire and heat resistance needs to be determined in co-operation with the authorities. How much heat does the gangway need to resist and for which period of time? Depending on the outcome the design needs to be adapted to fulfill the requirements.
- During the research the introduction of forces into the laminate through the tip was neglected. The tip needs to be designed, taking into account the different angles at which the gangway can connect to the structure and a different forces and speeds. The tip is also the area where most damages occur. Designing a tip which will break at unexpected impacts and thereby preventing damage to the booms will save costs in the long run, but replacing a damaged tip should be a quick step to prevent downtime.
- As the eigenfrequency is critical and a longer gangway is desired by Ampelmann further research needs to be done for alternative ways to increase this. Options are changing the geometry of the gangway or placing tuned mass dampers in the deck to increase the stability of the system.
- Testing of the connections between railing and diagonal/vertical members needs to be performed to determine the effectiveness of the provided solution. Showing these initial test results together with the design analysis to the certifying authorities will create trust in the design methodology.
- Alternative connections for the railing need to be investigated. The current Computer Numerical Control (CNC) bracket withstand the forces but is a bonded connection, undesired according to the certification agencies. Ideally the gangway will be designed such that there are no connections required, or at least as little as possible.
- The rigidity of the deck needs to be analyzed. Due to excessive walking and/or impacts the core might detach from the facesheet or be indented. Adding extra layers on top of the deck, either carbon- or glass fiber, will increase the rigidity of the deck.

If a complete new start would be made there are a couple of things that might benefit from change. First of all changing the geometry with the load carrying railing members at a higher height and closing it of at the top. This would be beneficial for both the twisting and for the eigenfrequency. The use of prepreg can be reconsidered and especially the High Modulus Carbon (HMC) carbon. A vacuum infusion process with regular High Elongation Carbon (HEC) fibers will save at least 50% of the costs compared to the prepreg used in the basic design.

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# Appendix A

# Key performance indicator calculations

## A.1 Bending stiffness

To calculate the bending stiffness of the different concepts, first the location of the Center of Gravity (c.o.g.) needs to be determined. The bending stiffness is calculated around this point for a correct comparison. All concepts are symmetric around a single axis, meaning the y-location of the Center of Gravity (c.o.g.) is on the axis of symmetry.

### Bending stiffness around y-axis

The bending stiffness around the y axis in Figures 3.2a, 3.2b and 3.2c, is the most important one in the design. This is the direction in which the structural weight is acting.

**1: Sandwich deck with loaded railing** The location of the c.o.g. is defined from the bottom middle of the deck, the location where the axis system is drawn in Figure 3.2a, and calculated using Equation (A.1).

$$cog_z = \frac{\sum y_i A_i}{\sum A_i} = \frac{\frac{h_{deck}}{2} A_{deck} + 2\left(\left(h_{railing} - \frac{h_{bar}}{2}\right) A_{bar}\right)}{A_{deck} + 2A_{bar}} \tag{A.1}$$

With the c.o.g. known, it can be used in Equation (A.2) which is adapted from Kollár, [29]. The missing terms, the Young's moduli, can be calculated using Equation (A.3). This equation calculates the Young's modulus based on the plystack through the $a_{11}$ term, Daniel, et al. [10]

$$\begin{aligned} EI_{yy_{concept1}} &= \frac{w_{deck}}{a_{11_{deck}}}\frac{h_{deck}^2}{2} + \frac{2w_{deck}}{d_{11_{deck}}} + \frac{2h_{deck}^3}{12a_{11_{deck}}} + E_{deck}A_{deck}\left(cog_z - \frac{h_{deck}}{2}\right)^2 \\ &+2\left(\frac{w_{bar}}{a_{11_{bar}}}\frac{h_{bar}^2}{2} + \frac{2w_{bar}}{d_{11_{bar}}} + \frac{2h_{bar}^3}{12a_{11_{bar}}}\right) + 2E_{bar}\left(A_{bar}\left(h_{railing} - \frac{h_{bar}}{2} - cog_z\right)^2\right) \end{aligned} \tag{A.2}$$

$$E_i = \frac{1}{t_i a_{11_i}} \tag{A.3}$$

**2: Sandwich panel U-shape** The U-shape concept uses a slightly different approach. It is based on "*table A.1*" of the book of Kollár, et al. [29, Appendix A]. It uses the calculation method for a U-shaped section. In order for this method to hold, the sandwich panels need to be made into a "representative laminate". This is done using Equation (3.1). An extra step is needed to calculate the c.o.g. location, note that the location calculated in Equation (A.5) is taken from the top of the railing.

$$EA = \frac{2h_{side}}{a_{11_{side}}} + \frac{w_{deck} - 2t_{deck}}{a_{11_{deck}}} \tag{A.4}$$

$$cog_z = \frac{1}{EA}\left(\frac{2h_{side}}{a_{11_{side}}}\frac{h_{side}}{2} + \frac{w_{deck} - 2t_{deck}}{a_{11_{deck}}}h_{side}\right) \tag{A.5}$$

With the c.o.g. known, Equation (A.6) can be used to calculate the $EI_{yy}$ of the concept.

$$EI_{yy_{concept2}} = \frac{w_{deck} - 2t_{deck}}{a_{11_{deck}}}\left(h_{side} - cog_z\right)^2 + \frac{w_{deck} - 2t_{deck}}{d_{11_{deck}}} + \frac{2}{a_{11_{side}}}\left(\frac{cog_z^3}{3} + \frac{\left(h_{side} - cog_z\right)^3}{3}\right) \tag{A.6}$$

**3: Sandwich deck with loaded railing and tube** This concept is the same as concept one except it has an extra tube under the deck. Therefore extra terms are added to Equations (A.1) and (A.2) to get to Equations (A.7) and (A.8). Once again the $E_i$ properties are calculated using Equation (A.3).

$$cog_z = \frac{\sum y_i A_i}{\sum A_i} = \frac{\frac{h_{deck}}{2}A_{deck} + 2\left(\left(h_{railing} - \frac{h_{bar}}{2}\right)A_{bar}\right) + \left(-r_{tube}A_{tube}\right)}{A_{deck} + 2A_{bar} + A_{tube}} \tag{A.7}$$

$$\begin{aligned} EI_{yy_{concept3}} &= \frac{w_{deck}}{a_{11_{deck}}}\frac{h_{deck}^2}{2} + \frac{2w_{deck}}{d_{11_{deck}}} + \frac{2h_{deck}^3}{12a_{11_{deck}}} + E_{deck}A_{deck}\left(cog_z - \frac{h_{deck}}{2}\right)^2 \\ &+2\left(\frac{w_{bar}}{a_{11_{bar}}}\frac{h_{bar}^2}{2} + \frac{2w_{bar}}{d_{11_{bar}}} + \frac{2h_{bar}^3}{12a_{11_{bar}}}\right) + 2\left(E_{bar}A_{bar}\left(h_{railing} - \frac{h_{bar}}{2} - cog_z\right)^2\right) \\ &+\pi\left(\frac{r_{tube}^3}{a_{11}} + \frac{r_{tube}}{d_{11}}\right) + E_{tube}A_{tube}\left(\left|r_{tube} - cog_z\right|\right)^2 \end{aligned} \tag{A.8}$$

## Bending stiffness around z-axis

When the gangway slews sideways the bending stiffness around the z-axis come into play. If the structure is not stiff enough, landing the gangway to the platform is difficult due to excessive tip movement.

**1: Sandwich deck with loaded railing** It is assumed that the railing only takes up bending moment around the y-axis. The bending stiffness around the z-axis is therefore only determined by the deck. It is calculated using Equation (A.9).

$$EI_{zz_{concept1}} = \frac{h_{deck}}{a_{11_{deck}}}\frac{w_{deck}^2}{2} + \frac{2h_{deck}}{d_{11_{deck}}} + \frac{2w_{deck}^3}{12a_{11_{deck}}} + 2\left(\frac{h_{bar}}{a_{11_{bar}}}\frac{w_{bar}^2}{2} + \frac{2h_{bar}}{d_{11_{bar}}} + \frac{2w_{bar}^3}{12a_{11_{bar}}}\right) + 2E_{bar}\left(A_{bar}\left(\frac{w_{deck}}{2} - \frac{w_{bar}}{2}\right)^2\right) \tag{A.9}$$

**2: Sandwich panel U-shape** The U-shape is symmetric around around the z-axis. Based on the formula from Kollár, et al. [29], Equation (A.10) is used. Once again the $a_{ij}$ & $d_{ij}$ terms are those of the sandwich panel, calculated using Equation (3.1).

$$EI_{zz_{concept2}} = \frac{h_{side}}{a_{11_{side}}}\frac{w_{deck}^2}{2} + \frac{2h_{side}}{d_{11_{side}}} + \frac{w_{deck}^3}{12a_{11_{deck}}} \tag{A.10}$$

**3: Sandwich deck with loaded railing and tube** The same assumption holds as for concept 1, the railing will not take up loads, however the tube does. Combining the equations from Kollár, et al. [29], Equation (A.11) is found.

$$EI_{zz_{concept3}} = \frac{h_{deck}}{a_{11_{deck}}}\frac{w_{deck}^2}{2} + \frac{2h_{deck}}{d_{11_{deck}}} + \frac{2w_{deck}^3}{12a_{11_{deck}}} + 2\left(\frac{h_{bar}}{a_{11_{bar}}}\frac{w_{bar}^2}{2} + \frac{2h_{bar}}{d_{11_{bar}}} + \frac{2w_{bar}^3}{12a_{11_{bar}}}\right) + 2E_{bar}\left(A_{bar}\left(\frac{w_{deck}}{2} - \frac{w_{bar}}{2}\right)^2\right) + \pi\left(\frac{r_{tube}^3}{a_{11}} + \frac{r_{tube}}{d_{11}}\right) \tag{A.11}$$

## A.2 Torsional rigidity

The second important parameter needed is the resistance to torsion. Two important properties are needed. First of all the shear center needs to be determined, this location has influence on the amount of torque acting on the structure. The distance between the c.o.g. and the shear center is, together with the side area, responsible for the torque on the structure. The second property is the torsional rigidity $GJ$.

**Concept 1: Sandwich deck with loaded railing** As stated in Section 3.3, it is assumed that only the deck will take the torsion. This result in the location of the shear center in the middle of deck since it is a closed and double symmetric structure.

The calculation of the torsional rigidity of the deck is taken from Kollár, [29] and can be seen in Equation (A.12).

$$GJ_{concept1} = \frac{2w_{deck}^2 h_{deck}^2}{a_{66_{deck}} w_{deck} + a_{66_{deck}} h_{deck}} \tag{A.12}$$

**Concept 2: Sandwich panel U-shape** The closed walls of the U-shape concept have an influence on the wind load, the wind load will be significantly larger. Next to that, the shape results in a shear center location below the structure increasing the torsion load. Using the formula stated by Kollár, [29] Equation (A.13) is used. In which the $d_{66}$ terms are the sandwich panel values coming from Equation (3.1).

$$GJ_{concept2} = 4\left(\frac{2w_{deck} - 2t_{deck}}{d_{66_{deck}}} + \frac{2h_{side}}{d_{66_{side}}}\right) \tag{A.13}$$

**Concept 3: Sandwich deck with loaded railing and tube** In this case, just like concept 1, the railing is assumed to not contribute to the torsional rigidity of the structure. The deck and tube will carry the torsion and are therefore incorporated in Equation (A.14), which is based on Kollár. [29]

$$GJ_{concept3} = \frac{2w_{deck}^2 h_{deck}^2}{a_{66_{deck}} w_{deck} + a_{66_{deck}} h_{deck}} + \frac{2r_{tube}^3 \pi}{a_{66_{tube}}} \tag{A.14}$$

## A.3 Masses

One of the main loads on the gangway is its own weight. The extra load of people or cargo are relatively small compared to the mass of the gangway. To get a better understanding on the influence of mass on the displacement for the different structures, the weight needs to be defined. Due to size difference between the main boom and Telescoping Boom (T-boom) both masses will be calculated and added to get the final gangway weight. In these calculations excess resin inflow in the foam is neglected, so are externally mounted, brackets and connections.

**Concept 1: Sandwich deck with loaded railing** The weight of concept 1 is depended on three aspects, the laminate of the deck, the foam inside the deck and the railing. Equation (A.15) is used for both the main boom and the T-boom.

$$\begin{aligned} m_{total} = m_{deck} + 2m_{railing} = \\ \left(A_{deck} L \rho_{laminate} + \left(w_{deck} h_{deck} - A_{deck}\right) L \rho_{foam}\right) + 2\left(A_{bar} L \rho_{laminate}\right) \end{aligned} \tag{A.15}$$

**Concept 2: Sandwich panel U-shape** The mass of the two parts of gangway concept 2 are calculated using Equation (A.16).

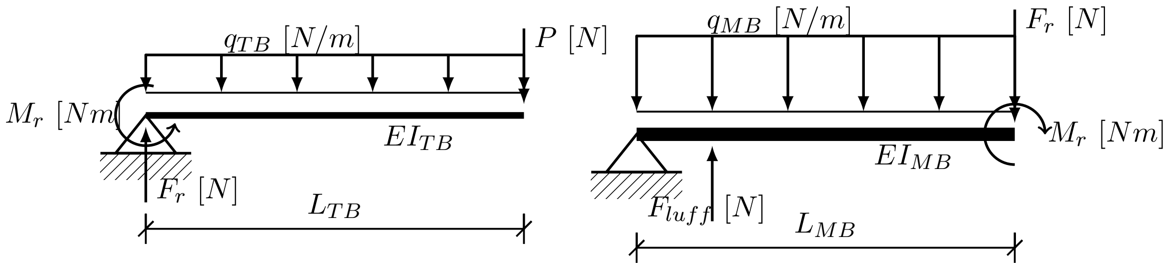
$$\begin{aligned} m_{total} = m_{deck} + 2m_{side} = \\ \left(A_{deck} L \rho_{laminate} + \left(w_{deck} h_{deck} - A_{deck}\right) L \rho_{foam}\right) \\ +2\left(A_{side} L \rho_{laminate} + \left(w_{side} h_{side} - A_{side}\right) L \rho_{foam}\right) \end{aligned} \tag{A.16}$$

**Concept 3: Sandwich deck with loaded railing and tube** The mass calculation for concept 3 is equal to that of concept 1 with the addition of the tube, resulting in Equation (A.17).

$$m_{total} = m_{deck} + 2m_{railing} + m_{tube} = \\ \left(A_{deck} L \rho_{laminate} + \left(w_{deck} h_{deck} - A_{deck}\right) L \rho_{foam}\right) + 2\left(A_{bar} L \rho_{laminate}\right) + A_{tube} L \rho_{laminate} \tag{A.17}$$

## A.4 Deflection

The gangway booms have different properties, the main boom has a higher bending stiffness but is heavier. This difference in properties results in a non-constant deflection. The Free Body Diagrams (FBDs) of T-boom and main boom can be found in Figures A.1a and A.1b, respectively.




**(a)** T-boom deflection

**(b)** Main boom deflection

**Figure A.1:** Free body diagrams of the gangway deflection

The displacement of the gangway in cantilever mode is calculated using simple beam deflections, Equation (A.18). The individual calculations can be found in Equations (A.19) for the T-boom deflection and (A.20) for the main boom deflection and angle.

$$\delta(tip) = \delta_{MB} + \delta_{TB} + \theta_{MB} L_{TB} \tag{A.18}$$

$$\begin{aligned} \delta_{TB} &= \frac{q_{TB} L_{TB}^4}{8EI_{TB}} + \frac{P L_{TB}^3}{3EI_{TB}} \\ F_r &= P + q_{TB} L_{TB} \\ M_r &= P L_{TB} + \frac{q_{TB} l_{TB}^2}{2} \end{aligned} \tag{A.19}$$

$$\begin{aligned} \delta_{MB} &= \frac{q_{MB} L_{MB}^4}{8EI_{MB}} + \frac{F_r L_{MB}^3}{3EI_{MB}} + \frac{M_r L_{MB}^2}{2EI_{MB}} \\ \theta_{MB} &= \frac{q_{MB} L_{MB}^3}{6EI_{MB}} + \frac{F_r L_{MB}^2}{2EI_{MB}} + \frac{M_r L_{MB}}{EI_{MB}} \end{aligned} \tag{A.20}$$

## A.5 Twist

The amount of twist due to torsion can be calculated using Equation (3.3). The torsional rigidity $GJ$ is calculated using Equations (A.12), (A.13) and (A.14), leaving the torsion as remaining unknown.

The torsion acting on the gangway is created by a wind load acting on the side of the gangway. The amount of wind force depends on the wind speed, equal for all concepts, and the area, different for the concepts. Finally the torsion is depended on the location the wind is assumed to act on the location of the shear center of the structure. It is assumed that the wind load is acting on the c.o.g. in all concepts. The torque acting on the concepts is calculated using Equation (A.21).

$$T_{concept} = \left(0.613v_{wind}^2 A_{concept}\right)(cog_z - SC_z) \tag{A.21}$$

In which $v_{wind}$ is the wind speed in $m/s$, $A$ is the area of the side exposed to the wind in $mm^2$ and $SC$ is the shear center location of the structure.

# Appendix B

# Gurit SE 84LV prepreg datasheet

# SE 84LV

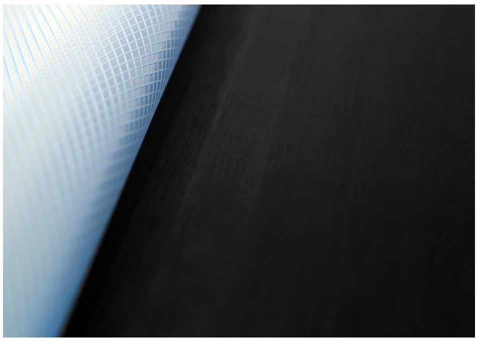
## LOW TEMPERATURE CURE EPOXY PREPREG

- Versatile, high-strength prepreg system
- Curable at temperatures as low as 80°C (176°F)
- Can be processed with vacuum-only processing
- Excellent tack
- Low Viscosity – Ideal for use with heavy fibre weights
- Germanischer Lloyd Certified
- Lloyd's Register Certified

## INTRODUCTION

**SE 84LV is an exceptionally versatile hot-melt, epoxy prepreg. It can be cured at temperature as low as 80°C (176°F), or can be used for faster moulding of components at 120°C (248°F). This is achieved with an extremely good outlife of up to 8 weeks at 18-22°C (64-72°F). It is a toughened system, and offers excellent mechanical properties on a wide variety of reinforcing fabrics and fibres.**

SE 84LV is commonly used in vacuum bagging, press-moulding, autoclave and other pressure moulding processes.



SE 84LV is a very low viscosity system used with heavy fibre weights where low-flow processing conditions (vacuum bag pressure and minimum cure temperature), are likely to be used. With its high compressive strength it is widely used in large heavily loaded components, such as yacht hulls, and spars. It has been selected for use by various America's Cup syndicates and boats racing in the Volvo Ocean Race.

SE 84LV is widely used in sandwich structures with honeycomb, foam and balsa cores, primarily with the toughened SA 80 Adhesive Film.

## PROCESSING NOTES - GENERAL

### PREPARATION

When preparing the lay-up the prepreg should be removed from the freezer and allowed to thaw in a sealed bag. This may take 6 to 24 hours depending on roll size. This prevents atmospheric moisture from condensing on the prepreg which may cause voiding on cure. The mould surface should be release coated and must have been tested for vacuum integrity prior to lay-up.

### LAYING-UP

The following procedure is recommended for preparing vacuum cured laminates.

1. Place the lay-up on a tool or caul sheet which has been treated with a release agent or film. Insert a thermocouple into the lay-up near the centre ply of the thickest edge section, outside the net trim line. A separate prepreg nylon peel ply is available for covering a mould tool prior to lay-up in order to leave a clean, textured surface for subsequent bonding.

2. Apply a peel ply to the surface of the lay-up. Note that for good secondary bonding of a peel-plied surface of an SE 84LV prepreg laminate, a nylon peel ply, such as Gurit's Stitch Ply A, is strongly recommended. This is particularly important where the cure temperatures are in excess of 90°C (194°F). Cover the peel ply entirely with a perforated release film. Normally, no edge resin bleeder system is used. For thin sections, Gurit WL3600P90 grade release film are recommended, while for sections of 4mm and above, Gurit WL3600P release film is also suitable. With WL3600P the amount of resin bled away is controlled by the number of dry plies of resin bleeder cloth placed over the perforated release film.

3. Install a vacuum bag by standard techniques. Insert at least two vacuum stems through the bag connecting one to the vacuum source and the other, at a point on the part furthest from the source, to a calibrated vacuum gauge. Position part in the oven or autoclave and draw vacuum to check for bag or system leaks.

4. Commence the heat-up cycle, typically between 0.3°C(0.5°F)/min and 2°C(3.6°F)/min to the final cure temperature. At 85°C (185°F), the temperature should be held up for 10 hours. Faster cures may be obtained at elevated temperatures, e.g. 6 hours at 90°C (194°F), 3 hours at 100°C (212°F) or 1 hour at 120°C (248°F). All temperatures measured by the previously installed thermocouple. When curing at 80°C (176°F) a minimum of 12 hours is recommended. Vacuum should be maintained as high as possible, with a minimum of 85% throughout the cure cycle.

5. Upon completion of cure, turn off heat and cool until part temperature has fallen below 60°C (140°F). When fully cooled, the part may be debagged, trimmed and machined as necessary. A post-cure is not required.

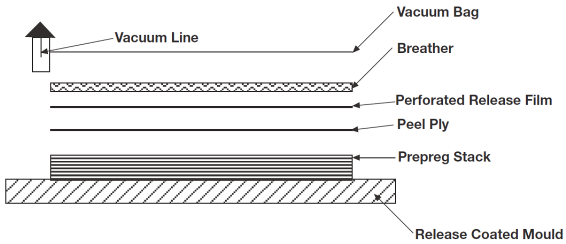
## PROCESSING NOTES - CURING

### CURE CYCLES

For a good balance of composite properties, it is recommended that the laminate is cured at 80°C (176°F) for a minimum of 12 hours. A laminate may be cured in two stages - if, for example, making a cored component. However in a two stage cure, a minimum of 4 hours at 85°C (185°F) or 5 hours at 80°C (176°F) is recommended before debagging a skin, and it must be ensured that this skin is cured for the equivalent of at least 10 hours at 85°C (185°F) or 12 hours at 80°C (176°F) before going into service.

SE 84LV may be cured at higher temperatures for a shorter time. At a cure temperature of 100°C (212°F) cure can be achieved in 3 hours or at 120°C (250°F) cure can be achieved in 1 hour.

It is not recommended to cure SE 84LV under vacuum pressures of less than 85%. If a ramp rate of less than 0.3°C/min (0.5°F/min) is used, users should satisfy themselves that this allows adequate flow.




### CURING AT 80°C (176°F)

When curing at 80°C (176°F) it is important to ensure the temperature is monitored off the trailing thermocouple. 80°C (176°F) should be treated as the minimum cure temperature for SE 84LV; 70-75°C (158-167°F) will not generate adequate mechanical properties.

### THIN LAMINATES

When using very thin laminates (e.g. with a total laminate fibre weight of less than 300gm$^{2}$), care needs to be taken to avoid extracting excessive amounts of resin during the cure process. To avoid this, a microporous release film can be used, and for particularly critical components, a prepreg peel ply should be used.

## CORE BONDING

Various core materials can be used with the prepreg system, including foams and honeycombs. However, due to the wide variety of PVC and other foams available, and the cure temperatures involved, special procedures have been developed which must be carefully followed. For details of these processes, please contact Technical Services.

When using Nomex™ or aluminium honeycombs, the separate SA 80 adhesive film is recommended and full details of use are provided on the separate SA 80 data sheet. This adhesive film is supplied on a lightweight glass carrier, or in some cases it can be supplied directly coated onto one face of the SE 84LV prepreg.

The system is fully compatible with Ampreg wet layup epoxy systems and therefore all types of cores may be bonded to a first skin by using a separate 'wet-bonding' operation. In this case, the addition of filler powders to the appropriate resin system is required to provide the correct paste-like consistency.

## PRODUCT INFORMATION

### AVAILABILITY

SE 84LV prepregs are available in a wide variety of fabric forms and collimated unidirectional tapes. Unidirectional materials are normally supplied on a single release paper and fabrics on a single polythene film. Please contact Customer Support to discuss specific requirements and availability. The product formats listed below also benefit from 3rd Party Certification.

| PRODUCT DESCRIPTION | CERTIFICATION |
|---|---|
| Unidirectional Epoxy Prepreg 150g/m2, 200g/m2 300g/m2, 450g/m2 | Germanischer Lloyd |
| SE84LV/HEC/120/37/+/-3% & 200g, 300g, 450g, 600g | Lloyd's Register |
| SE84LV/IMC/120/37/+/-3% & 200g, 300g, 450g, 600g | Lloyd's Register |

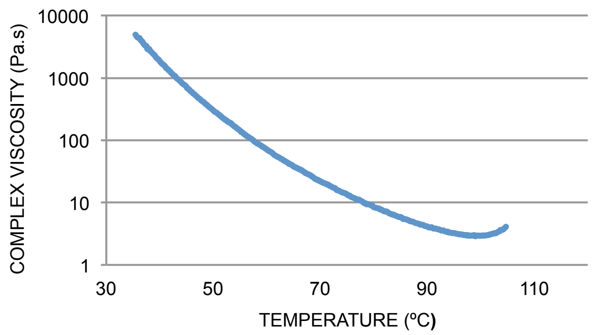
| PRODUCT DESCRIPTION | CERTIFICATION |
|---|---|
| SE84LV/HMC/120/37/+/-3% & 200g, 300g, 450g, 600g | Lloyd's Register |
| SE84LV/UHMC/120/37/+/-3% & 200g, 300g, 450g, 600g | Lloyd's Register |
| SE84LV/RC200T (& 400g (XC416T)) | Lloyd's Register |
| SE84LV/RC416T | Lloyd's Register |
| SE84LV/XC305 & 400g, 600g (XC411 & XC611) | Lloyd's Register |
| SE84LV/XE905 | Lloyd's Register |
| SE84LV-RE100 H4 | Lloyd's Register |
| SE84LV-RE200 P | Lloyd's Register |

## PREPREG PROPERTIES

### RHEOLOGY DATA

SE 84LV resin viscosity profile conducted at 1°C (1.8°F) per minute.

| PROPERTY | VALUE | |
|---|---|---|
| Minimum Viscosity | 2.9 Pa.s | 28.8 P |
| Temperature at Minimum Viscosity | 99°C | 210°F |




### TRANSPORT & STORAGE

When stored sealed & out of direct sunlight.

| STORAGE TEMP | | UNIT | VALUE |
|---|---|---|---|
| -18°C | 0°F | months | 24 |
| +18-22°C | +64-72°F | weeks | 8 |

All prepreg materials should be stored in a freezer when not in use to maximise their useable life, since the low temperature reduces the reaction of resin and catalyst to virtually zero. However, even at -18℃ (0°F), the temperature of most freezers, some reaction will still occur. In most cases after some years, the material will become unworkable.
When not in use SE 84LV products should be maintained at -18℃ (0°F). To avoid contamination on their surfaces, allow rolls to reach room temperature before unwrapping.

### HEALTH AND SAFETY

Please refer to product SDS for up to date information specific to this product.

### MINIMUM CURE TIME & TEMPERATURE

Recommended minimum cure is 12 hours at 80°C (176°F) using vacuum bag processing.

| PROPERTY | OVEN / VAC BAG | | TEST STANDARD |
|---|---|---|---|
| Typical Laminate | 8 plies of SE 84 LV 300g/m$^2$ unidirectional prepreg with 35% resin content | | - |
| Typical Ramp Rate | 1 – 2°C (2 – 4°F) per minute | | - |
| Cure Temperature | 80°C (176°F) | 120°C (248°F) | - |
| Cure Dwell Time | 12 (hours) | 1 (hour) | - |
| Cure Pressure | -1bar (14.5Psi) | | - |
| De-mould Temperature | < 60°C (140°F) | | - |
| Dry $Tg_1$ (DMA) | 98°C / 208°F | 115°C / 239°F | ISO 6721 (DMA) |

*suitable for use in conjunction with hot-in / hot-out rapid component manufacture is possible using appropriate press tooling

### CURING LARGE STRUCTURES

Gurit provides detailed processing notes for large structures to be built using SE84LV / SA 80; these notes are available from the Technical Department on request.

# MECHANICAL PROPERTIES

Cured using standard vacuum bag processing techniques and a minimum cure time of 12hrs at 80°C (176°F). Values are representative of the typical properties to be expected but do not constitute a guaranteed specification.

## CURED RESIN PROPERTIES

| PROPERTY | SYMBOL | SE 84LV RESIN CAST | TEST STANDARD |
|---|---|---|---|
| Tensile Strength | $\sigma_T$ | 82 MPa | ISO 527-2 |
| Tensile Modulus | $E_T$ | 3.9 GPa | ISO 527-2 |
| Flexural Strength | $\sigma_F$ | 123 MPa | ISO 178 |
| Flexural Modulus | $E_F$ | 3.5 GPa | ISO 178 |
| Compressive Strength | $\sigma_C$ | 163 MPa | ISO 604 |
| Glass Transition Temperature | $Tg_1$ | 115°C | ISO 6721 |

## UNIDIRECTIONAL LAMINATE PROPERTIES

Properties presented are averages of multiple batch data from a variety of fibre suppliers. Customers with specific requirements should contact Gurit technical support who can recommend appropriate fibres and formats.

| PROPERTY | SYMBOL | UNIT | HEC FIBRE* | IMC FIBRE* | HMC FIBRE* | UHMC FIBRE* | TEST STANDARD |
|---|---|---|---|---|---|---|---|
| Typical Fibre Density | $\rho_{fibre}$ | $g/cm^3$ | 1.8 | 1.79 | 1.82 | 1.84 | - |
| Fibre Modulus | $E_{fibre}$ | GPa | 227 - 257 | 275 - 310 | 365 - 405 | 420 - 455 | - |
| Resin Content | % | % | 32 - 37 | 32 - 37 | 33 - 37 | 35 | ASTM D 3171 Method II |
| Fibre Volume Fraction | $v_t$ | % | 55.0 | 55.5 | 54.4 | 54.3 | ASTM D 3171 Method II |
| 0° Tensile Strength** | $X_T$ | MPa | 2458 | 2894 | 2658 | 1980 | ISO 527-5 |
| 0° Tensile Modulus** | $E_t$ | GPa | 134 | 170 | 222 | 250 | ISO 527-5 |
| 0° Compressive Strength** | $X_C$ | MPa | 1354 | 1417 | 1166 | 1070 | SACMA SRM1-94 |
| 0° Compressive Modulus** | $E_{C11}$ | GPa | 121 | 153 | 192 | 227 | SACMA SRM1-94 |
| 90° Tensile Strength | $Y_T$ | MPa | 39.2 | 33.2 | 30.1 | 26.0 | ISO 527-5 |
| 90° Tensile Modulus | $E_{T22}$ | GPa | 8.3 | 8.4 | 7.1 | 6.6 | ISO 527-5 |
| 0° Flexural Strength | $X_F$ | MPa | 1448 | 1406 | - | - | ISO 14125 |
| 0° Flexural Modulus | $E_{F11}$ | GPa | 106 | 129 | - | - | ISO 14125 |
| 0° ILSS | $X_{ILSS}$ | MPa | 86.6 | 88.6 | 82.3 | 77.8 | ISO 14130 |

*HEC = High Elongation Carbon, IMC = Intermediate Modulus Carbon, HMC = High Modulus Carbon, UHMC = Ultra-High Modulus Carbon

**Normalised to 60% fibre volume fraction

## WOVEN LAMINATE PROPERTIES

Properties presented are averages of multiple batch data, where possible witnessed by a third party surveyor on a standard fibre type. Customers with specific requirements should contact Gurit technical support who can recommend suitable fibres and formats.

| PROPERTY | SYMBOL | UNIT | RC200T | RC416T | TEST STANDARD |
|---|---|---|---|---|---|
| Resin Content | - | % | 42 | 40 | ASTM D 3171 Method II |
| Cured Ply Thickness | - | mm | 0.23 | 0.43 | ASTM D792 |
| Fibre Volume Fraction | - | % | 47 - 53 | 50 - 59 | ASTM D 3171 Method II |
| 0° Tensile Strength* | $X_T$ | MPa | 719 | 1006 | ISO 527-4 |
| 0° Tensile Modulus* | $E_t$ | GPa | 60.6 | 59.1 | ISO 527-4 |
| 90° Tensile Strength* | $Y_T$ | MPa | 662 | 858 | ISO 527-4 |
| 90° Tensile Modulus* | $E_{T22}$ | GPa | 61.6 | 58.9 | ISO 527-4 |
| 0° Compressive Strength* | $X_C$ | MPa | 759 | 649 | SACMA SRM1-94 |
| 0° Compressive Modulus* | $E_c$ | GPa | 58.3 | 55.6 | SACMA SRM1-94 |
| 90° Compressive Strength* | $Y_C$ | MPa | 731 | 659 | SACMA SRM1-94 |
| 90° Compressive Modulus* | $E_{C22}$ | GPa | 59.0 | 55.2 | SACMA SRM1-94 |
| 0° Flexural Strength | $X_F$ | MPa | 847 | 895 | ISO 14125 |
| 0° Flexural Modulus | $E_{F11}$ | GPa | 51.2 | 49.4 | ISO 14125 |
| 90° Flexural Strength | $Y_F$ | MPa | 857 | 892 | ISO 14125 |
| 90° Flexural Modulus | $E_{F22}$ | GPa | 51.5 | 50.6 | ISO 14125 |
| ILSS | $\tau_M$ | MPa | 74.8 | 55.8 | ISO 14130 |

*Normalised to 55% fibre volume fraction

## MULTIAXIAL LAMINATE PROPERTIES

Properties presented are multiple batch data, where possible witnessed by a third party surveyor on a standard fibre type. Customers with specific requirements should contact Gurit technical support who can recommend suitable fibres and formats.

| PROPERTY | SYMBOL | UNIT | XC411 | TEST STANDARD |
|---|---|---|---|---|
| Resin Content | - | % | 40 | ASTM D 3171 Method II |
| Cured Ply Thickness | - | mm | 0.43 | ASTM D792 |
| Fibre Volume Fraction | - | % | 47 - 59 | ASTM D 3171 Method II |
| +45° Tensile Strength* | $X_T$ | MPa | 1124 | ISO 527-4 |
| +45° Tensile Modulus* | $E_t$ | GPa | 63.8 | ISO 527-4 |
| -45° Tensile Strength* | $Y_T$ | MPa | 1237 | ISO 527-4 |
| -45° Tensile Modulus* | $E_{T22}$ | GPa | 64.5 | ISO 527-4 |
| +45° Compressive Strength* | $X_C$ | MPa | 595 | SACMA SRM1-94 |
| +45° Compressive Modulus* | $E_c$ | GPa | 62.0 | SACMA SRM1-94 |
| -45° Compressive Strength* | $Y_C$ | MPa | 645 | SACMA SRM1-94 |
| -45° Compressive Modulus* | $E_{C22}$ | GPa | 60.2 | SACMA SRM1-94 |
| +45° Flexural Strength | $X_F$ | MPa | 815 | ISO 14125 |
| +45° Flexural Modulus | $E_{F11}$ | GPa | 41.5 | ISO 14125 |
| -45° Flexural Strength | $Y_F$ | MPa | 1004 | ISO 14125 |
| -45° Flexural Modulus | $E_{F22}$ | GPa | 57.0 | ISO 14125 |
| ILSS | $\tau_M$ | MPa | 49.7 | ISO 14130 |

*Normalised to 55% fibre volume fraction

## NOTICE

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**E** contact@gurit.com

**W** www.gurit.com

# Appendix C

# MATLAB code flow charts

## C.1 Flow chart code section 1

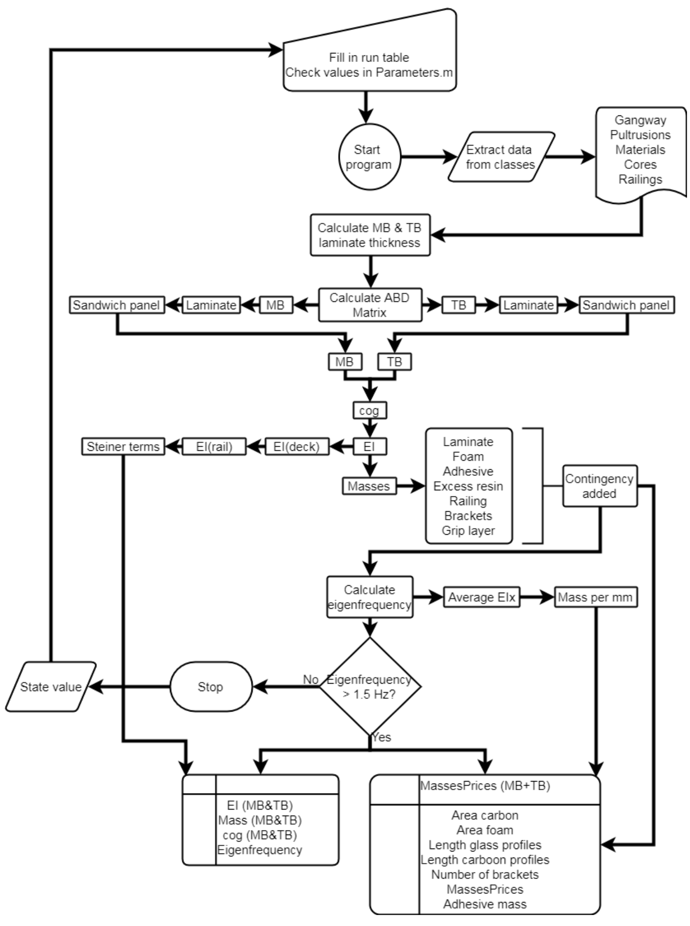



**Figure C.1:** Flow chart of section 1

## C.2 Flow chart code section 2

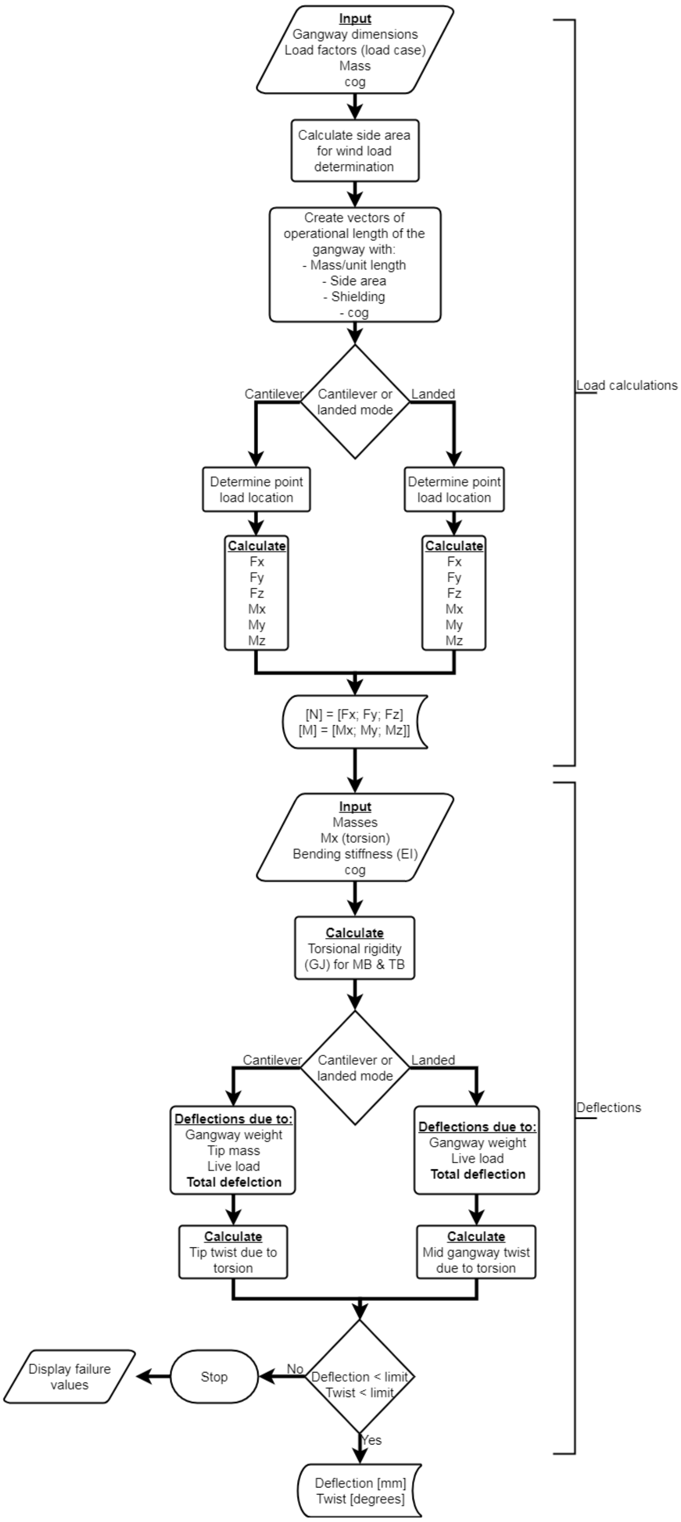



**Figure C.2:** Flow chart of section2

## C.3 Flow chart code section 3

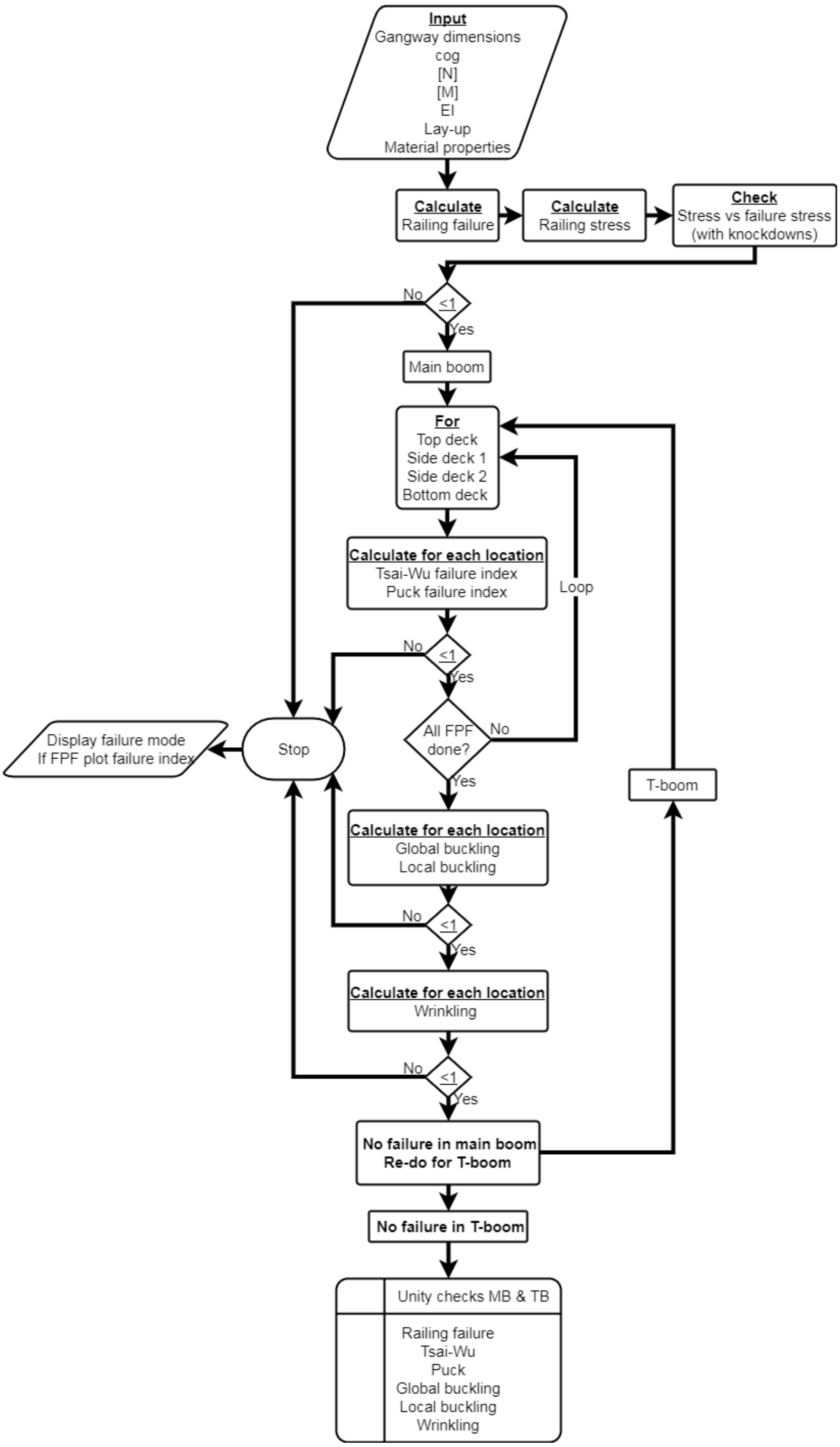



**Figure C.3:** Flow chart of section 3

## C.4 Flow chart code section 4

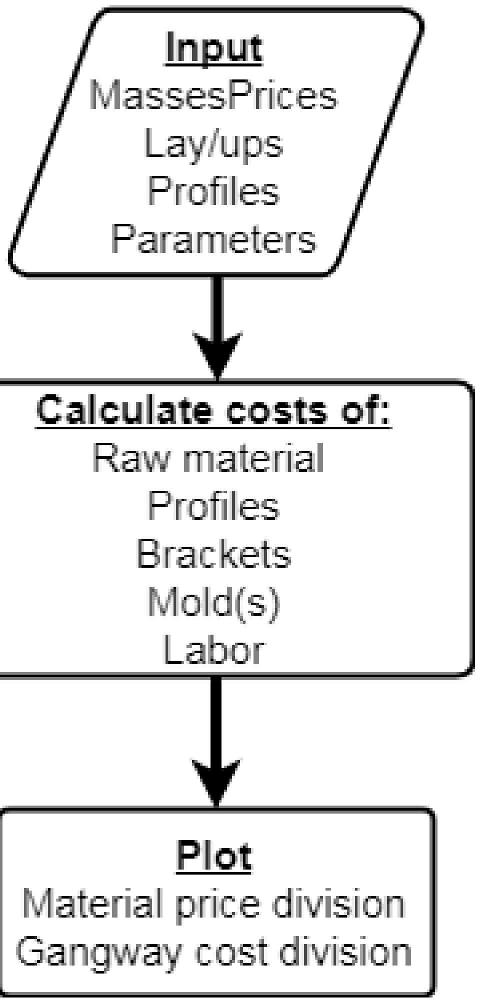



**Figure C.4:** Flow chart of section 4

## C.5 Flow chart code section 5

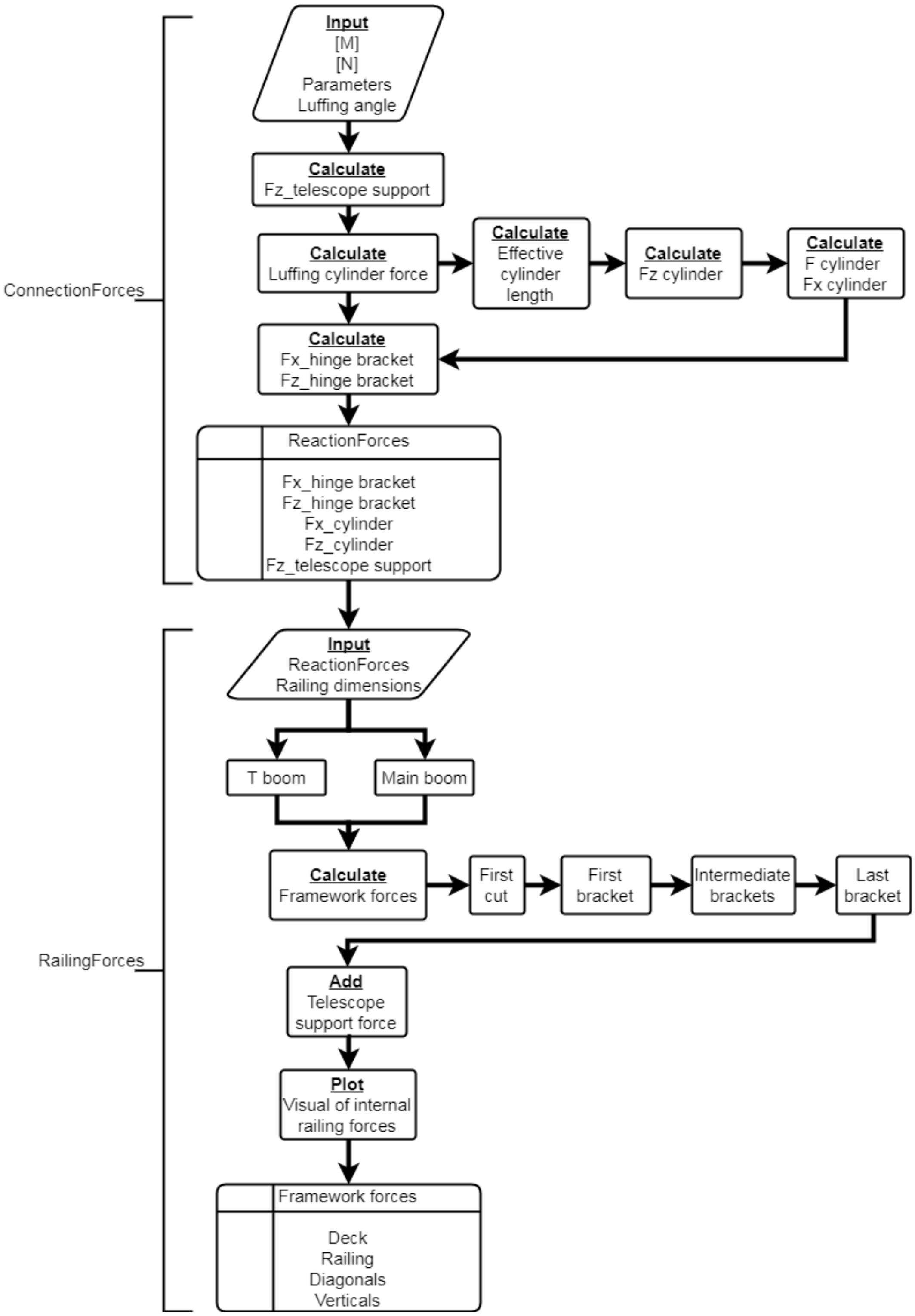



**Figure C.5:** Flow chart of section 5

# Appendix D

# Run parameters used for basic design

## D.1 Main input file

```
% This is the main file to run the Structural analysis of a Gangway system
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Properties
clear all; close all; clc;
format shortG;
dbstop if error
addpath(genpath(pwd))
% runs
plystack_MB          = [0 0 45 -45 0 0 90 90 0 0 -45 45 0 0];    % Lay-up ...
    sequence MB
plystack_TB          = [45 -45 0 0 90 0 0 -45 45];        % Lay-up sequence TB
core_MB              = 50;                        % MB core thickness in [mm]
core_TB              = 50;                        % TB core thickness in [mm]
 % Create run table
 % Material = 90 degree layers, Material2 = 0 degree layers, Material3 = ...
     +-45 Biax
 % Materials: SE84LV, SE84LV_HMC(Lloyds approved)
 % Cores: PVC60, PVC48, PVC40, M60, M130 (all PVC & M Lloyds approved)
 % Profiles: 38x38x3, 44x44x6, 60x60x4.5, 75x75x6, 120x39x3, ...
     C60x60x4.5(Carbon E*3) Exel || 80x40x5, 40x40x5, 40x40x3 Bijl
 % Current limitaion: Only 1 load case per run (NO-PT, !NO-CT!, EC-3PT, ...
     !EC-CT!, EC-EL)

  fldNmsC        = {
'Length_MB'  'Length_TB' 'Tip_load'  'Width_MB'  'Width_TB'  'Material'   ...
    'Material2'   'Material3'    'Core'    't_core_MB'   't_core_TB'    ...
    'plystack_MB'     'plystack_TB'       'Profile'      'Loadcase'    ...
    'H_railing'  'Profile_vert_diag'};
  tblC  = {
15400          12600         100          850          750          'SE84LV_HEC' ...
    'SE84LV_HMC'  'SE84LV_45'    'M130'     core_MB       core_TB           ...
    plystack_MB       plystack_TB         'C60x60x4.5'  'EC-CT'       1100 ...
        '38x38x3'
```

```
            };
    runTbl = cell2struct(tblC, fldNmsC, 2);
      [res] = MainFile(runTbl);
end
```

## D.2 Parameter collection file

```
classdef Parameters < handle
    % Parameters contains all semi-constant parameter
    % Created with MATLAB ver.: 8.1.0.604 (R2013a)
    % Copyright (c) 2017, Ampelmann Operations B.V.
    % All rights reserved.
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    properties(GetAccess = 'public', SetAccess = 'public')
        g;                          % gravitational constant [m/s^2]
        resolution;                 % precision [mm]
        Frequency_requirement;      % Minimal frequecy cantilever mode [Hz]
        Tip_mass;                   % Assumed tip mass [kg]
        Mass_multiplier;            % extra mass as contingency
        first_TB_support;           % distance from end of MB support [mm]
        Tele_support;               % Distance between telescoping ...
            supports [mm]
        KD_fatigue;                 % knockdown for fatigue
        KD_mat_scat;                % knockdown for material scatter
        KD_environment;             % knockdown for environmental influences
        KD_impact;                  % knockdown for impact
        l_cyl_horizontal;           % [mm]
        l_cyl_vertical;             % [mm]
        Mass_est_bracket            % Weight of a single bracket [kg]
        Price_prepreg0;             % [Ă/m^2]
        Price_prepreg90;            % [Ă/m^2]
        Price_prepreg45;            % [Ă/m^2]
        Price_foam;                 % [Ă/m^2]
        Price_profile;              % [Ă/m]
        Price_bracket;              % [Ă/piece]
        Price_hour;                 % [Ă/hr]
        Price_adhesive;             % [Ă/m^2]
        Foam_scrap;                 % [%] of foam wasted in production
        Carbon_scrap;               % [%] of carbon wasted in production
        Profile_scrap;              % [%] of profile wasted in production
        Rho_glass;                  % Density of glass [kg/mm^3]
        W_horizontals;              % Width of horizontal beams [mm]
        H_horizontals;              % Height of horizontal beams [mm]
        T_horizontals;              % Thickness of horizontal bemas [mm]
        Deflection_limit_canti;     % How much deflection per unit length [mm]
        Deflection_limit_landed;    % How much deflection per unit length [mm]
        Twist_limit_canti;          % how much degrees per length
        Twist_limit_landed;         % how much degrees per length
        Vacuum_consumables;         % price of consumables [Ă]
        Bracket_mold;               % price of bracket mold [Ă]
        Deck_mold;                  % price of deck mold [Ă]
        Production_hours;           % amount of hours needed for ...
            production [hr]
        Mass_adhesive;              % adhesive mass [kg/mm^2]
    end
```

```
    methods
        function obj = Parameters(varargin)
      obj = obj.setProperties(varargin{1});
        end
    end
    methods(Access = 'public')
        function obj = setProperties(obj,type)
            switch type
                case 'constant'
                    obj.g                          = 9.81;     % [m/s^2]
                    obj.resolution                 = 1;        % [mm]
                    obj.Frequency_requirement      = 1.5;      % [Hz]
                    obj.Tip_mass                   = 50;       % [kg]
                    obj.Mass_multiplier            = 1.3;
                    obj.first_TB_support           = 2500;     % [mm]
                    obj.Tele_support               = 3000;     % [mm]
                    obj.KD_fatigue                 = 0.9;
                    obj.KD_mat_scat                = 0.8;
                    obj.KD_environment             = 0.8;
                    obj.KD_impact                  = 0.65;
                    obj.l_cyl_horizontal           = 1400;
                    obj.l_cyl_vertical             = 3385;
                    obj.Mass_est_bracket           = 0.8;
                    obj.Price_prepreg0             = 69.82;
                    obj.Price_prepreg90            = 26.00;
                    obj.Price_prepreg45            = 39.25/2;
                    obj.Price_foam                 = 91.54;
                    obj.Price_profile              = 11;
                    obj.Price_bracket              = 50;
                    obj.Price_adhesive             = 15.84;
                    obj.Price_hour                 = 100;
                    obj.Foam_scrap                 = 1.2;
                    obj.Carbon_scrap               = 1.3;
                    obj.Profile_scrap              = 1.1;
                    obj.Rho_glass                  = 1800*10^-9;
                    obj.W_horizontals              = 30;
                    obj.H_horizontals              = 30;
                    obj.T_horizontals              = 2.5;
                    obj.Deflection_limit_canti     = 100;
                    obj.Deflection_limit_landed    = 100;
                    obj.Twist_limit_canti          = 3000;
                    obj.Twist_limit_landed         = 10000;
                    obj.Vacuum_consumables         = 5000;
                    obj.Bracket_mold               = 5000;
                    obj.Deck_mold                  = 20000;
                    obj.Production_hours           = 160;
                    obj.Mass_adhesive              = 0.25E-6;
                otherwise
                    warning('No parameters found');
            end
        end
        % compute derived properties
        function obj = setDerivedProperties(obj)
        end
    end
end
```

# Appendix E

# Design code verification

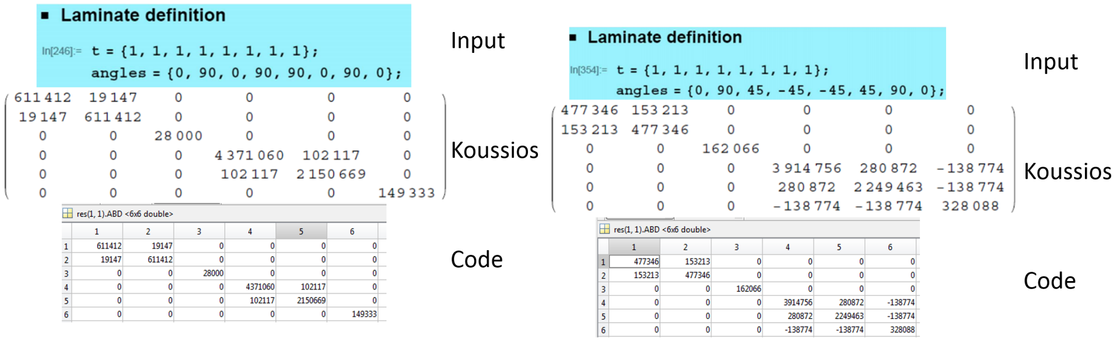
## E.1 ABD matrix

The ABD matrix is the basis of composite engineering, it is needed to calculate the stiffness of a laminate based on the plies used and their orientation. A wrong ABD calculation will result in a useless design since the determination of the eigenfrequency and multiple failure modes are calculated using this matrix.

Verification of the ABD matrix calculation has been done by comparing the outcomes of the code with examples as given by Sotiris Koussios during the course of *Design and analysis of composite structures I* at the faculty of Aerospace Engineering of the Delft University of Technology in 2015. [30] The calculation of the different ABD matrices was done as follows:

1. The material properties and ply thickness as used by Koussios are entered in the material class.
2. The laminate ply angle are entered to create the laminate.
3. ABD matrix term are calculated.

Figures E.1a and E.1b show the results of two of the checks performed. In total six different laminates were calculated all with the same result. The ABD matrix calculator is good to use, a second check will be performed when the first-ply-failure will be validated as the ABD is part of that calculation.




**(a)** ABD matrix of a symmetric cross-ply laminate

**(b)** ABD matrix of a quasi-isotropic laminate

**Figure E.1:** ABD matrix comparison between design code and examples provided by Sotiris Koussios

## E.2 Forces and moments

The verification of the forces and moment calculations is based on the same formula's as used in the design code. It is a check to see if the code does what it is supposed to do. Both the cantilever and landed load case has been verified. The results can be found in TableE.1 for the cantilever case and Table E.2 for the landed one. The average calculation uses the average weight of the complete gangway whereas the code calculations the forces and moments per location.

In Table E.1 a small discrepancy can be noted in $M_y$ due to the gangway weight. This difference is due to the fact that the gangway consists of a main boom and T-boom with different weights and a certain overlap.

**Table E.1:** Verification of forces and moment calculation cantilever load case using the maximal values

| Load | Unit | Average calculation | Code calculation | Difference |
|---|---|---|---|---|
| $F_y$ due to wind | [kN] | 9.77 | 9.77 | 0% |
| $F_z$ due to gangway weight | [kN] | 24.23 | 24.23 | 0% |
| $F_z$ due to tip load | [kN] | 0.98 | 0.98 | 0% |
| $M_y$ due to gangway weight | [kNm] | 284.1 | 286.9 | 1% |
| $M_y$ due to tip load | [kNm] | 23 | 23 | 0% |
| $M_x$ due to wind load | [kNm] | 114.6 | 114.6 | 0% |

In Table E.2 a bigger discrepancy can be seen for the $M_y$ due to the gangway mass. A 12.2% difference is significant. This discrepancy can be explained due to the overlap of the two booms. The average calculations equally divides the mass of the complete gangway over its length whereas the code uses the overlapping mass in the middle of the gangway. The double mass in between the two supports result in a higher bending moment. The code calculation provides a better representation compared to the simplified calculation.

**Table E.2:** Verification of forces and moment calculation landed load case using the maximal values

| Load | Unit | Average calculation | Code calculation | Difference |
|---|---|---|---|---|
| $F_y$ due to wind | [kN] | 4.89 | 4.89 | 0% |
| $F_z$ due to gangway weight | [kN] | 12.11 | 12.17 | 0.5% |
| $F_z$ due to tip load | [kN] | 0.49 | 0.49 | 0% |
| $M_y$ due to gangway weight | [kNm] | 71.02 | 79.67 | 12.2% |
| $M_y$ due to point load | [kNm] | 5.75 | 5.75 | 0% |
| $M_x$ due to wind load | [kNm] | 14.33 | 14.33 | 0% |

## E.3 Tsai-Wu first-ply-failure

Validation of the first-ply-failure calculations using the Tsai-Wu failure criterion has been done. A reference case has been taken from the paper published by Kuo-Shih Liu and Stephen W. Tsai, *A progressive quadratic failure criterion for a laminate.* [26]

Figures E.2, E.3 and E.4 show the comparisons between the case in the paper, the graphs on the left, and the calculation performed by the code on the right. In order to get the results the following steps were performed:

1. The properties of the materials used in the paper are entered in the materials class.
2. A laminate is created of 1 mm thick such that the stress, taken from the paper, is equal to the force per unit width needed for the calculation of the first-ply-failure. The layers are placed such that the laminate is equal to the one used in the paper.
3. For these laminates the ABD matrix is calculated in order to determine the stresses in the individual plies.
4. Two points are chosen on the graph of each load case, these values are entered in the code and the program is executed. The results should be equal to 1 as the chosen points are on the boundary, meaning the laminate is about the fail.

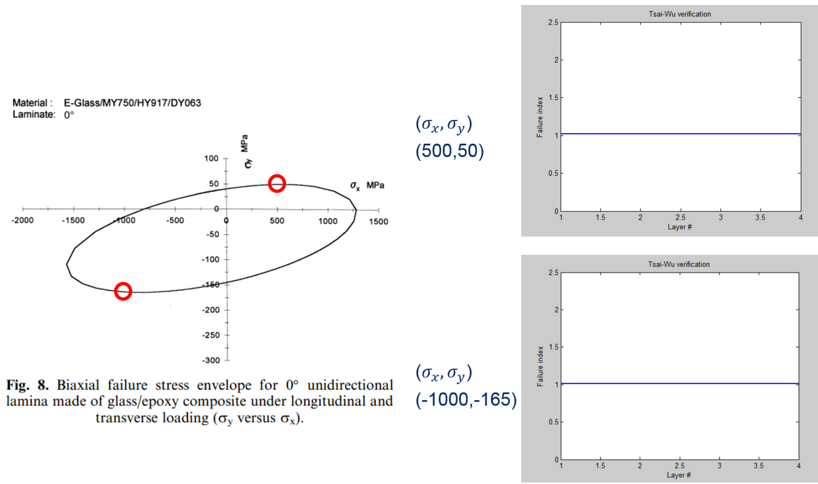



**Figure E.2:** Comparison of the Tsai-Wu criterion of a UD laminate loaded in x- and y-direction

As can be seen in Figure E.2 both points work out fine. The code works for the combined loading in x- and y-direction.

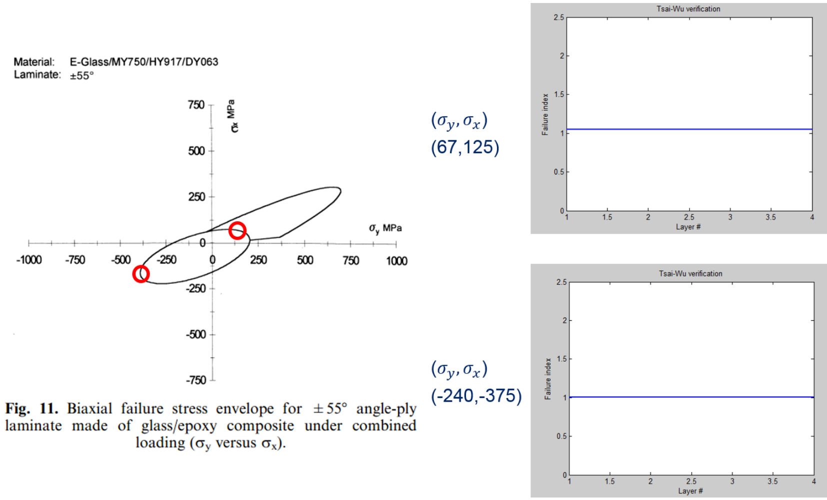



**Figure E.3:** Comparison of the Tsai-Wu criterion of a ±55° laminate loaded in x- and y-direction

In the left graph of Figure E.3 something special can be seen, the boundary consists of two lines. The oval boundary(lower one), is the first-ply-failure. The other line is the last-ply-failure, the combination stress and shear at which the laminate will completely loose its load carrying capabilities. For the two points on the graph the calculation done by the code is about equal to 1, for laminates consisting of plies at an angle the code is validated.

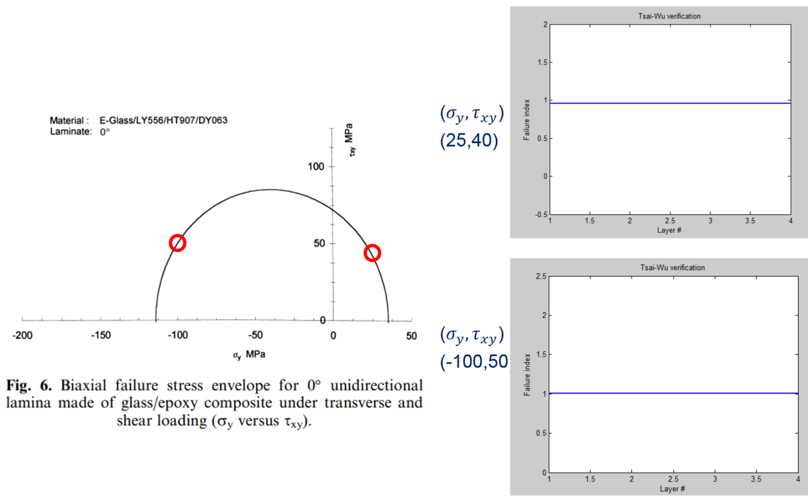



**Figure E.4:** Comparison of the Tsai-Wu criterion of a UD laminate loaded in y-direction and shear

The last check performed is depicted in Figure E.4, a combination of shear stress and normal stress is analyzed. The calculated first-ply-failure index is about equal to 1 at the chosen points.

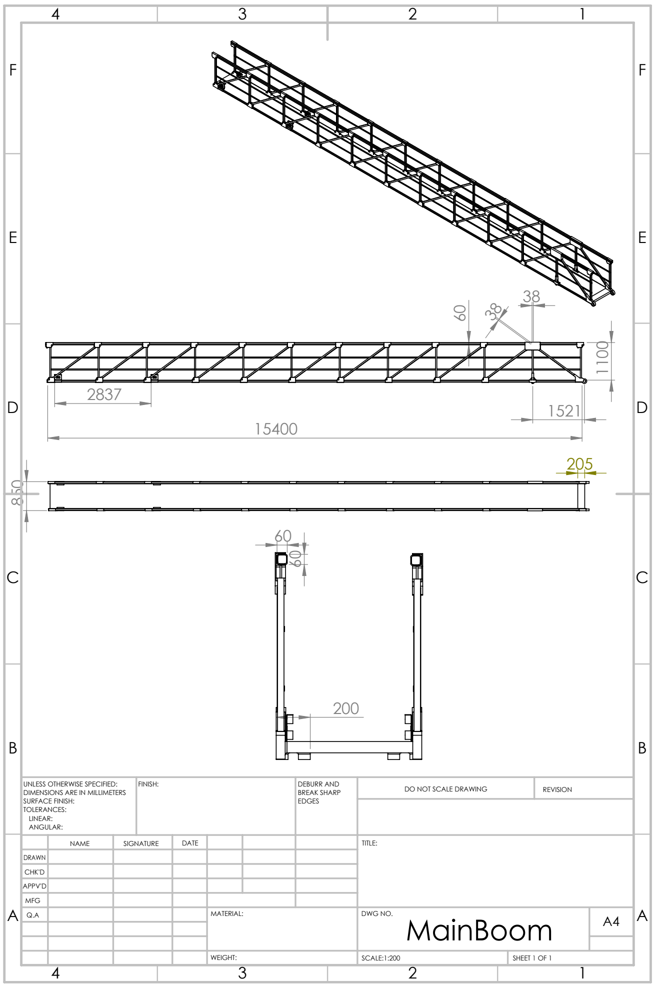
All six points which are calculated turn out to be correct. These consist of different load case, different materials and both tensile and compression loads are used. It can be concluded that the calculation of the first-ply-failure indexes of the Tsai-Wu criterion is correctly implemented in the design code.

# Appendix F

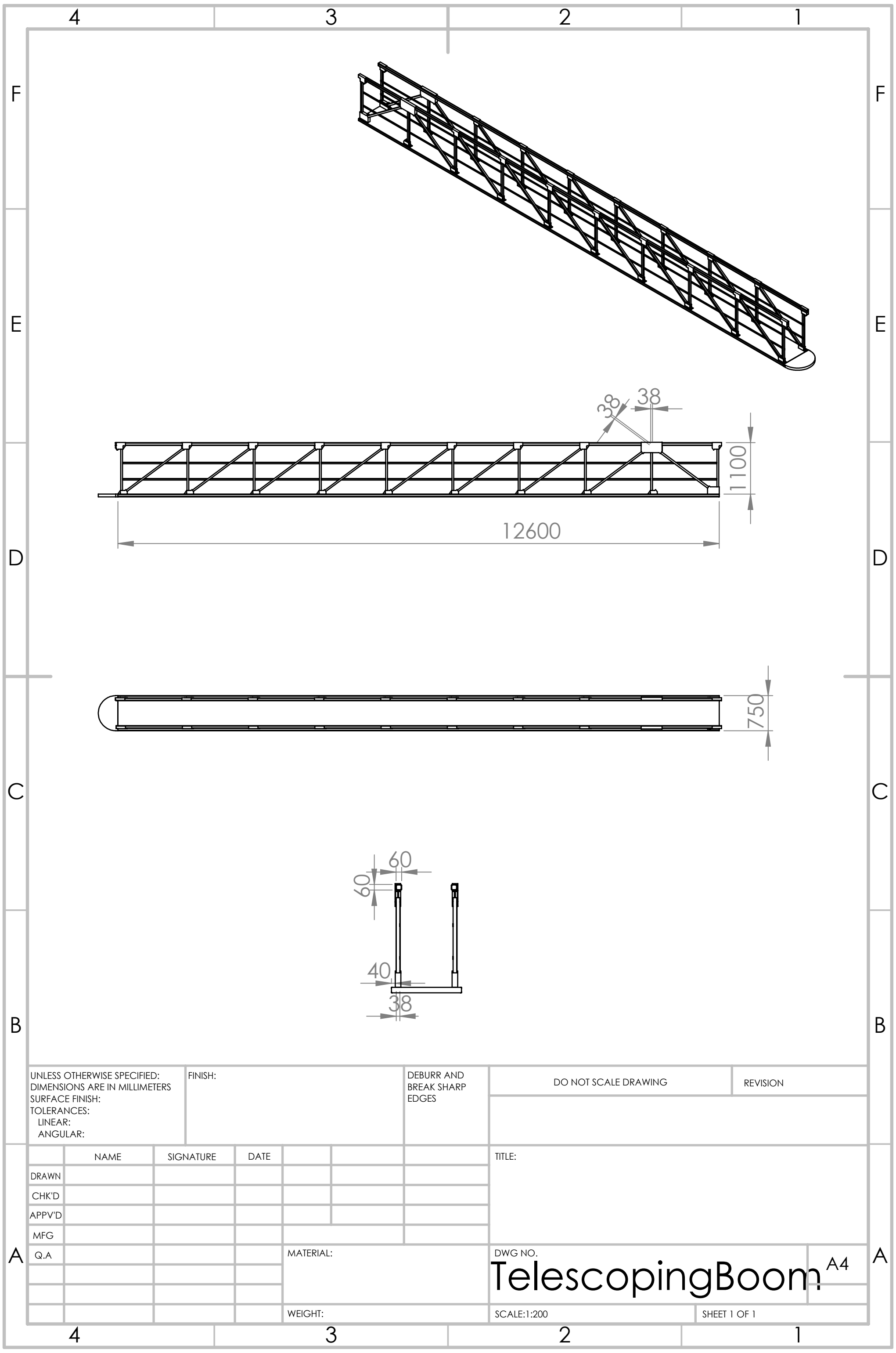
# Gangway and bracket dimensional drawings

## F.1 Gangway dimensions

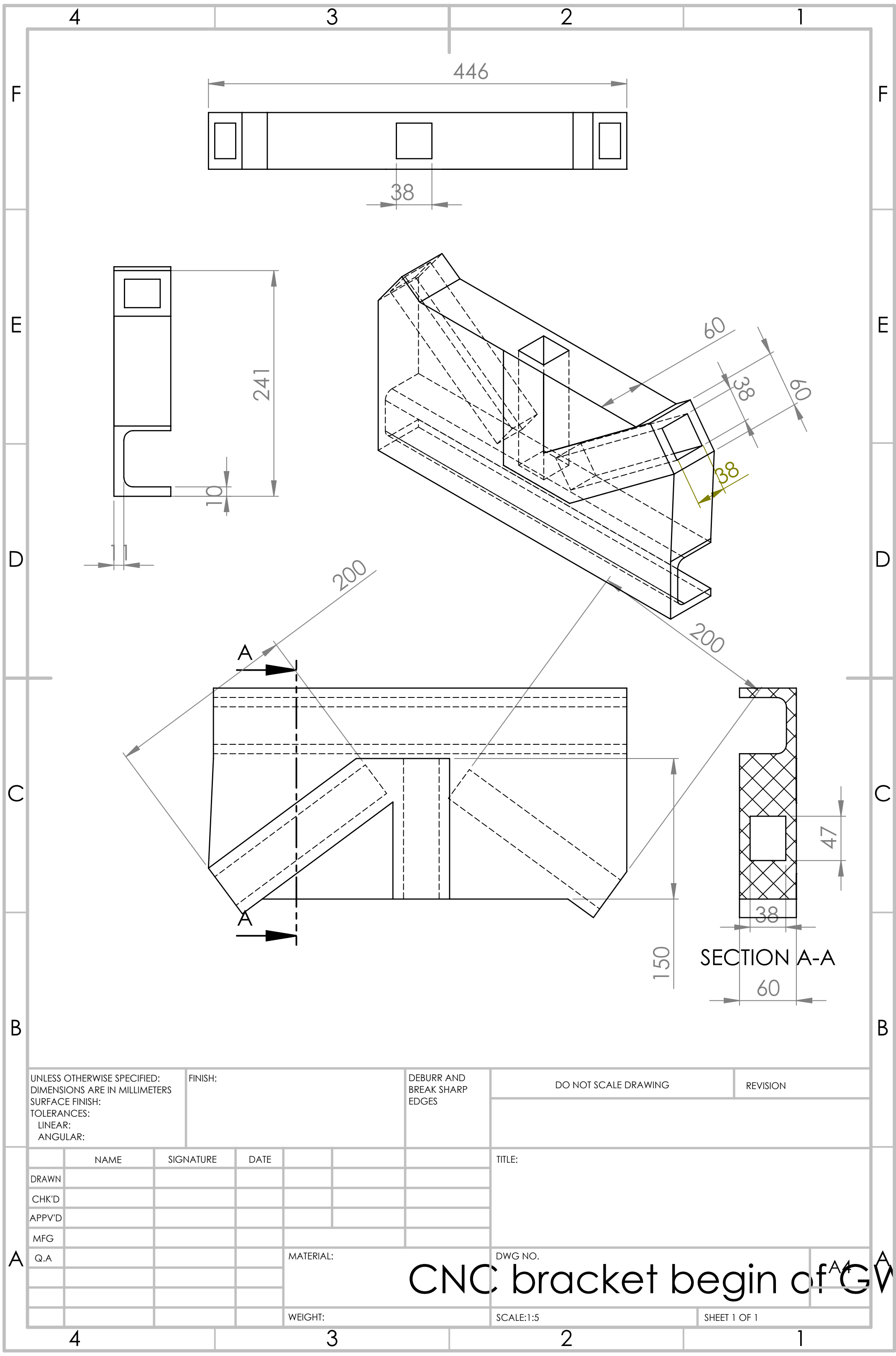
### F.1.1 Main boom



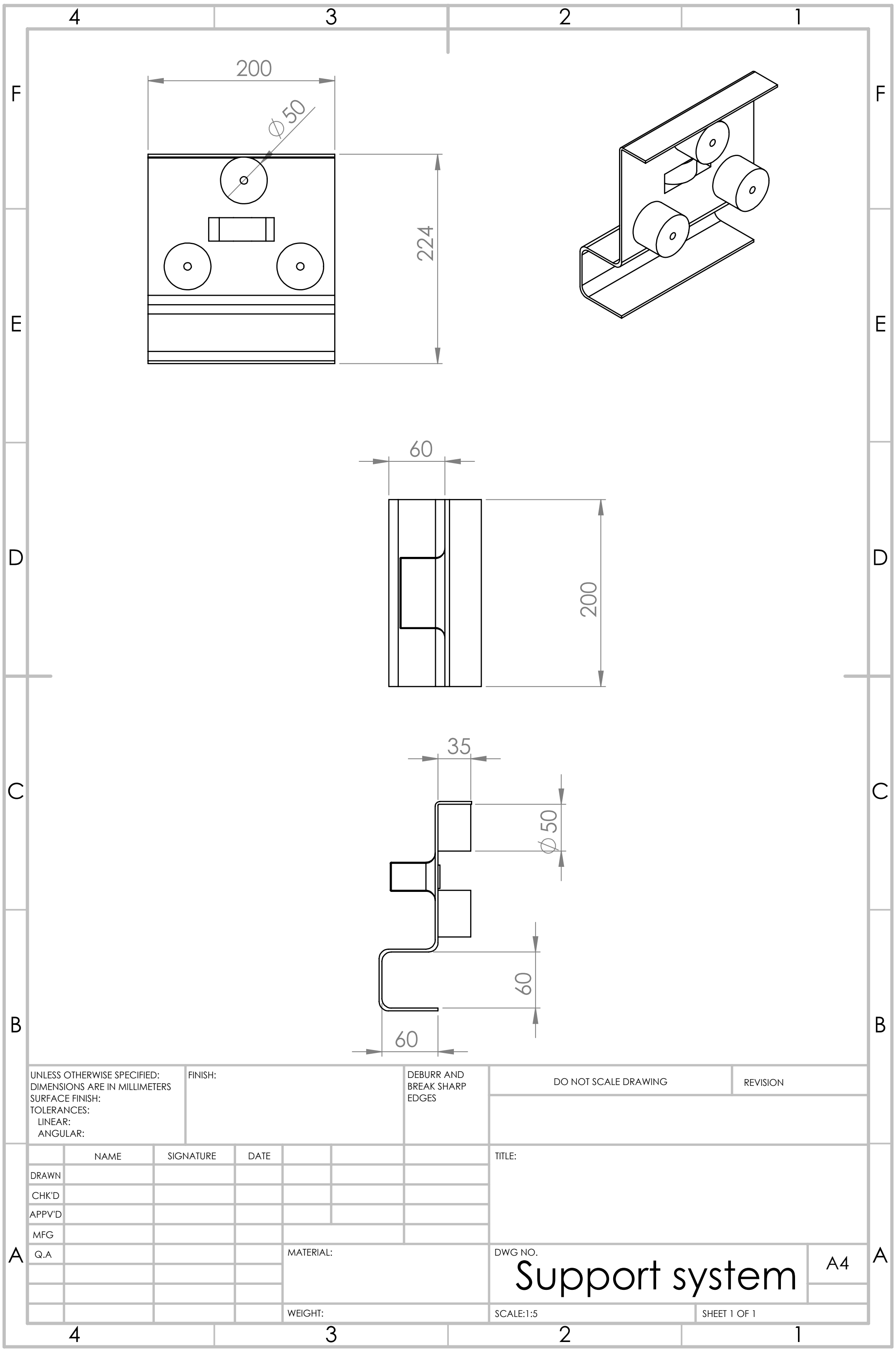
### F.1.2 Telescoping boom



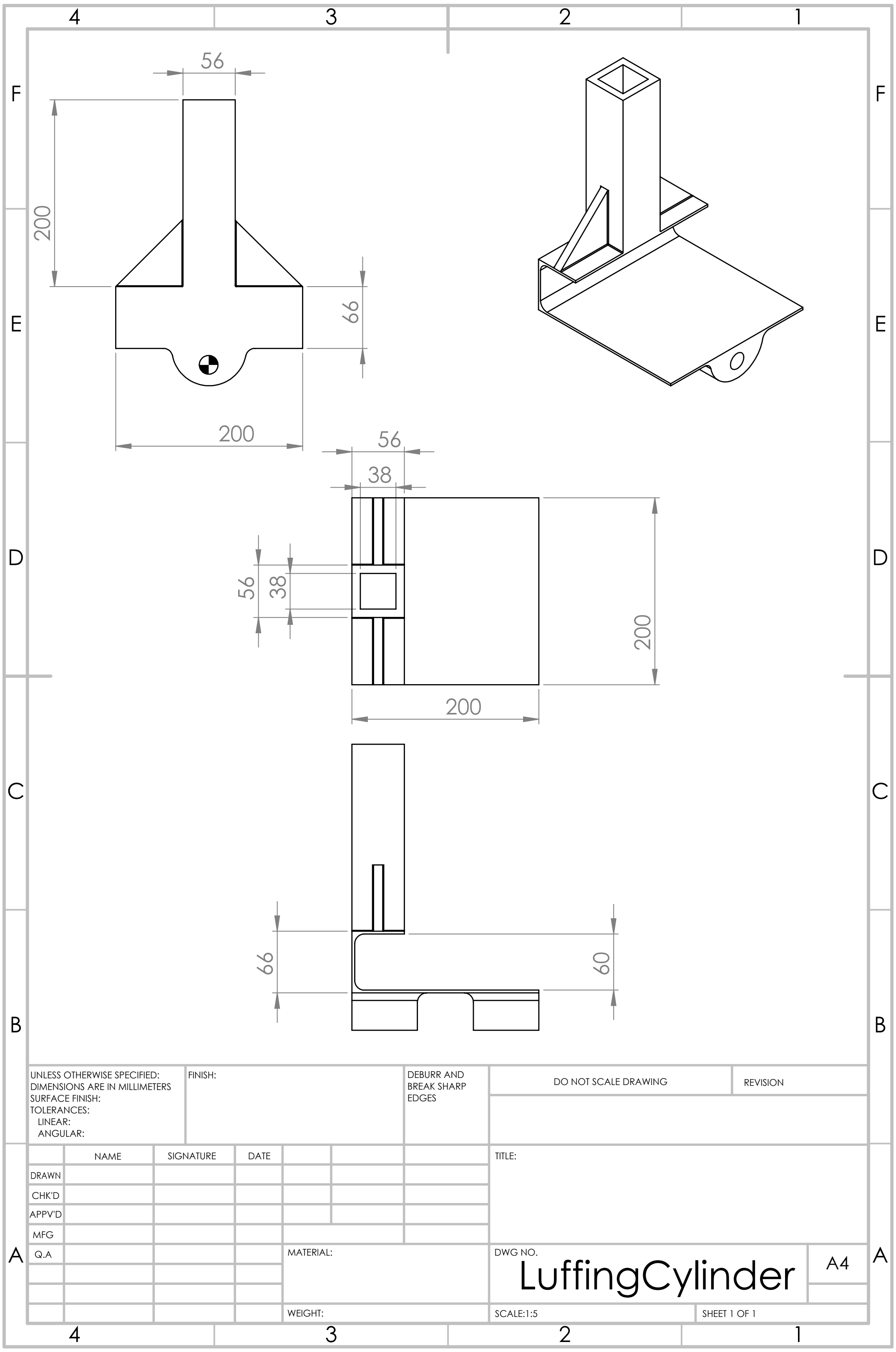
## F.2 Railing bracket dimensions



## F.3 Telescoping support dimensions



## F.4 Luffing cylinder dimensions



## F.5 Hinge point dimensions