Evaluation of a Lightweight Composite Bottom Plate for Air Cargo Containers

Master Thesis

Woytek Bode
1311409
TU Delft

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Preface

My first contact with DSM was through the Nuon Solar Team, a student project at the TU Delft. For the World Solar Challenge we designed and built a solar powered electric vehicle and raced it across Australia facing many other university teams. DSM is one of the main sponsors of the project and helped with advice and materials for the production of the composite parts of the car.

I applied in 2010 for a position as structural engineer at the team and got accepted. At the time I already finished my Aerospace Engineering Bachelor and started with the "Design and Production of Composite Structures" master. Together with DSM, we discussed which materials, mould system and production processes would be best for our application.

The project came to an end successfully when we finished second only behind the Tokai University team. I started looking for a way to continue my studies and decided to ask for an internship at DSM Composite Resins. I got a positive response and worked on a resin project for six months. After my internship I continued with this project for my graduation.

This report will describe the process I used to find a composite solution for a customer in the difficult market of air cargo containers. During this year long project, Guillaume Ratouit from DSM Composite Resins is project manager and my supervisor. He helps guide the project and supports me when and where necessary. Achim Johannes from DSM Functional Materials is the project owner and is responsible for business decisions.

I want to thank both Guillaume and Achim for their collaboration and for the opportunity and responsibility that they have given me to take on this project. My coordinators at the Technical University of Delft – Otto Bergsma and Roel Marissen – deserve credit for guiding me through the last phase of graduation.

Abstract

Air cargo containers are used to load luggage, freight, and mail on aircraft. They allow a large quantity of cargo to be bundled into a single unit. This study aims to investigate the replacement of the current 14,1 kg aluminium floor with a 40 % lighter composite in Nordisk containers. The result of these weight savings is yearly cost reductions or an increased turnover for airliners.

I have performed analytical and finite element calculations and have conducted small and full scale tests based on the calculation results and requirements. The tests show that the composites do not have sufficient stiffness which caused excessive deflections in the full scale roller tests. Severe wear on the underside of the composite plates made operation impossible after 800 cycles compared to the aluminium 13 000 cycles.

Analytical calculations show that decreasing the requested weight savings to 30 % might be necessary. For a sufficient stiffness, a composite weight of 9,6 kg is achievable.

List of Figures

[1] Nordisk Aviation Products, 2012.
[2] Cargo Composites, 2010.
[3] The Cargo Law, 1999.
[4] Cho and Bloomberg, 2012.
[5] Zenkert, 1997.
[6] Hibbeler, 2005.
[7] Lantor BV, 2008.

[8]Advanced Materials Composites (PTY) Ltd., 2016.
[9]Gurit, 2016.
[10]Taber Industries, 2016.
[11]Instron, 2014.
[12]ISO, 1998.
[13]Diatex SAS, 2016.

[14] Milliken & Company, 2015.

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1 Introduction

Unit Load Device

A unit load device (ULD) is a pallet or container used to load luggage, freight, and mail on aircraft. It allows a large quantity of cargo to be bundled into a single unit. This leads to fewer units that have to be loaded onto and unloaded from the aircraft which saves ground crews precious time. The chance of delayed flights due to problems with cargo is greatly reduced with ULDs.

ULDs come in two forms: pallets and containers. ULD pallets are sheets of aluminium with rims designed to attach cargo nets. ULD containers are closed containers made of aluminium or combination of aluminium (frame) and plastic/composite (walls). They are available in many different sizes and the main ULD under consideration in this report is the standardized LD3 container with a volume of 4,5 m^3 and a bottom plate size of 1440 mm by 1412 mm.

A joint development

DSM Functional Materials is asked by Nordisk Aviation Products to help develop a composite bottom plate for one of their air cargo containers. Nordisk already has lightweight containers in their portfolio but their construction is still based on an aluminium floor which has the potential to be replaced with a lighter alternative. For the next step in weight reduction, Nordisk wants to develop a composite floor (bottom plate) together with DSM Functional Materials.

Participating from DSM are project owner Achim Johannes (DSM Functional Materials), technical resource Woytek Bode (DSM Composite Resins, DSM functional Materials) and project manager, supervisor and technical

Figure 1.1: An example of an ULD: the Nordisk Alulite AKE.[1]

resource Guilaume Ratouit (DSM Composite Resins). Participating from Nordisk are head of engineering Frode Erikson and project engineer Christian Arnesen. While DSM will develop the composite plate, Nordisk will be responsible for the container design itself and the attachment of the composite bottom plate to the aluminium frame.

A new ultra lightweight container

The LD3 air cargo container is produced and sold by Nordisk in different models. At the moment the Nordisk UltraLite AKE is the lightest model at 55 kg, it has composite side walls and installing a composite floor allows the weight to drop to 50 kg. This will further distance the cheap and heavy aluminium containers from the more expensive but lightweight composite containers.

The surface area of the plate is roughly 2m^2 per LD3 container with Nordisk expecting a sales volume of 5000 units per year.[2] Due to the probable in-

[1]Nordisk Aviation Products, 2012.
[2]Johannes, 2012.

creased container sales price, initial sales volume is around 500 units per year but will grow to the current 5000 per year in time. Further expected growth in sales is around 5 percent per year.

A new strategy

Airliners are expected to change to this new container due to the advantages in regards to weight savings. The aim is to save roughly five kilograms per container compared to the Nordisk Ultralite AKE. The airliner can choose to increase the amount of cargo or the number of passengers transported on a flight. The result is yearly cost reductions or increased turnover[3]. These financial benefits mean that the return of investment (ROI) is high and the additional cost per container is outweighed by the benefits.

Considering the benefits for airliners mentioned above, an increased product cost for this container is justified. The reason why Nordisk is willing to use more composites in their containers is to achieve the required weight savings. Furthermore, they can use the weight reduction to differentiate their products from competitor's products.

About this report

A separate literature study is performed for this thesis which provides interesting and useful background information that is applied here. The literature study is not a required read for this thesis.

The chapters of this report are in a chronological order. Chapter 2 on page 5 reiterates the problem statement drafted in the literature study followed by a theoretical study of the problem in chapter 3 on page 9.

Chapters 4 (page 39) and 5 (page 65) treat the small scale tests and full scale tests respectively. The concepts selected for small scale tests follow from the theoretical approach chapter. These test results are then used to narrow the concepts down to two concepts suitable for the full scale tests.

Chapter 6 on page 91 summarises the test results and forms the conclusion of this thesis. Chapter 7 on page 97 gives some recommendations for possible future research.

[3] Lufthansa Cargo AG, 2012; Maynard, 2008.

Throughout the report, references are cited in the text by using small superscript numbers. These numbers link to a citation at the foot of the current page. Further details on these citations can be found in appendix G on page 172.

2 The problem statement

Since the year 2000, the kerosene price went up from a steady €0,18 per litre to €0,71 per litre in 2012 within just twelve years. In the end of 2008 there was even a peak of €0,94 per litre of kerosene followed by a steep drop due to the financial crisis[1].

In the year 2000, fifteen percent of the price of a plane ticket was made up by jet fuel costs[2]. Now, this percentage has risen up to forty percent. From these numbers it is understandable that most airliners are focusing on saving fuel.

For this reason, airliners are looking for lightweight air cargo containers. Since aircraft typically carry several LD3 containers – ranging from eight to thirty-two in very large aircraft – on each flight, the weight savings on one container are multiplied by the total number of containers on board. This makes it very worthwhile to use lightweight containers.

Ideal situation

Nordisk is one of the largest air cargo container suppliers in the world. Currently there are already several containers in their portfolio that offer weight savings compared to the classic full aluminium variant. One container – the TwinLite AKE – weighs 60 kg and the second – the UltraLite AKE – weighs 55 kg.

These containers are more expensive but offer lower tare weight compared to the classic Alulite AKE containers which have a tare weight of 76 kg. Airliners make the trade-off if they are willing to invest in lighter containers that save cost during their service life or spend less on heavier containers

[1] U.S. Department of Energy, 2013.
[2] U.S. Department of Energy, 2013.

that will eventually cost more due to higher fuel costs during their service life.

Ideally, Nordisk would like to offer a container that brings even more weight savings while still meeting all of the requirements and not being too expensive. The container would be more robust so that it would have to be repaired less often than traditional containers. A full composite container would be suited for these goals since it can be completely redesigned with these requirements in mind.

Problem

Due to the increased kerosene price, weight savings become increasingly more important for airliners. This creates demand for lightweight air cargo container, which Nordisk intends to fill with its current offering and in the future with even lighter containers. The full composite container described in the previous section takes a long time to develop and might even need advances in materials and production techniques. For the short term, a further optimisation of the current container is a good alternative.

Nordisk has decided that for their current Ultralite containers, the aluminium floor is to be replaced with a composite variant. The design of a composite floor that is both lightweight and durable might prove to be challenging. Parts that are durable often use an excess of material and lightweight parts are usually not the most durable. That makes the design of a composite floor that performs equally or better with less material difficult.

ULDs in general are not treated according to protocol.[3] This results in high wear and tear on the containers due to: accidents with forklifts, abusive handling, wrong loading and other common malpractices. A proper composite design is required to both offer the intended weight savings and to cope with the handling loads. The floor stiffness should be comparable to the current aluminium plate and if it is lower, at least be sufficient for good perfomance on conveyor systems.

[3] Flying Typers, 2015.

Solution

DSM Functional Materials is asked by Nordisk Aviation Products to develop the composite bottom plate for the UltraLite ULD. DSM's knowledge in polymers and composites is necessary to come to a design that satisfies all stringent requirements. Cooperation is critical since Nordisk has many years of experience in designing and testing ULDs.

For Nordisk this will result in a better and more complete portfolio with more sales as a result. Airliners are able to save fuel costs due to the lower container weight which means their pricing can be more competitive or their margins can be increased. For airliner customers, passengers or freighters, the rates could see a slight drop which results in direct cost savings.

Proposal

Since Nordisk does not have a lot of in-house experience in composites, DSM Functional Materials will handle the technical aspect of this project while Nordisk will help with defining the design envelope and testing procedures.

The design of the composite floor will be such that the performance of the container is not impacted in a negative way. The initial design will be performed with calculations and later followed with small scale testing. Full scale testing will be done after several promising concepts have been designed.

DSM will supply composite knowledge and facilities to aid in the design process and will take responsibility for the production of the plates if the project is successful. When the project is finished, the produced plates will be sold to Nordisk.

Problem statement

The final problem statement is drafted as follows:

A composite floor for air cargo containers with comparable performance to aluminium floors can be designed to lower the Nordisk lightweight container tare weight. This results in improved sales for Nordisk, reduced fuel cost for airliners and lower prices for customers.

3 Theoretical approach

The problem statement from the previous chapter gives insight in how the research should be set up. It is important that the current containers are studied so that correct conditions and requirements can be set up for the design of the composite plate. This is done in the separate literature study which will be used extensively for this chapter. In section 3.2 this information is used to create a design envelope that will be used to guide the design.

In section 3.4 the design envelope is used to select different materials that are expected to meet the criteria for this design. These materials are then used to create several concepts that are expected to perform well. This is done while keeping in mind each material's properties, using them where they are most likely to add performance.

Each concept is verified to meet the requirements by simple analytical calculations and by the use of finite element analysis in section 3.5. The concepts can then be sorted based on mechanical performance and other important parameters such as cost. The final section lists adjusted requirements based on the learnings from this chapter.

Concepts that offer the best chance to perform successfully in this application will have small scale specimens produced for further testing. Several tests are set up that should give a good view on the small scale performance of the samples. See chapter 4

From the small scale test results, the most promising concepts are selected to be produced in full scale to measure their performance in an actual container. For this purpose, an ULD roller track is produced over which a container with a composite bottom plate can be cycled. See chapter 5

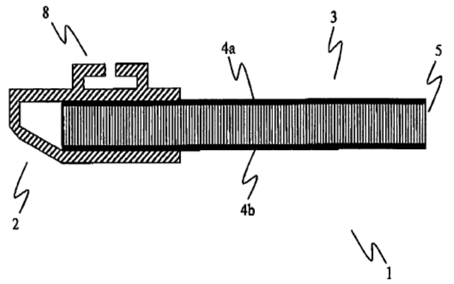


Figure 3.1: Drawing extracted from patent EP2431302A1

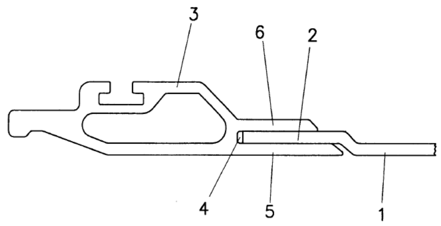


Figure 3.2: Drawing extracted from patent EP0592940B1

3.1 Patent summary

This section will summarise four patents found during the literature research. More information is present in the literature study itself so only the basic information will be given here.

EP2431302A1 (Figure 3.1)

This patent describes a basic solution for the implementation of a sandwich composite plate as the bottom plate for an air cargo container. A common connection method is used to attach the thick composite plate to the metal frame. This patent offers no actual new solutions for a composite bottom plate but the fact that a patent has been granted on such a basic solution might prove to be a problem if a composite sandwich solution is viable.

EP0592940B1 (Figure 3.2)

Although this patent does not actually describe a composite solution, the used metal extrusion might be suitable for use with a thin composite sheet. The connection between the sheet and frame is more reliable when the

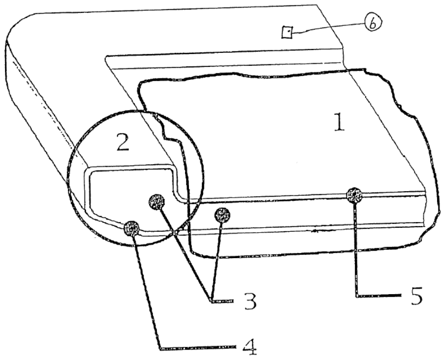


Figure 3.3: Drawing extracted from patent WO2007090363A1

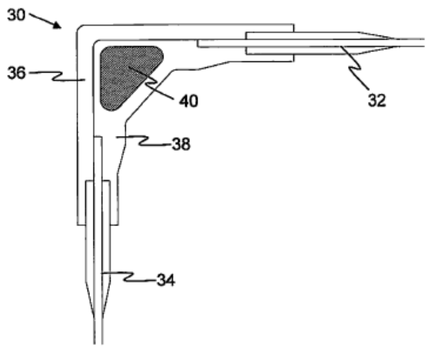


Figure 3.4: Drawing extracted from patent WO2010045572A1

sheet is sandwiched between two metal flanges compared to having only one flange available for fastening.

WO2007090363A1 (Figure 3.3)

This patent seems to be mainly focussed on a pallet design instead of a container floor design where the frame and floor sheet are produced in one part. This solution is probably able to be built lightweight since it incorporates the frame, corner pieces, bottom plate and connection into one product. Disadvantages would most likely be easy indentation and rapid wear.

WO2010045572A1 (Figure 3.4)

This patent does not discuss a possible solution for a composite floor plate but is still interesting since it focusses on a fully composite super structure. Most containers today still use an aluminium frame so this patent matches well with this study in it's intent to use more composites for – presumably – weight reduction.

3.2 Initial requirements

Air cargo containers and pallets are used to quickly load and offload the aircraft. A container is typically filled with passenger luggage or freight to a maximum of 1588 kg. Special carts and lifts are used to transport the containers to and from the aircraft.

Several types of air cargo containers are used in service but only the LD3 (AKE) container is considered in this report. This Nordisk container has a 2,5 mm thick aluminium floor measuring 1440 mm by 1412 mm. The current weight of the floor panel is 14,1 kg.[1].

Nordisk wants to build an ultra lightweight air cargo container with a weight below 50 kg using a new composite bottom plate. The basis for this new container will be the current UltraLite AKE which weighs 55 kg. This section lists the conditions and requirements that will be used to start the design process.

Conditions

Because aircraft are used to transport people and cargo around the entire planet, ULDs literally travel all over the world. This means that they are exposed to very different conditions every day. They might for example be taken from a very cold climate to a very hot climate. ULDs should be able to handle these extreme changes in conditions. In these circumstances, the containers have an average lifetime of seven to ten years with large variations of these numbers.

Examples of changing conditions are temperature, humidity, direct sunlight and rain. The temperatures can range from tropical to freezing in either very dry conditions, very humid conditions or anything in between. Moisture rich environments pose a threat for the air cargo container. In a

[1] Bode, 2016.

composite bottom plate local delamination or wear might result in premature failure due to the freezing of trapped water as the temperature drops. UV resistance is critical for composite side-walls and roof structures but for the bottom plate it is not that important as it does not see much sun light.

If the container is properly handled, metal and rubber roller systems inside aircraft are the most important design factors for the bottom sheet. However, for practical operation, which should also be taken into account, it is important to consider the use of forklifts for handling. Containers are pushed over concrete, which wears container and pallet bases. Strictly speaking this falls under improper use, but is still very common. Proper handling of containers is advised but not always respected.

The containers might be handled differently, depending on the airport they are handled at. And wherever you go, forklifts are used to lift heavy objects, including air cargo containers. This causes indirect damage by load cases induced in the container for which it was not designed. Also, small accidents with the forklifts happen frequently, punching holes through the container side-walls and denting or bending the extruded frame.

Since it is not realistic to expect a similar durability at a lower weight, the container is expected to require more care during handling and might not have an equal service life as a full aluminium container.

A typical LD3 container is loaded with a maximum of 1588 kg worth of cargo in 4,5 m^3. This means that the container can only be filled completely if the cargo has an average density lower than $1588\,kg/4{,}5\,m^3 = 353\,kg/m^3$. The density of the cargo determines if the container is volume critical or weight critical. Whilst in the air cargo compartments of an aircraft, the G-forces caused by aircraft manoeuvres induce loads in mainly the container floor. Since the container bottom plate is supported by small rollers, there are point loads exerted perpendicular to the floor. These point loads can cause local damage.

For the edges and side panels, damage is usually due to (small) collisions with a forklift, creating holes or dents. Lifting of the container causes inwards bending of the base plate and wear over time. Sometimes, forklift blades cause puncture of the bottom sheet when a pallet or container is lifted. Examples of extreme damage to containers can be seen in figures 3.5

[2] Cargo Composites, 2010.
[3] The Cargo Law, 1999.

Figure 3.5: Damaged ULD containers.[2]

Figure 3.6: LD3 container sucked into the engine cowling of a Boeing 767.[3]

Figure 3.7: The roller floor of a Boeing 747 cargo jet.[4]

and 3.6.

Current common aluminium repairs include the replacement of extrusions and corner inserts and the weld repair of extrusion cracks and holes. Sometimes, extrusions are bent back to normal. The side-walls are repaired with patches after puncture but the sheet is replaced if the damage is too extensive. The bottom plate needs to be straightened if the cold forming is causing the plate to bend outwards too much. No regular maintenance is conducted; repairs are only performed when necessary.

Initial requirements

Technical discussions between DSM and Nordisk are initiated to list the requirements for the composite bottom plate. This list will guide the research, tests and initial design. The most important requirement and the sole reason this project has been started is a weight reduction of at least 40% compared to an aluminium bottom plate.

The other requirements are more aimed towards mechanical performance

[4] Cho and Bloomberg, 2012.

and lifetime. Nordisk requested that the composite plate should have equal or less deformation to aid handling of the container. The plate should be able to handle all present load cases. The last requirement is resistance to wear and tear. Containers are moved around continuously, in many different ways. Sometimes they are dragged over rough surfaces, usually they are rolled on small steel rollers built in aircraft and container floors. The bottom plate is subjected to high point loads and abrasion which it should be able to withstand.

The initial requirements from the literature study are:

- Weight savings of at least 40% compared to aluminium plate
- Cost price less than €150
- Similar or higher stiffness
- Distributed load of 1588 kg on the bottom plate
- Resistance to wear due to handling on rough surfaces and roller systems
- Resistance to point loads due to roller systems

3.3 Analytical analysis

Membrane and bending stresses play an important role during the deformation of the bottom plate in air cargo containers. In this section I will show that for thin plates membrane deformation is critical while for thicker plates bending deformation is most important. This leads to specific design considerations for thin and thick composite concepts which are used in section 3.4.

Simplified model of membrane stresses

Figure 3.8 shows a simplified schematic of a thin bottom plate fixed in the frame of a container. For simplicity, the plate is modelled as a clamped 2D beam and all parameters are considered per unit width. The distributed load q causes a downwards deformation w.

Assume that the thin plate has no bending stiffness which causes the load q to be carried purely by in-plane membrane (normal) loads. This is only possible if the beam has a deflection w such that there is a vertical component of the reaction forces. This state resembles a so-called catenary form seen in suspended wires.

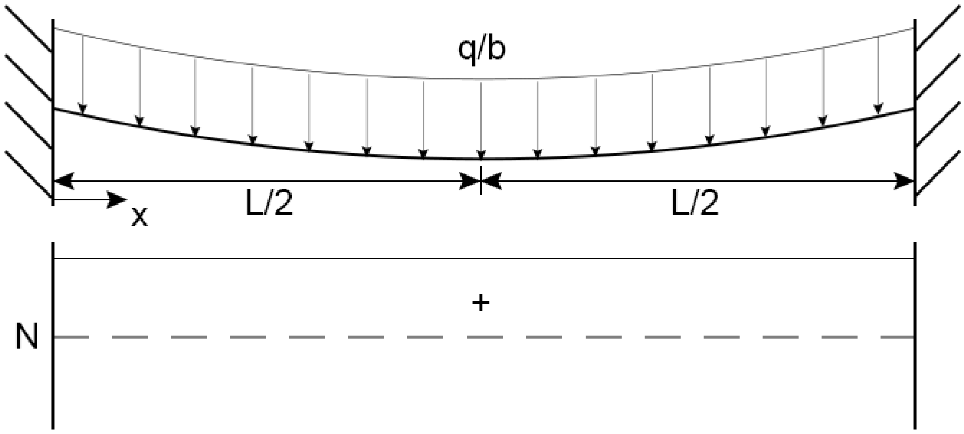


Figure 3.8: Schematic representation of a thin bottom plate with a distributed vertical load. The normal force diagram (N) is shown below the schematic.

A normal force diagram is given in figure 3.8 which shows the normal force is constant throughout the beam.

The maximum deflection $w_{membrane}$ in mm in this case is given by equation 3.1[5]. Here, L is the beam length in mm, $\frac{q}{b}$ is the distributed load per unit width in N/mm^2 and $\frac{EA}{b}$ is the membrane stiffness per unit width in N/mm.

$$w_{membrane} = L \left(\frac{3\frac{q}{b}L}{64\frac{EA}{b}} \right)^{1/3} \tag{3.1}$$

Note that this equation is derived for isotropic materials but we will assume that it is applicable to composite materials as well. The equation uses an approximated hyperbolic cosine deflection curve with a relatively small error. However, when considering wide beams, the prevention of the lateral deformation results in a smaller deflection than formula 3.1 indicates. This stiffening effect is taken into account by using $E/(1-\nu^2)$ instead of E where ν is the Poisson ratio of the material[6].

[5]Young and Budynas, 2002.
[6]Young and Budynas, 2002.

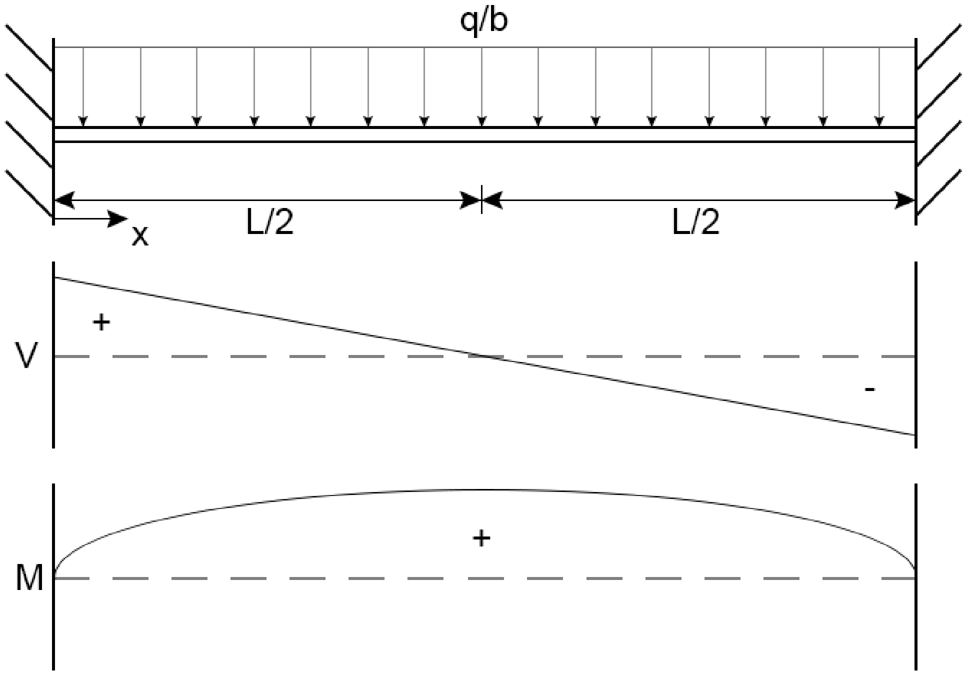


Figure 3.9: Schematic representation of a thick bottom plate with a distributed vertical load. The shear force diagram (V) and bending moment diagram (M) are shown below the schematic.

Simplified model of bending stresses

Figure 3.9 shows a simplified schematic of a thick bottom plate fixed in the frame of a container. For simplicity, the plate is modelled as a clamped 2D beam. The distributed load $\frac{q}{b}$ causes a downwards deformation w.

Assume that the thick plate has a significant bending stiffness per unit width $\frac{EI}{b}$ and therefore does not experience large deflections. As a result, we can neglect membrane (normal) stresses and assume that the load is carried entirely by bending moments and shear stresses.

A shear force and bending moment diagram are given in figure 3.9. The shear forces vary linearly and are greatest near the supports. The bending moment is greatest at $x = L/2$ and has a quadratic character.

The maximum shear deflection w_{shear} in mm and the maximum bending

[7] Zenkert, 1997.

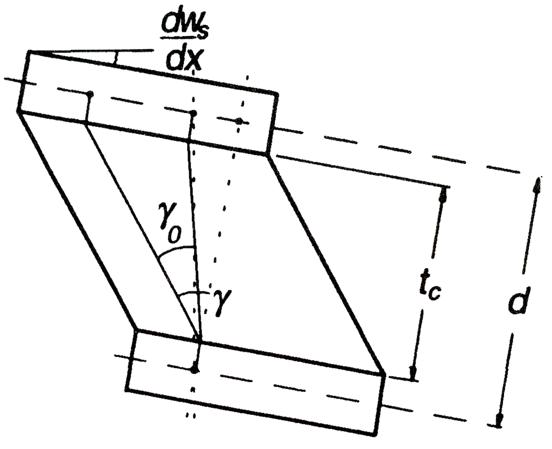


Figure 3.10: Shear deformation of a sandwich element.[7]

deflection $w_{bending}$ are given in equations 3.2 and 3.3 respectively[8]. The two separate deflections can be superimposed to obtain the total deflection w. L is the beam length in mm, $\frac{q}{b}$ is the distributed load per unit width in N/mm^2, S is the shear stiffness per unit width in N/mm and D is the bending stiffness per unit width b in N mm.

$$w_{shear} = \frac{\frac{q}{b}L^2}{8S} \tag{3.2}$$

$$w_{bending} = \frac{\frac{q}{b}L^4}{384\frac{EI}{b}} \tag{3.3}$$

Here, S and D are given by equations 3.4 and 3.5. G_c and E_f are the core shear modulus and facing modulus in MPa, t_c and t_f are the core and facing thickness in mm and d is the distance between the centroids of the faces $d = t_c + t_f$. See figure 3.10 for more detail.

$$S = \frac{G_c d^2}{t_c} \tag{3.4}$$

[8]Zenkert, 1997.

$$D = \frac{E_f t_f d^2}{2} \tag{3.5}$$

These equations are valid if the facesheet (f) is thin compared to the core (c) thickness ($t_f \ll t_c$), the core is weak ($E_c \ll E_f$) and the facing shear modulus is large ($G_c \ll G_f$).

The d^2 term is very important since this means that an increase in the core thickness increases the stiffness quadratically. Sandwiches have a relatively high stiffness because of this effect.

Let us consider the member shown in figure 3.11 to further explain the d^2 term. The bending stiffness around the x-axis is given in equation 3.6[9]. In this equation I_x is the area moment of inertia about the x axis. $\bar{I}_{x'}$ is the area moment of inertia about the area's neutral axis x'. Distance d_y measures from neutral axis x' to the x axis. The $A{d_y}^2$ term in this equation is called the Steiner term.

$$EI_x = E(\bar{I}_{x'} + A{d_y}^2) \tag{3.6}$$

For a sandwich design with fixed face sheets but a variable core thickness, E, A and $\bar{I}_{x'}$ stay constant. Distance d_y increases proportionately with the core thickness t_c. Due to the Steiner term, the bending stiffness has a quadratic relation with the core thickness.

Importance of membrane and bending stresses

From equation 3.1 it is obvious that the membrane stiffness $\frac{EA}{b}$ of the plate is very important for thin plates. Composites with a high specific in-plane stiffness should be selected for the thin plate concepts.

From equations 3.2 and 3.3 it is obvious that the bending stiffness D and shear stiffness S are important for thick plates. Specifically, the core thickness t_c is important due to its quadratic influence on both stiffness values. A thick core with a high shear modulus should be selected for the thick plate concepts.

[9] Hibbeler, 2005.
[10] Hibbeler, 2005.

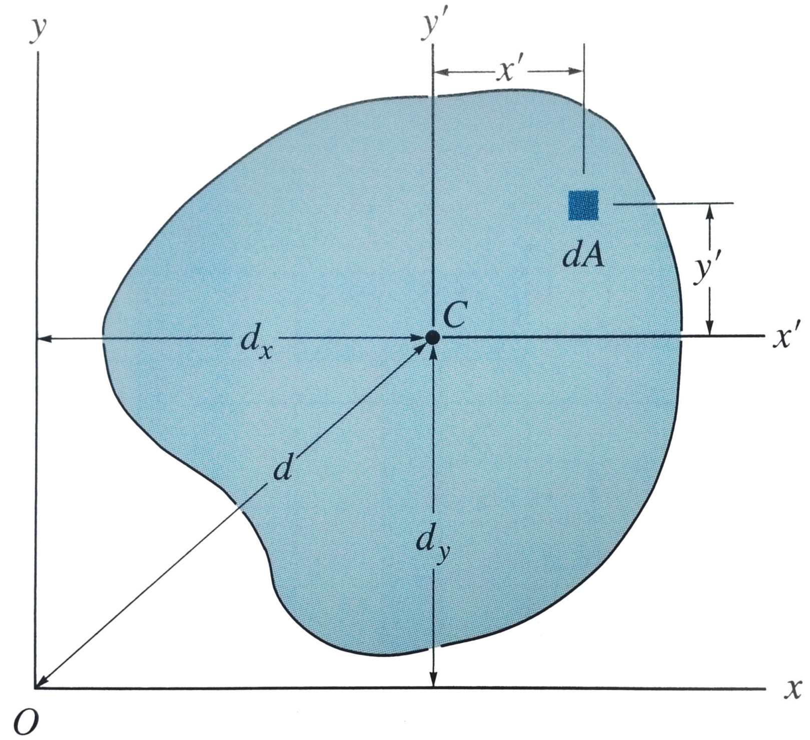


Figure 3.11: Schematic representation of a cross-sectional area.[10]

Importance of fibre orientation

Composites are anisotropic, this has positive and negative consequences. One advantage is that the placement of fibres can be used to tailor the material to the loads. This makes it possible to design highly optimized structures and parts.

The part considered for this study is a flat plate with almost square dimensions. The actual load case is not known which makes it difficult to optimize the fibre placement. Since the plate is part of a thin-walled box structure, assume that the plate is required to carry local loads, bending loads and in-plane shear loads.

Since the deflection of a plate segment is a function of its length we can expect fibres placed in the 0/90° direction to make the greatest contribution due to the shortest fibre path. However, the floor must also carry shear loads since shear resistance of the container box structure stems from the panels. Besides this, a minimum of three fibre directions is preferred to account for unknown smaller load cases that could otherwise lead to unexpected (matrix) failure.

Because of the aforementioned reasons, a quasi-isotropic composite plate makes the most sense for this problem. By laying fibres both in the 0/90° and ±45° directions the composite is able to transfer loads in all directions. This structure is called quasi-isotropic since it approaches isotropic behaviour.

3.4 Initial concept selection

In the literature study for this report a small selection of materials is presented (see table 8.4). These materials will form the basis for the composite concepts used for initial calculations. Different combinations will be created that are expected to meet the initial requirements and the early analytical analysis of the problem.

Two general groups of concepts have been defined, one group with a similar thickness as aluminium and the other with a much larger thickness. The first group will be able to be used without any changes to the current container frame. The thick plates from the second group require a changed frame geometry to allow proper assembly and interface strength.

Thin plate concepts

For the first group of concepts, solid laminates and thin felt filled laminates (see figure 3.12) are considered for their robustness and ease of manufacturing and assembly. A plate with a similar thickness as the aluminium plate (±2,5 mm) will allow the same basic frame to be used. This makes integration of the composite plate into the aluminium frame easy.

From section 3.3 we know that for thin plates the membrane stiffness EA is a very important design consideration. This does not mean that the bending stiffness is unimportant, the total deflection will be a function of both mechanisms. A greater thickness is beneficial for local point load introductions which result in high local shear loads.

Fortunately, composites in general have a lower density (1380 kg/m^3 to 1850 kg/m^3) than aluminium (2780 kg/m^3) which allows the weight of a composite plate to be lower for an equal thickness[11]. When considering the 40 % weight reduction requirement from section 3.2, the composites are roughly in the range of 2,5 mm to 3 mm.

When designing for a high membrane stiffness EA, the specific stiffness parameter is a useful comparison tool. The specific stiffness is obtained by dividing the material modulus E by its density ρ. It allows a direct comparison between the modulus of elasticity of several materials.

The quasi isotropic stiffness of composites can be estimated with the Krenchel factor[12]. Although this factor is a greatly simplified, for simple calculations the accuracy is sufficient. With a Krenchel factor of 0,375, the specific stiffness of a quasi isotropic glass fibre composite is estimated to be 8 MPa m^3/kg while aluminium has a specific stiffness of 26 MPa m^3/kg.

Carbon fibre outperforms aluminium at 30 MPa m^3/kg. Taking into account the 40 % reduction in weight and thus cross-sectional area, we can estimate a full glass composite to have a membrane stiffness of 18 % of the aluminium plate. In contrast, a full carbon composite plate is estimated to have 70 % of the aluminium membrane stiffness.

For this group, monolithic and felt hybrid sandwich laminates are considered using glass, carbon and aramid fibres. Carbon and aramid fibres are very expensive so a full carbon or aramid concept does not fit the cost price requirement from section 3.2. Instead, these fibres will be used to offer additional stiffness or wear resistance to a glass composite.

The felt composites have additional thickness compared to full glass composites, which is expected to result in a noticeable increase in local bending stiffness between two rollers for example. Non symmetric layups are considered so that expensive aramid fibres can be placed on the underside of the plate to act as a wear resistant layer where it is most useful.

A full aramid concept is included in the list as a reference. It is expected to perform well in this application and is therefore considered a useful composite benchmark next to the aluminium reference. As mentioned before, the cost price will to high for this concept to be considered as a solution.

[11] Bode, 2016.
[12] Harris, 1999.
[13] Lantor BV, 2008.

Figure 3.12: Lantor Soric felt glass composite sandwich structures.[13]

Thick plate concepts

For the second group of concepts, sandwich structures are considered. A composite sandwich is made by bonding two high stiffness composite skins to a low density foam or honeycomb core. The core provides thickness to the structure and has to have good compression and shear properties. Since the density of the core is very low (in the range of $30\,\mathrm{kg/m^3}$ to $150\,\mathrm{kg/m^3}$) the weight increase is small compared to the stiffness increase.

From section 3.3 we know that for thick plates the core thickness is the most important design consideration. A high bending stiffness can be obtained without resorting to high modulus but expensive materials such as carbon fibre.

The bending stiffness per unit width EI/b of the aluminium floor is $93{,}75 \times 10^9$ N mm. Consider a glass fibre sandwich with a total facing weight equal to 60 % of the aluminium plate. A core thickness of 2,9 mm is enough to obtain the same bending stiffness per unit width D. Note that this does not mean that the sandwich performs better as the membrane and shear effects should also be taken into account.

One disadvantage of sandwich structures is a more difficult assembly due to the plate thickness. This requires a change in the container frame design to accommodate the thicker panel. Rivets are impossible to use for the connection so a bonding solution has to be designed which brings additional difficulties. Sandwich structures are also more susceptible to damage in regard to point loads and impact compared to monolithic structures due to their lower flexibility and thin face sheets. Such loads can – amongst other damage – cause breakage and de-bonding of the skin.

PVC foam and impregnated paper honeycomb core (IPHC) sandwich concepts are considered with glass and aramid fibres. The additional stiffness of expensive carbon fibres are not necessary for these concept. Aramid fibres are used to improve local damage and wear resistance. A sandwich thickness of 5 mm to 25 mm will be used in the calculations.

List of initial concepts

Table 3.1 shows the list of initial concepts set-up based on the considerations from the previous sections. A finite element analysis will be performed on both the aluminium reference plate and the composites in section 3.5. The results of this analysis can be found in figure 3.17 on page 33.

Table 3.1: Initial list of concepts used for the finite element analysis.

Material	**thickness** [mm]	**orientation** [°]	**weight** [g/m^2]	**ply**
Aluminium	2,5			Al7021-T6
Glass	1,7	1 x ±45 3 x 0/90 1 x ±45	450 450 450	Glass Glass Glass
Glass/carbon	1,9	1 x ±45 3 x 0/90 1 x ±45	400 450 400	Carbon Glass Carbon
Glass/aramid	2,1	1 x 0/90 3 x ±45 1 x 0/90	460 300 460	Twaron Glass Twaron
Aramid/felt/glass	3,2	2 x 0/90 1 x ±45 1 x ±45 1 x 0/90	170 450 450 450	Twaron Glass Soric TF-2 Glass Glass
Aramid/felt/carbon	3,3	2 x 0/90 1 x ±45 1 x ±45 1 x 0/90	170 450 450 400	Twaron Glass Soric TF-2 Glass Carbon
Aramid	2,7	1 x 0/90 1 x 0/90 1 x ±45 1 x 0/90 1 x 0/90	170 460 460 460 170	Twaron Twaron Twaron Twaron Twaron
Material	**facesheet thickness** [mm]	**orientation** [°]	**weight** [g/m^2]	**ply**
Aramid/foam/glass	0,9	2 x 0/90 1 x ±45	170 450	Twaron Glass Airex T90.60
Aramid/honeycomb/glass	1,0	2 x 0/90 2 x ±45	170 300	Twaron Glass Daron41 IPHC

3.5 Finite element analysis

Finite element analysis (FEA) is used to compare the mechanical performance of the different concepts. A FEA program called Kolibri is used. Kolibri is designed and programmed by Lightweight Structures B.V. and is intended as a preliminary design tool. It makes obtaining results a simple and fast process, ideal for this project. Should more details be required than other more advanced FEA suites can be considered.

The Kolibri 3.0 software package allows the analysis of beams and plates with either metal or a composite lay-up applied. The results are shown in 3D using colours on the structure. Many calculation results can be shown but the most important ones are the structure deformation and the failure ratio.

Although FEA software is very useful to do extensive calculations on structures, it is very important that all of the material properties, constraints, load cases and software parameters are correctly set. The problem with this particular project is that the exact load cases that act on the container floor are very hard to determine. A good estimation can be used for the calculations, allowing the comparison between different concepts. This does mean that the calculations are not representative for the actual product in use.

The FEA model

The bottom plate of the container is a simple flat plate measuring 1440 mm by 1412 mm which makes it easy to model. In Kolibri 3.0, a plate with those dimensions is created and the edges are constraint for movement in the x, y an z directions and constraint for rotation around the x, y and z axes. In the actual container, the plate will be riveted and/or bonded to the extruded aluminium frame. It is assumed that this frame offers enough stiffness so that these constraints are valid.

There are two load cases applied. The first one corresponds to the container loaded to its maximum loading weight (1588 kg) while being suspended on the aluminium extrusion edges so that the entire load is carried by the composite plate (figure 3.13). The second load case represents the container being loaded with 5000 kg on the floor while standing on rollers (figure 3.14 and 3.15). The rollers (see figure 3.7) are modelled as point loads on the lower side of the plate.

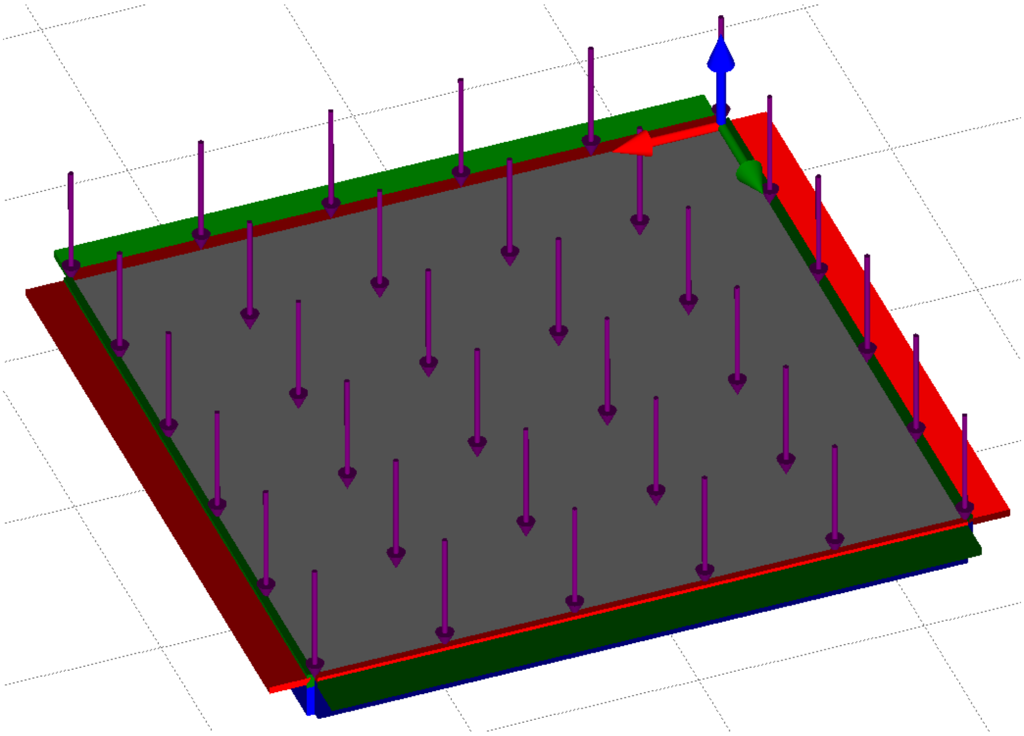


Figure 3.13: Constraint with the maximum allowable cargo weight loaded into the container while it is suspended on the extrusion frame.

From table 6.1 in the literature study the maximum overhang in the major direction is 362 mm and the maximum overhang on the minor axis is 254 mm. The roller pitch in the major direction is at most 673 mm and in the minor direction it is at most 254 mm. Note that the container is rolled sidewards on the system so the minor axis represents the rolling direction. It is assumed that the container is placed such that the maximum overhang is reached. This represents a fully loaded container in an airplane with G-forces working on it.

If the floor is thin relative to the size of the plate, deflections can be substantial. In this case, membrane stresses are most important as discussed in section 3.3. Linear calculations are not valid as these only take into account the bending stiffness of the plate. This is because the undeformed state does not allow the out-of-plane load to be carried by in-plane stresses.

As a rule of thumb, whenever the deflection is larger than the thickness of the plate, non-linear calculations should be applied. The load is then

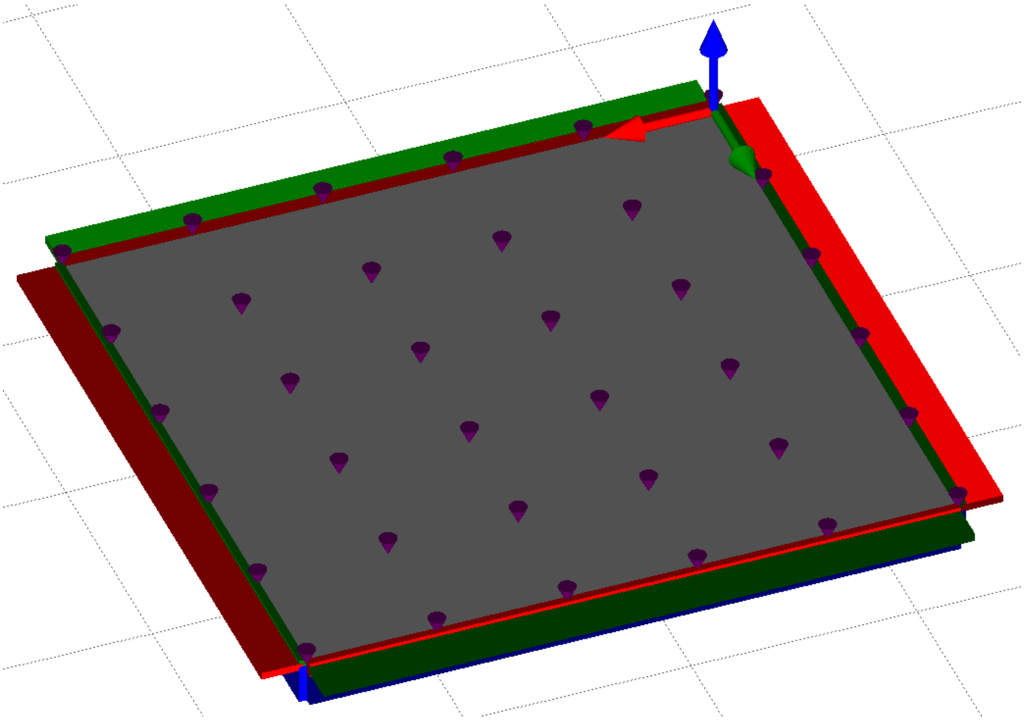


Figure 3.14: Constraint with the container maximally loaded while it is supported on rollers and under influence of G-forces. [top view]

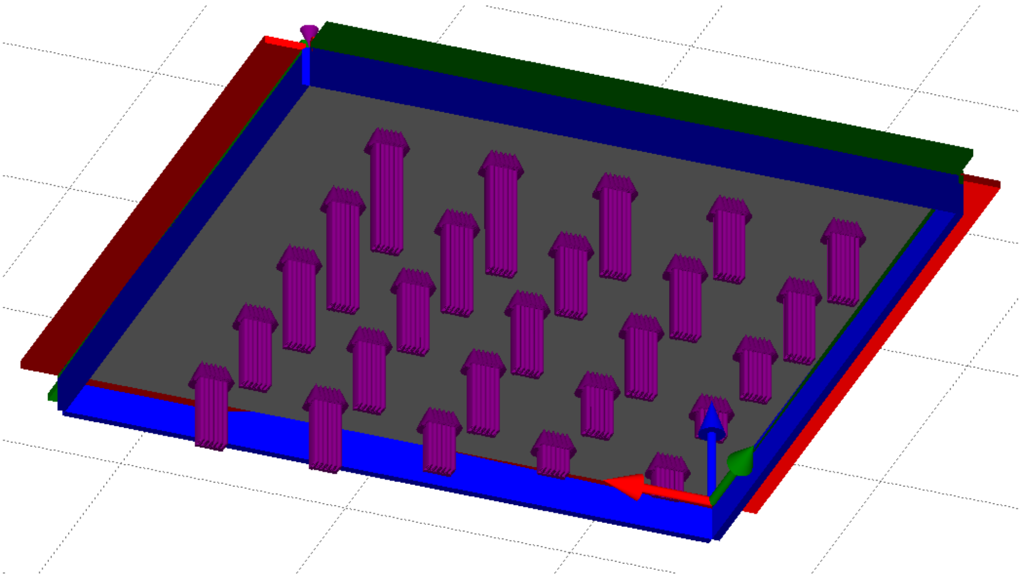


Figure 3.15: Constraint with the container maximally loaded while it is supported on rollers and under influence of G-forces. [bottom view]

Table 3.2: Step size analysis for a clamped aluminium bottom plate measuring 1,440 m by 1,412 m loaded with a pressure of $-7891\,\mathrm{N/m^2}$ (1580 kg) on the top surface.

Deflection according to linear model [mm]				
	extra fine mesh	*normal mesh*		
	398,42	411,21		

Deflection according to non-linear model [mm]				
	12 iteration steps		*6 iteration steps*	
Initial step size	*extra fine mesh*	*normal mesh*	*extra fine mesh*	*normal mesh*
0,001	15,849	15,840	15,836	15,834
0,01	15,850	15,841	15,836	15,834
0,05	15,853	15,841	15,836	15,834
0,1	15,860	15,844	15,838	15,835
0,2	15,913	15,862	15,850	15,840
0,5	16,065	15,897	16,005	15,882

applied in consecutive steps of for example 0,1. This means that a linear calculation is performed with 10% of the load-case. The resulting deflection profile is then used as the initial state for the second calculation with a 20% load and so forth.

The load steps are continued until a load step of 1 is reached, the applied load is now equal to the load case and the calculation is complete. Using load steps allows membrane stresses to build up in the plate so that both bending and membrane stiffness is taken into account.

Table 3.2 shows the results of deflection calculations performed on an Al7021-T6 aluminium bottom plate. The first set of deflection results is obtained by using linear calculations. This gives an unrealistic deflection of roughly 400 mm.

The second set of deflection results from table 3.2 is obtained via non-linear calculations. These numbers – a deflection of roughly 16 mm – are far more realistic than the linear model results. This means that non-linear calculations will be used for the finite element analysis of the composite concepts.

The convergence of these results is checked as a function of the initial step

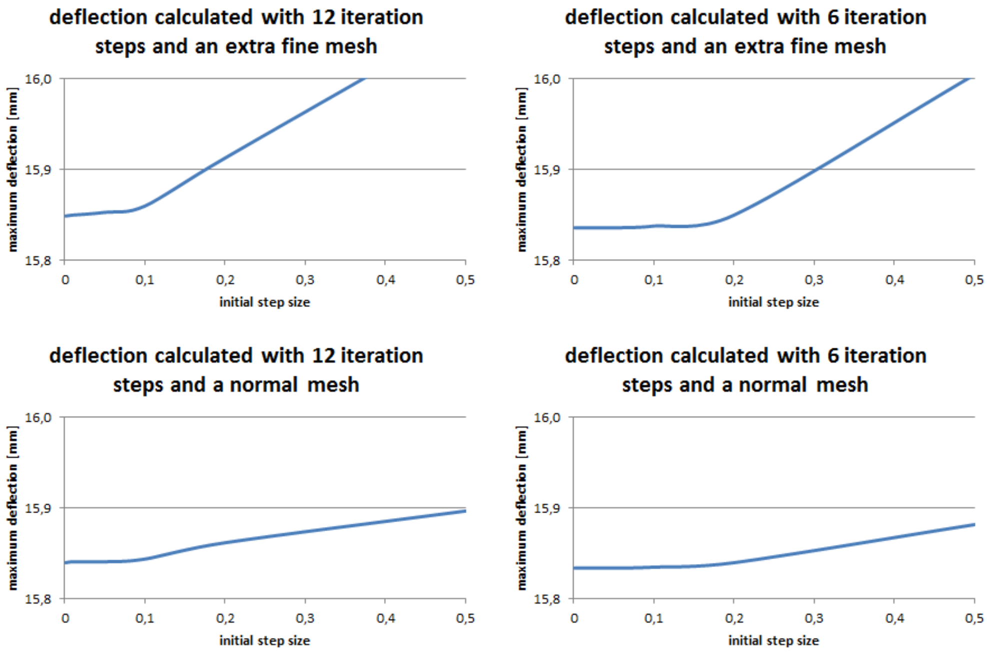


Figure 3.16: Deflection of an aluminium bottom plate as a function of initial step size, iteration steps and the mesh size.

size, the number of iteration steps and the mesh size. The number of iterations is a factor that Kolibri uses to determine the next step size. In general, a smaller step size results in more iterations and thus a longer calculation time.

Figure 3.16 shows the data from table 3.2 in graph format. I conclude that the initial step size is the most important parameter and that a step size of 0,1 is sufficient for a convergent result.

Material parameters

The parameters used for the calculations can be found in table 3.3. Note that the actual materials available were mostly 0/90° woven fabrics but for simplicity these were modelled as UD plies in Kolibri. For a ±45° woven fabric, two UD plies were added to the Kolibri layup rotated 45° and −45° respectively.

Table 3.3: List of parameters used for Kolibri during the finite element analysis.

	Carbon UD	**Glass UD**	**Glass UD**	**Twaron 2200 UD**	**Twaron 2200 UD**	**AL7021-T6**
Aerial weight [g/m^2]	200	150	225	85	230	–
Density [kg/m^3]	1470	1870	1870	1220	1220	2780
Layer thickness [mm]	0,222	0,115	0,173	0,131	0,354	2,5
E_1 [MPa]	117	39	42	61	53	76
E_2 [MPa]	12	11	12	11	11	76
G_{12} [MPa]	3,3	3,1	3,5	3,2	3,2	27
μ_{12}	0,325	0,31	0,306	0,335	0,335	0,33
μ_{23}	0,991	0,873	0,899	0,937	0,921	–
μ_{31}	0,033	0,084	0,087	0,061	0,070	–
S_1 [MPa]	2487	1287	1408	1587	1509	380
S_2 [MPa]	30	30	30	30	30	380
S_{12} [MPa]	60	75	75	58	58	250

Results

In this section a summary of the FEA results will be given and two calculation examples – the aluminium concept and one composite concept – will be discussed in more detail. In figures 3.18 and 3.19 (page 35), the deflection results are given for the aluminium concept and the composite aramid/felt/glass concepts respectively.

The first FEA load-case is selected to compare the composites to the aluminium because this case is expected to be critical. In this case, the plate is clamped at its edges and loaded uniformly with 1588 kg. Figure 3.17 on page 33 shows the deflection-weight plot for the different concepts. This plot gives an overview of the different composite concepts and how they compare to both the current aluminium design and to each other in this particular load case.

Note that there are more parameters that determine a successful composite bottom plate. Examples are: impact strength, abrasion resistance and point load strength. Handling of the containers exposes the floor to many loading situations. In some cases the overall stiffness and strength is important while in others local damage resistance and tolerance is critical.

Figure 3.17 shows that most of the composite concepts are within a band on

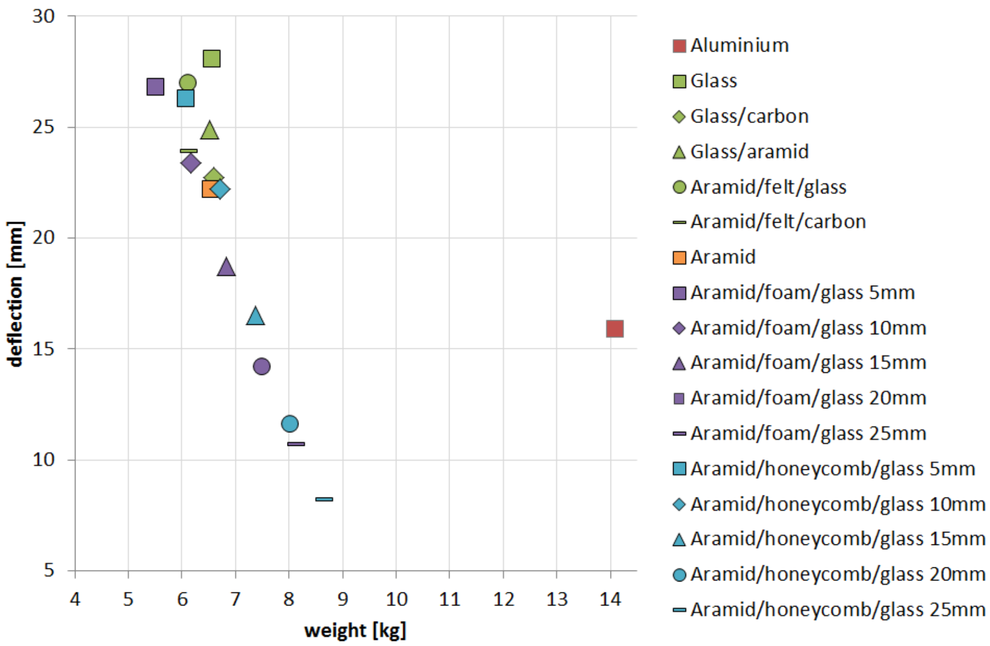


Figure 3.17: Overview of deflection vs. weight for different composite concepts and aluminium as calculated with Kolibri. The first load case mentioned in section 3.5 is used.

the plot. This is mainly apparent due to the sandwich concepts. As shown in section 3.3, an increase in thickness results in an increase in weight and stiffness. This is because the layup itself is not changed, resulting in a relation between weight and deflection. If stiffer fibres would be used – for example carbon fibres – then a more vertical shift is noticed. This can be seen when comparing the full glass concept with the glass/carbon concept. This is due to the additional stiffness of carbon fibres combined with their lower density.

Figure 3.18 shows the deflection plot of the current aluminium bottom plate when constrained at the edges and loaded with 16 000 N distributed on the surface. The high stiffness of aluminium results in a low deflection of 16 mm. The deflection pattern is very smooth since the applied load case is evenly distributed over the surface.

Figure 3.19 shows the deflection plot for the composite aramid/felt/glass sample. The lower stiffness of the composite results in a similar deflection figure as the aluminium plate but with a higher maximum of 27 mm.

The deflection data is useful since it can be effectively used to compare concepts. Although the calculations cannot be used to predict real life performance – due to lack of information on real life load cases – they give a good representation of the stiffness of each composite plate compared to the aluminium plate.

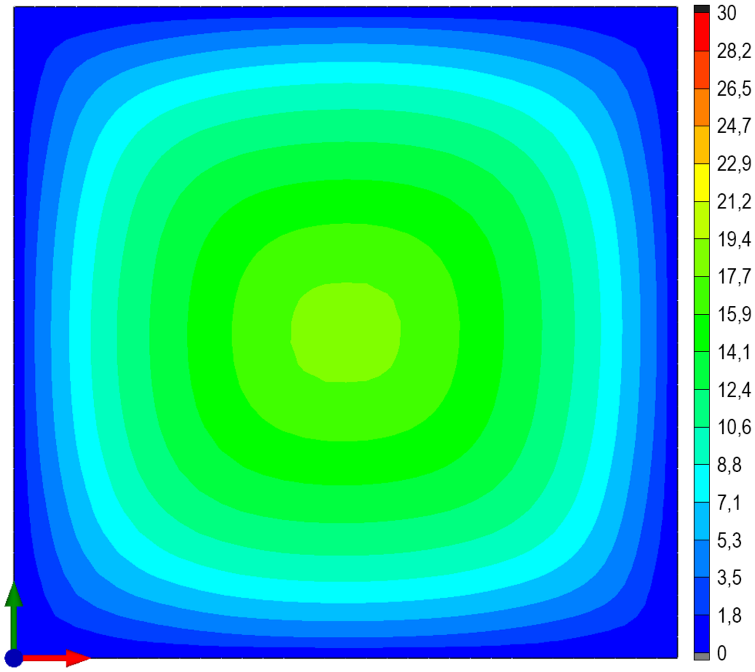


Figure 3.18: Non-linear deflection for aluminium Al7021-T6 in mm.

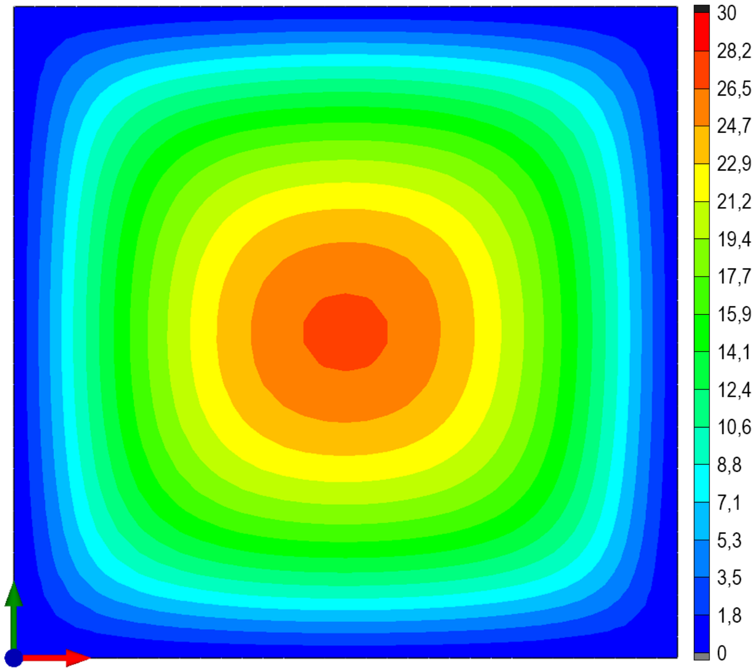


Figure 3.19: Non-linear deflection for aramid/felt/glass concept in mm.

3.6 Adjusted requirements

The first requirement states that the composite plate must be 40 % lighter than its aluminium counterpart. This comes directly from Nordisk and is important to make the design change to a composite floor worthwhile. The use of a composite bottom plate adds cost, complexity, possible unforeseen issues and requires investments in tools and personnel.

Note that the assembly of the composite plate in the aluminium frame will likely require a bonding agent which adds to the weight. Therefore, the weight savings for the plate are increase by 3 % for a total of 43 % to allow for additional assembly weight.

Section 3.3 shows that for thin composites, it is unlikely that the overall stiffness of the aluminium plate can be matched. This is due to a combination of the lower specific modulus of selected fibres and the required weight savings of 43 %. A full glass composite was estimate to have roughly 18 % of the aluminium membrane stiffness.

Thick composites are more able to be designed with a high bending stiffness which allows them to compensate for the lower membrane stiffness. The result is that sandwich panels are able to have deflections that are similar or lower than aluminium, depending on the load-case.

Section 3.5 confirms the theory discussed above. The thin composites have a greater deflection than the aluminium plate in the selected load-case. The thick sandwich composites, with a sufficiently thick core, offer a comparable stiffness. Because sandwich structures have several disadvantages, the stiffness requirement is adjusted so that thin plates can still be considered.

It is not clear whether or not the current aluminium plate is over designed. As such, the minimum membrane stiffness for thin composites is set to 20 % based on the full glass composite. Thick composites should be designed to have a bending stiffness such that the deflection of the composite is equal to or smaller than the deflection of the aluminium plate in the load case used for the finite element results.

The load-case used in the FEA results where the floor is only supported by the frame while loaded with 1588 kg is expected to be critical. This load-case will be used to design the small scale tests in chapter 4.

The resistance to wear and point loads should be such that no detrimental impact to the mechanical performance of the material is expected. The wear resistance of the composite is considered acceptable if this is at least 50 % of the aluminium wear considering the generally lower hardness of composites.

The adjusted requirements are now as follows:

- Weight savings should be at least 43 % of the aluminium plate
- Cost price should be less than €150
- A thin composite should have a membrane stiffness of 20 % of the aluminium plate
- A thick composite should have an equal or larger bending stiffness than the aluminium plate
- Distributed load of 1588 kg on the bottom plate as load case
- Resistance to wear should be at least 50 % of the aluminium plate
- Resistance to point loads should be such that no detrimental impact to the mechanical performance occurs

4 Small scale approach

The previous chapter laid down the groundwork for initial small scale testing and later full scale testing. The conditions a typical air cargo container experiences and the requirements that follow are examined and listed. From this information, a concept study is performed to find materials that are deemed suitable for this application.

Section 4.1 treats the process of selecting the most promising materials for the small scale tests. Different composite concepts are designed using the information from chapter 3. In chapter 3, analytical calculations and finite element calculations were used to assess each concept's mechanical performance and to gain further information about the design challenges.

The conceptual phase is now completed and the small scale test program is laid out in section 4.2. The importance of each test is explained and details on the method of testing are given. Finally, the test results are given in section 4.3.

4.1 Small scale concept selection

This section discusses the small scale concept selection process. Data and insight gained from chapter 3 is used to make a decision on the test concepts and to shape the test program. Because of the focus on mechanical performance in the theoretical approach, some additions to the concepts are made in this chapter to account for practical issues.

FEA and analytical results

The first concepts are selected by making use of figure 3.17 on page 33. This graph shows the overall plate deflection of a loaded container supported by its edge frame as a function of the floor weight.

In this plot there is a clear separation visible between the thin concepts (<5 mm) and the thick concepts (>10 mm). As explained in section 3.3, the deflection of the thin concepts is mainly dependent on the membrane stiffness EA whereas the deflection of the thick concepts is mainly dependent on the bending stiffness EI.

As a result the thin concepts are within a small deflection range with little variation while the sandwich concepts spread a much wider deflection range. This is because the EA value varies only with the material stiffness and thickness while the EI value scales quadratically with d_y. See table 4.7 and table 4.2 for the concept stiffness and thickness data respectively.

Based on the finite element analysis, the sandwich panels offer the lowest attainable deflection. Their bending stiffness can be designed such that it even allows for lower deflections of the container floor than the aluminium floor. A core thickness between 15 mm and 20 mm seems sufficient to match the aluminium deflection for the considered load case.

Considering the thin composites, the full aramid plate experiences similar deflections as the first 10 mm sandwich panels. The full glass plate experiences the largest deflections for this load case. Between these two extremes, the glass/carbon and glass/aramid monolithic composites and the felt composites can be found.

The felt composites offer similar deflection performance for this load case as their monolithic counterparts but generally have a bit more thickness. This is expected to be beneficial for short beam bending where the bending stiffness EI becomes increasingly important.

Early sandwich point load tests

As described in the previous subsection, sandwich structures offer very good stiffness which is desirable for this application. Unfortunately, the skins of the sandwich panels are in the order of 1 mm thin (see table 3.1) which makes them susceptible to local damage. I expected to encounter some problems with local point loads on the sandwich skins due to the rollers in a roller system. Therefore, an early point load test was performed on a 25 mm glass fibre foam sandwich.

The specimen is tested according to the point load resistance test described in section 4.2. Glass fibre facings are used so that possible damage can be

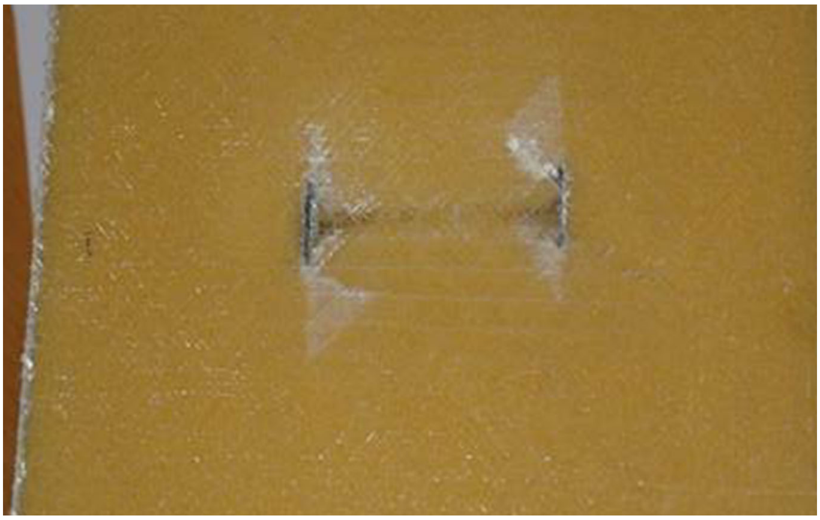


Figure 4.1: Damage after the point load test on a 25 mm glass fibre foam sandwich sample.

inspected visually. The facings consist of three layers of 300 g/m^2 stitched glass. The result can be seen in figure 4.1.

The damage is substantial with clear signs of core compression, fibre breakage and fibre delamination. The skins are too thin and the core compressive strength is too low. Unfortunately, the sandwich point load expectations are proven correct and at this point of the project I chose to focus on the more robust thin composites.

Early abrasion tests

It is expected that many fibres are not very resilient against abrasion. To foresee potential problems, an early abrasion test is performed on different materials. From this test a potential wear layer can be selected to protect the composite against wear damage.

The specimens are tested according to the wear and abrasion resistance test described in section 4.2. Aluminium and glass are tested to provide a reference while Dyneema and aramid fibre composites are tested to determine their potential as a wear layer. Finally, gelcoat coatings filled with solid or hollow glass spheres or silicon carbide are tested to evaluate their potential as a wear layer.

Table 4.1: Results of the early abrasion test given as weight loss after 500 and 1000 cycles.

Material	500 cycles [g]	1000 cycles [g]
Al7021-T6	0,18	0,33
Aramid fibre	0,27	0,55
Mixed Dyneema/glass fibre	0,50	1,28
High tensile polyester fibre	0,39	0,51
Glass fibre	1,52	2,91
Gelcoat with 10 % Eccosphere SI-250 hollow glass	0,98	2,24
Gelcoat with 50 % spheriglass 7010 solid glass	0,42	0,95
Gelcoat with 10 % 3M S38 hollow glass	0,41	1,29
Gelcoat with 20 % 3M VS5500 hollow glass	0,58	2,07
Gelcoat with 30 % silicon carbide	0,15	0,16

The results can be found in table 4.1. The average weight of the samples is 31 g and the weight loss after 500 and 1000 cycles is given in the table. The aluminium and glass samples provide a reference weight loss.

The glass fibre specimen is not very wear resistant which confirms the expectations. The glass bubble filled gelcoats reduce the wear but add additional weight and do not offer any mechanical performance benefits. The silicon carbide gelcoat almost completely stops the wear but the sharp sand like particles encapsulated in the gelcoat will most likely damage the roller systems so this solution should be avoided.

The mixed Dyneema/glass layer offers an improvement over the glass composite but the high tensile polyester layer and the aramid layer both offer superior wear resistance. The polyester fibres – similarly to the gelcoat solution – do not offer any substantial mechanical performance benefits in contrast to aramid fibres.

Based on these results we can conclude that a wear layer is highly desirable to protect the composite from wear and abrasion. A gelcoat or polyester fibre lining does offer protection but does also adds weight to the floor and does not offer mechanical performance benefits. A resilient outer fibre layer is seen as the most elegant solution to both offer protection and mechanical performance. Aramid stands out in this test due to its favourable mechanical properties and its wear resistance.

Basalt fibre and Corecork

Two additions are considered for the small scale tests: basalt fibre and cork core. Both are described below.

Basalt fibre

Basalt is mentioned in the literature study but is not included in chapter 3. Basalt fibres are comparable to glass fibres and have similar properties and price. To compare how basalt performs in this application, one concept will use basalt fibres instead of glass fibres .

Basalt composites show a 35 % to 42 % higher Young's modulus than E-glass as well as a better compressive strength and flexural behaviour, although a higher tensile strength is found for glass material.[1] The short-beam strength is similar for both materials which confirms that Basalt has good interface adhesion, not worse than the one between E-glass and epoxy matrix.[2,3]

Corecork

The idea that felt can add thickness to a composite without severely impacting the mechanical performance lead to a possible core made from cork. A 2mm layer of cork can be used as a core the same way that felt is used currently. Although the mechanical properties of cork are not very good, the material is deemed interesting enough to test in small scale. It is not expected that the corecork composite will perform the best but findings might help develop new ideas and solutions.

Final list of concepts

Table 4.2 on page 45 shows the final list of concepts that will be tested in small scale. This list is composed from the findings in the previous subsections. It represents the most promising concepts that deserve further investigation.

Based on the abrasion results, all concepts will have an abrasion layer based on aramid or Dyneema fibres. Most concepts will be tested with an aramid wear layer because this material stood out in the abrasion test.

[1] Lopresto, Leone, and Iorio, 2011.
[2] Singha, 2012.
[3] Velde, Kiekens, and Langenhove, 2003.

Concepts with felt as a thin core are the focus for the small scale tests. These composites have a bit more thickness to increase the local bending stiffness while retaining performance in membrane stress situations. Overall the felt concepts are considered to have the highest potential in this application.

Glass fibre will be the main material to be used because of its favourable performance over price ratio. The aramid fibres used in the wear layer reinforce the glass composite with a high tensile modulus and strength. One concept will also be reinforced with expensive carbon fibres. The high stiffness of these fibres makes them very suitable to use in this application but unfortunately a full carbon concept is not possible because of the prohibitively high cost price.

A full aramid concept is selected despite the fact that like a full carbon concept, its cost price would most likely be too high. The aramid specimen will be used as a best case scenario for thin composite concepts to compare against. This provides us with a better reference frame than just comparing against the aluminium plate with twice the mass.

Three additional concepts are added to the list that use the non-standard materials basalt and cork. An aramid/felt/basalt concept is designed to be able to be directly compared to the aramid/felt/glass concept. All glass fibres in the latter layup are replaced with basalt fibres but the basic design is exactly the same.

Two concepts are designed with a cork core, the first has one aramid outer layer while the other is symmetric with two aramid outer layers. Although I do not expected the cork samples to perform the best, it is interesting to see if the flexible thin core brings any advantages to the table.

In table 4.2, Soric TF-2 represents the felt core, a photo can be seen in figure 4.2. The woven materials used here all have a plain weave as shown in figure 4.3. The stitched glass is a type of unidirectional material where two layers of UD glass are stitched together for production purposes. A photo of this material can be seen in figure 4.4.

Table 4.2: List of concepts for small scale testing.

MTD number **Material**	**thickness** [mm]	**orientation** [°]	**weight** [g/m^2]	**ply**
Aluminium	2,4			AL7021-T6
130091	3,2	0/90	500	woven Dyneema/glass
Dyneema/felt/glass		0/90	500	woven Dyneema/glass
		±45	450	stitched glass
				Soric TF-2
		±45	450	stitched glass
		0/90	450	stitched glass
130088	3,0	0/90	170	woven aramid
aramid/felt/glass		0/90	170	woven aramid
		±45	450	stitched glass
				Soric TF-2
		±45	450	stitched glass
		0/90	450	stitched glass
130090	3,2	0/90	170	woven aramid
aramid/felt/carbon		0/90	170	woven aramid
		±45	450	stitched glass
				Soric TF-2
		±45	450	stitched glass
		0/90	400	woven carbon fibre
130141	3,6	0/90	170	woven aramid
aramid/felt/aramid		0/90	170	woven aramid
		±45	450	stitched glass
				Soric TF-2
		±45	450	stitched glass
		0/90	170	woven aramid
		0/90	170	woven aramid
130169	2,3	0/90	170	woven aramid
aramid		0/90	460	woven aramid
		±45	460	woven aramid
		0/90	460	woven aramid
		0/90	170	woven aramid
130247	3,2	0/90	170	woven aramid
aramid/felt/basalt		0/90	170	woven aramid
		±45	490	woven basalt
				Soric TF-2
		±45	490	woven basalt

Continued on next page

Table 4.2 -- *Continued from previous page*

MTD number **Material**	**thickness** [mm]	**orientation** [°]	**weight** [g/m^2]	**ply**
		0/90	490	woven basalt
130142	3,2	0/90	170	woven aramid
aramid/cork/glass		0/90	170	woven aramid
		±45	450	stitched glass
				CoreCork 2mm
		±45	450	stitched glass
		0/90	450	stitched glass
130143	3,7	0/90	170	woven aramid
aramid/cork/aramid		0/90	170	woven aramid
		±45	450	stitched glass
				CoreCork 2mm
		±45	450	stitched glass
		0/90	170	woven aramid
		0/90	170	woven aramid

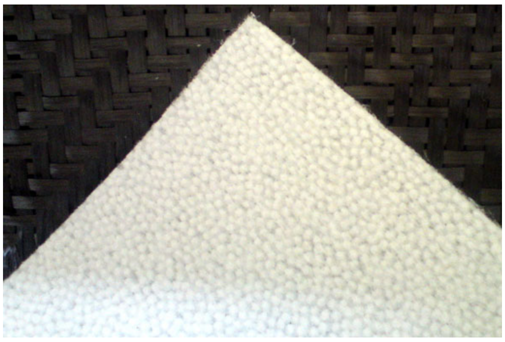


Figure 4.2: Photo of Soric TF felt mentioned in table 4.2.[4]

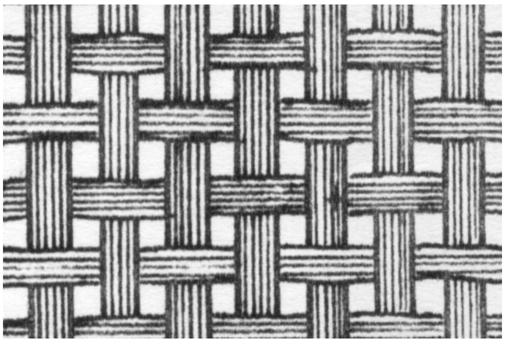


Figure 4.3: Image of a plain weave mentioned in table 4.2.

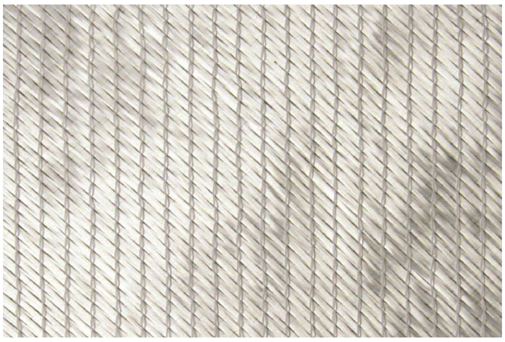


Figure 4.4: Photo of stitched glass mentioned in table 4.2.[5]

[4]Advanced Materials Composites (PTY) Ltd., 2016.
[5]Gurit, 2016.

4.2 Small scale test program

This section discusses the selection of tests to be performed on the small scale concepts from section 4.1. First the requirements are stated and for each requirement a small scale test is designed.

Selection of tests

Chapter 3 listed the requirement set for the composite floor. A summary of this list is given below.

- Weight savings should be at least 43 % of the aluminium plate
- Cost price should be less than €150
- Resistance to wear should be at least 50 % of the aluminium plate
- Resistance to point should be such that no detrimental impact to the mechanical performance occurs
- A thin composite should have a membrane stiffness of 20 % of the aluminium plate

From the literature study we know that, unfortunately, detailed information regarding the container load cases is not available. This makes it difficult to set up tests where a specific design value can be given. Nevertheless, some design targets are stated in chapter 3 that followed from a comparative study with the aluminium floor.

The small scale tests are given in table 4.3 and discussed in further detail in the subsequent subsections.

Testing program

The tests briefly discussed in the previous subsection are listed here in more detail. The full test methods used for qualification are available in annex B.

Weight

The goal of this project is to achieve weight savings on the container floor which makes this factor very important. Theoretical estimates of the composite weights are given in chapter 3. This provides us with a good basis but it is useful and more reliable to measure the weight for each concept.

Table 4.3: Range of tests to be performed on the chosen concepts.

Test	**Importance**
Weight	Weight savings result in fuel savings
Concept costs	Determine whether the concept cost is feasable
Wear and abrasion resistance	Container is exposed to abrasion during handling
Point load resistance	Roller floors cause high point loads
Residual compressive strength	Check for damage tolerance after point loads
Flexural properties	To compare the stiffness of the composite with aluminium. A low stiffness will result in deflections between the rollers that might cause operating difficulties.

The weight and dimensions of each sample are measured. This data is then used to extrapolate the weight to the full scale plate dimensions.

Concept costs

The benefits of the weight reduction are diminished if the price of the composite is too high. Some composites might be too expensive for commercialisation. Each sample will be evaluated for raw material costs, suitable production process and the expected number of units to be produced per year to estimate the cost price so that a trade-off can be made.

Wear and abrasion resistance

Forklifts are used to move the containers in ways they are not actually designed for. Nordisk expects the underside of the floor to be subjected to wear and abrasion as a result of this. An abrasion test gives a good indication which materials are suitable for these conditions.

This test uses a device called a Taber Abraser. This machine is mainly used as a way to determine the sand-ability of materials and does this by rotating a 10 cm by 10 cm sample underneath two abrasive rollers with 1 kg weights attached to them. See figure 4.5 for a schematic of the test. The rotational speed is one rotation per second. This creates a circular abrading pattern on the sample and the abrasion resistance can be quantified by the weight loss.

[6] Taber Industries, 2016.

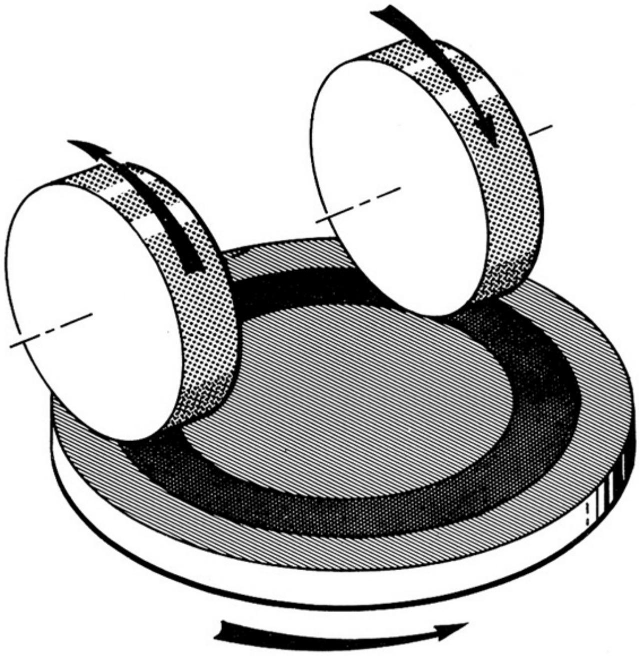


Figure 4.5: Schematic of the Taber abraser test acording to ASTM D4060.[6]

The ASTM D4060[7] standard is used for this test. CS-0 rubber wheels are lined with new P60 grit sanding paper for each sample. The test is run for 1000 cycles and the sanding paper is cleaned after 500 cycles. Suction is present to remove any debris caused by the sanding action from the sanding surface.

Point load resistance

The roller floors in aircraft and on container transport vehicles pose a durability risk for the container floor. These rollers can cause local damage and delamination due high roller point loads. Therefore, a test is performed where a roller shaped steel puncher loads the composite repeatedly with a force of 3000 N per cycle for 500 cycles. The roller is 2 inches (50,8 mm) long and 1 inch (25,4 mm) in diameter which is a common size for rollers used in the industry.

Figure 4.6 shows the test set-up for this test.

[7] ASTM International, 2001a.

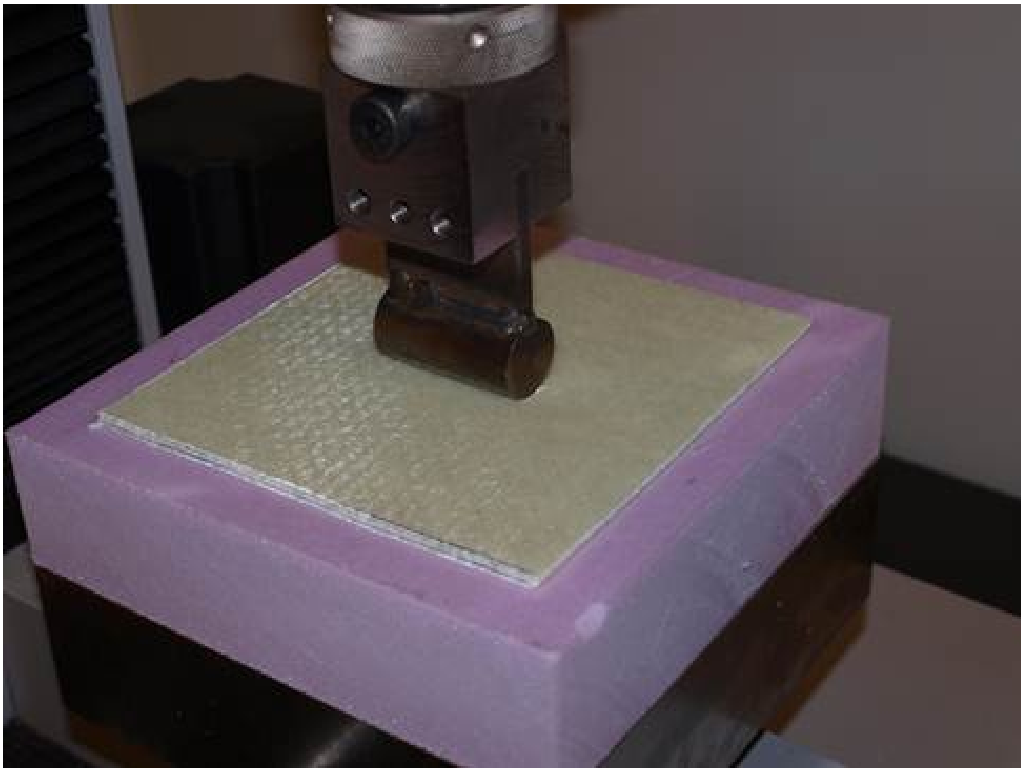


Figure 4.6: Test set-up of the point load test with a roller.

This test is performed at Nordisk facilities. To obtain the required force to be applied to the samples a simple calculation is performed. A container inside an aircraft cargo bay is loaded with at most 1588 kg of cargo and from the literature study we know that the IATA organization expects a maximum loading of three times the container maximum payload.

This equals to 46 735 N distributed over the container floor. If the rollers are spaced at 10 inches (254 mm) then the floor is supported by twenty-five rollers. The resulting load per roller is equal to 1869 N.

3000 N is selected to account for larger roller spacings which would increase the point load per roller. No rolling is applied in this test as the highest expected loads will occur during flight when the container is stationary within the cargo bay.

[8]Instron, 2014.

Figure 4.7: Photo of the ASTM6641 test fixture.[8]

Residual compressive strength

The damage from the point load resistance test is hard to measure quantitatively, as the samples are inspected visually. To account for this, a compression test is performed on both damaged and undamaged samples. This gives a quantitative measure in the damage tolerance of the different concepts after being subjected to a heavy point load. The ASTM 6641[9] standard is used for this test with specimens measuring 140 mm by 12 mm. See figure 4.7 for a photo of the compressive test fixture.

Flexural properties

To assess the mechanical properties of the concepts, flexural tests are performed. Samples are cut and tested according to ISO 14125[10] (three point bending, see figure 4.8). The samples are rectangular and measure 150 mm in length by 15 mm in width. Distance L in figure 4.8 is 120 mm, R_1 is 5 mm and R_2 is 2 mm. The thickness of the samples is given in table 4.2.

Samples that have an abrasion resistant layer are tested with this side in

[9] ASTM International, 2001b.
[10] ISO, 1998.

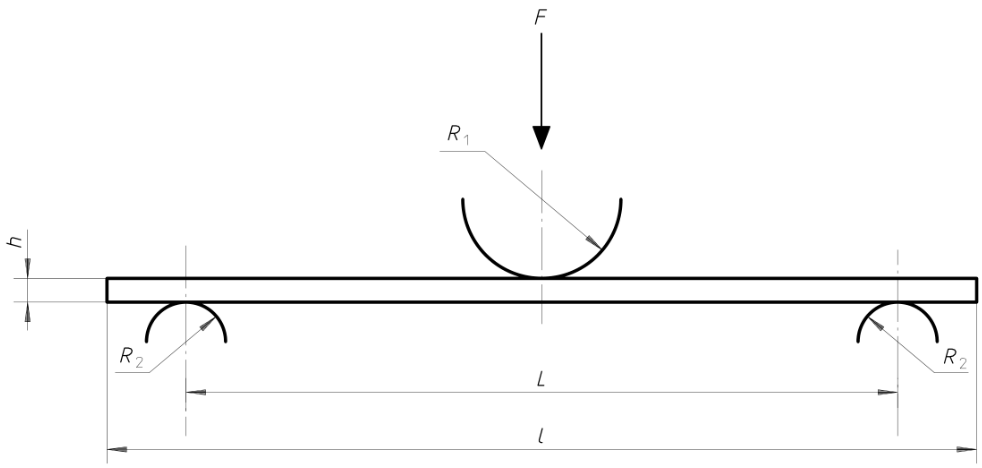


Figure 4.8: Schematic of three point bending from the ISO14125 document.[11]

compression as this matches the expected load case when the material is suspended between two rollers.

Requirements document

To have a clear understanding between DSM and Nordisk about what tests are going to be performed, I have created a small scale test requirements document. This states the tests, standards and applicable requirements that are agreed upon. This document can be found in annex B.

[11] ISO, 1998.

4.3 Small scale test results

This section will discuss the results of each test performed as described in section 4.2. Individual test results will be given and discussed first and an overview of the results can be found in table 4.7 on page 63.

Weight

All composite concepts were designed towards the design requirement of a 43 % weight saving from chapter 3. This means that they will inherently have a lower weight than the aluminium plate. Some variation between the composites is to be expected as the different plies have a different density, resin absorption and a discrete thickness.

The full aramid concept is the lightest composite mainly due to the low density of aramid fibres. The differences, however, are small and the majority of the felt and cork concepts are also lightweight with an average weight of 7 kg, less than half of the aluminium plate of 14,1 kg.

Concept costs

Several parameters are combined to obtain a reasonable estimation of the production costs for each concept. The cost price for each concept can be found in table 4.7. Section 5.4 gives more detail on the production methods and price calculations. The parameters used in the cost calculation are:

- Fibre lay-up
- Resin
- Number of units produced per year
- Production process
- Return of investment of the mould in years

Outliers are the aluminium design that costs just €65,- and the full aramid concept that is €251,-. It is important to consider that the weight difference between the concepts has a great effect on the operational costs and the cost price of the plate itself is marginal compared to the total lifetime costs.

Wear and abrasion resistance

Many samples have the same wear layer so a few tests are sufficient to determine their abrasion resistance. The best performer is the aluminium sample, which is expected as aluminium has a relatively high hardness compared to composites. Individual fibres may have a high hardness but the composite hardness is compromised due to the presence of a relatively soft matrix.

The aramid lined concepts perform second best, all three tested aramid specimen achieved roughly the same results. The results support the use of aramid as a wear protection layer. The Dyneema concept performed slightly worse in this test, the mixed Dyneema/glass weave was grinded of quicker. This probably has to do with the poor adhesion of resin to Dyneema fibres. Because of this, the resin is easily damaged and removed with abrasion which in turn reduces the protection the Dyneema offers. If the fibres are not supported, the abrasion resistance is diminished.

Point load resistance

The point load test is tough on the composite samples due to the risk of local damage and delamination. Situations where the composite has to cope with point loads are preferably avoided by composite engineers. On the tested samples, local delamination and/or fibre breakage is often visible. An overview of the point load performance of the concepts is given in table 4.4.

Figures 4.9 to 4.13 show the damage on some of the samples after the point load test.

The aluminium plate experienced only a minor indentation in this test and shows no visible cracks or damage. The strength is not expected to be impacted by the point load.

The aramid/felt/glass, aramid/felt/carbon, aramid/felt/aramid and full aramid concepts are considered the best composite performers. Minor delamination spots are visible on the aramid front side for all four concepts. A spread out delamination can be seen on the back side of the glass felt concept. This spot is not considered to have severe delamination and is not expected to dramatically impact the mechanical performance.

The aramid/felt/carbon and aramid/felt/aramid concept are expected to have a similar spread delamination on the back side but the opaque carbon and aramid fibres make this impossible to see. The full aramid specimen was slightly indented but shows no delamination on the back side. The

Table 4.4: Results of point load test on specimen.

Sample	**Description of visual damage**
AL7021-T6	No damage on the front side, very little indentation (figure 4.9)
Dyneema/felt/glass	A lot of delamination in the Dyneema layer on the front side, minor spread out delamination on the backside (figure 4.10)
aramid/felt/glass	Little delamination on the front side, minor spread out delamination on the backside (figure 4.11)
aramid/felt/glass (glass on front)	Cracks and delamination on the front side, no visible delamination on the back side (figure 4.13)
aramid/felt/carbon	Little delamination on the front side, no visible delamination on the back side (figure 4.12)
aramid/felt/aramid	Little delamination on the front side, no visible delamination on the back side
aramid/cork/glass	Delamination on the front side, large indentation
aramid/cork/aramid	Delamination on the front side, small indentation
aramid	Little delamination on the front side, very small indentation
aramid/felt/basalt	Delamination on the front side, no visible delamination on the back side

mechanical performance of this specimen is expected to be impacted the least by the point load damage out of all of the tested composites.

The Dyneema/felt/glass concept has extensive visible delamination present which is expected to have a larger impact on the mechanical performance than the aramid layered concepts. This reinforces the choice for aramid as a wear layer.

Both cork specimens show delamination on the front side combined with an indentation. The flexible cork core is likely the cause of the increased delamination damage compared to the other samples. The basalt concept also has opaque fibres which do not allow proper visual inspection of the back side of the sample. The front side shows delamination comparable to

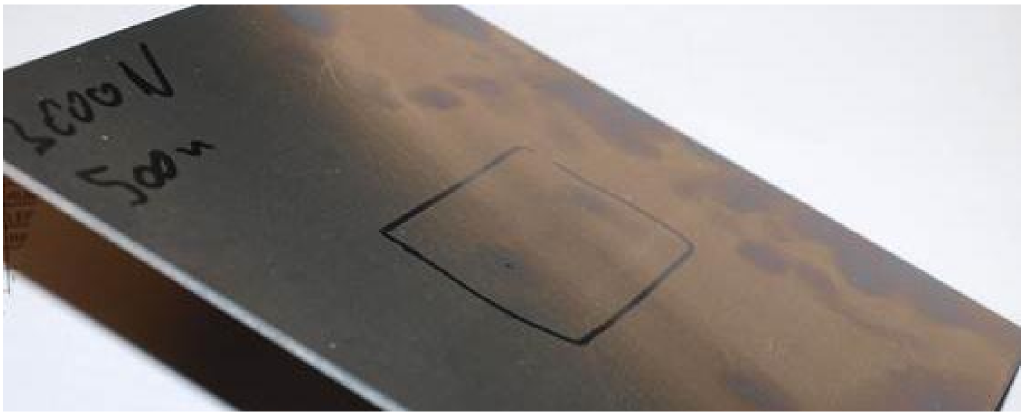


Figure 4.9: Damage after the point load test on the aluminium sample.

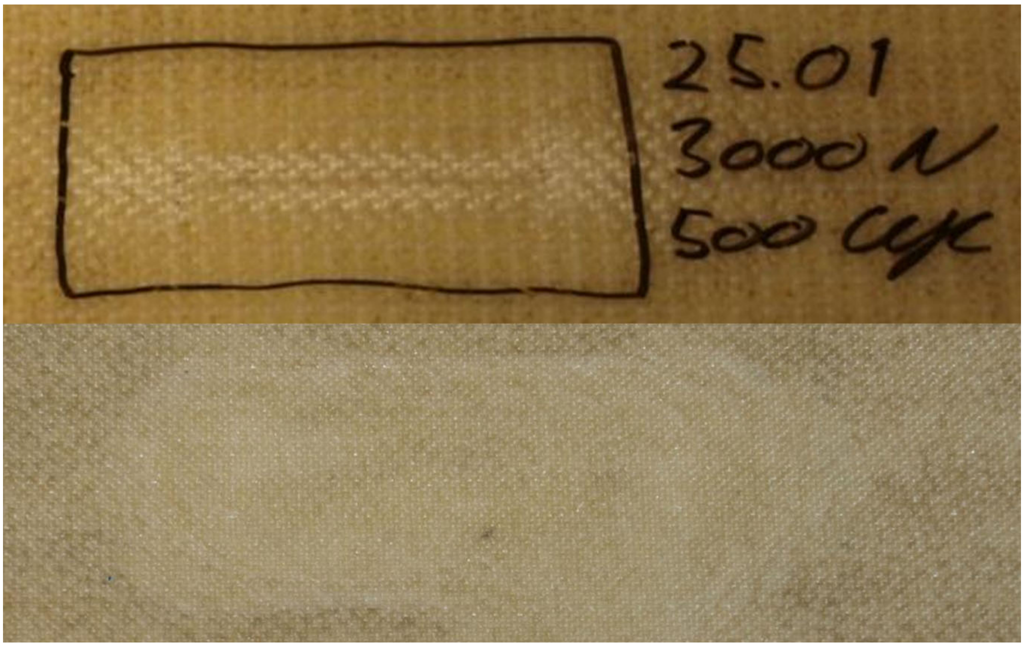


Figure 4.10: Damage after the point load test on the Dyneema/felt/glass sample. Top part is front side, bottom part is the back side.

the other aramid felt concepts.

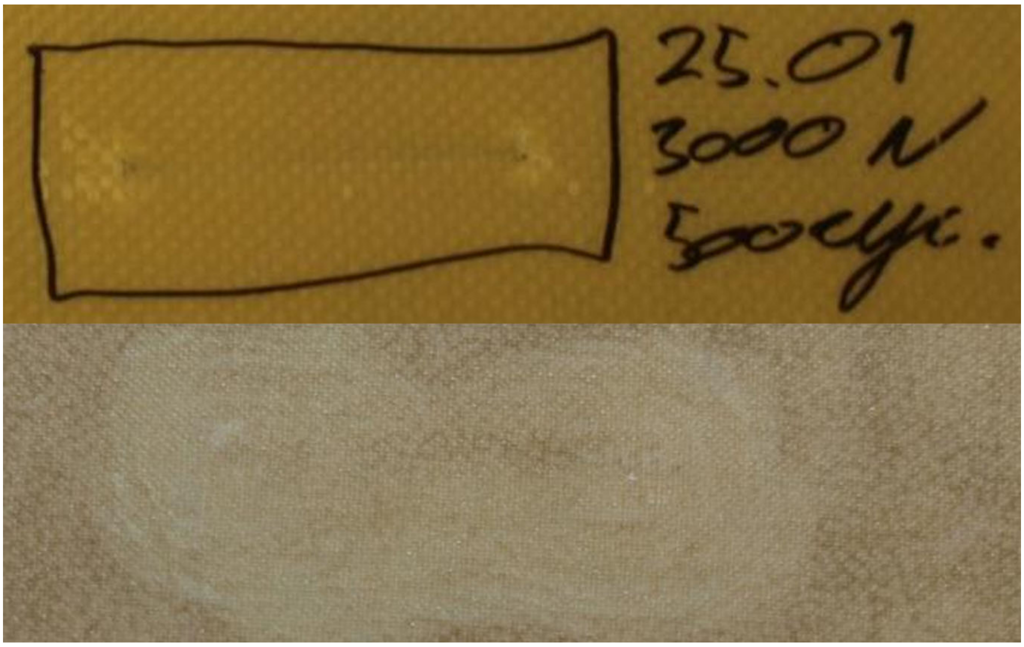


Figure 4.11: Damage after the point load test on the aramid/felt/glass sample. Top part is front side, bottom part is the back side.

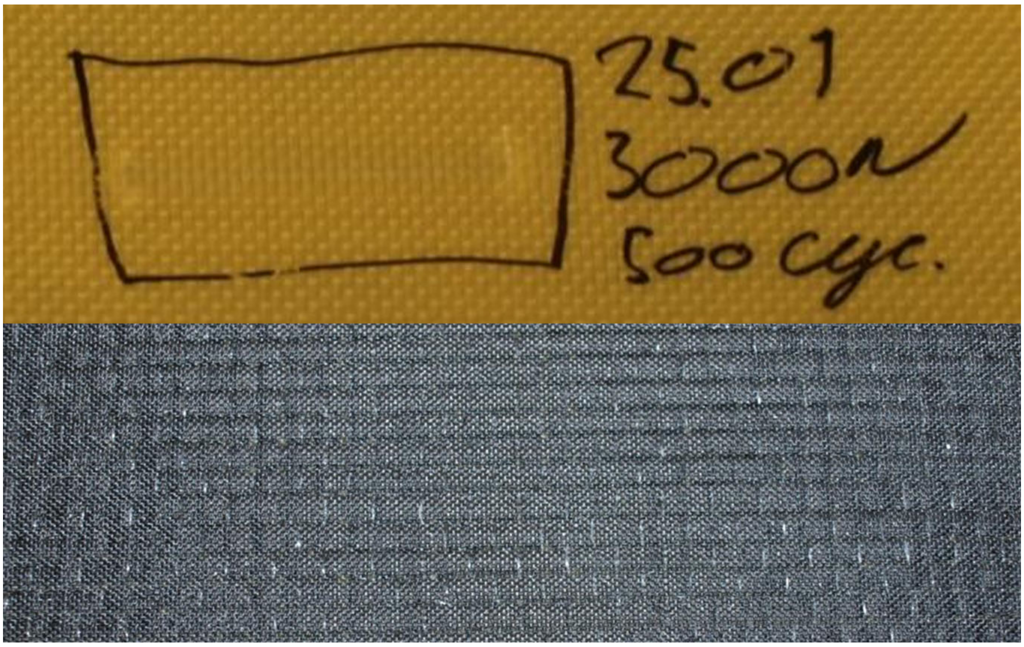


Figure 4.12: Damage after the point load test on the aramid/felt/carbon sample. Top part is front side, bottom part is the back side.

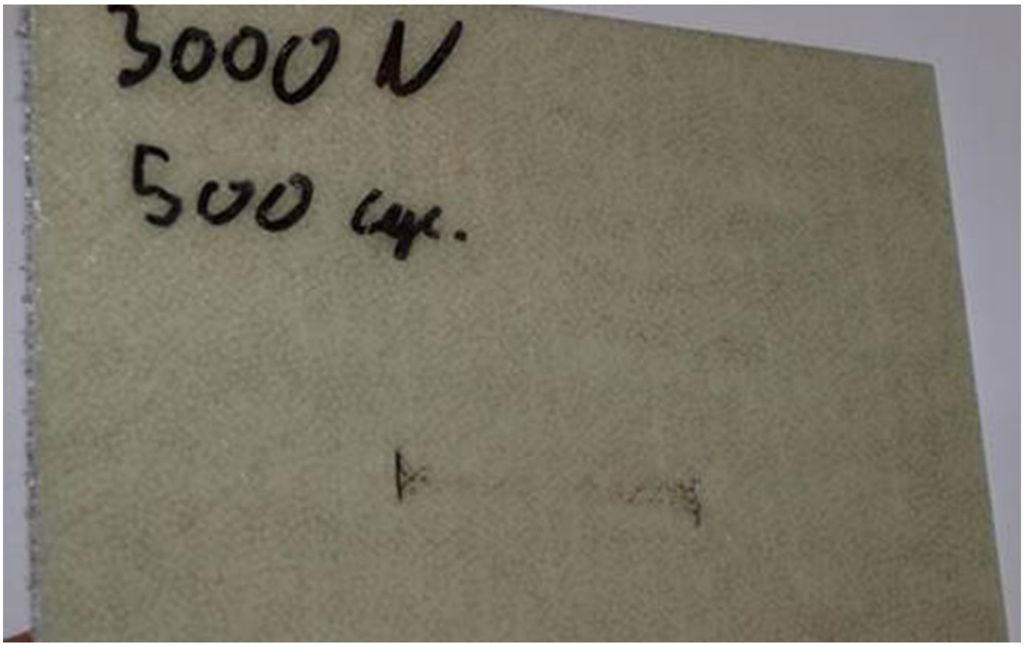


Figure 4.13: Damage after the point load test performed on the glass side of the aramid/felt/glass sample.

Table 4.5: Results of compression testing on undamaged and damage specimen.

Sample	Undamaged [MPa]	Damaged [MPa]	Residual [%]
aramid/felt/glass	111	78	71
aramid/felt/carbon	97	76	78
aramid	107	98	92

Residual compressive strength

Due to logistical reasons it was only possible to test three concepts for compression: the full aramid concept and two aramid/felt concepts with glass and carbon reinforcements. Damaged and undamaged samples were cut from the same specimen and are subjected to the test as described in section 4.2. The results can be found in table 4.5.

The undamaged and damaged compressive stiffness was found to be unchanged for all three specimen which is expected according to composite theory. As long as the damage is not too extensive, undamaged fibres are able to redistribute the loads so that the overall stiffness stays the same. Local damage will impact its strength because of stress concentrations that can lead to early failure.

The full aramid sample performed best with 92 % residual compression strength. The aramid/felt/glass and aramid/felt/carbon sample performed worse than the aramid sample and retained 71 % and 78 % of their original compressive strength respectively. One might expect the absolute compressive strength of the aramid sample to be less due to the lower bending stiffness of the individual fibres compared to glass or carbon fibres. However, this is not the case since the felt used in the other two samples lowers the material strength.

Overall the results are satisfactory as the visual damage is extensive but this test shows the damaged composites samples are still capable of carrying loads. Note that the damage spreads the entire width of the tested specimens which makes this a worst case scenario.

Flexural properties

The results of the flexural tests can be found in table 4.6.

Table 4.6: Results of flexural testing on specimen.

Sample	flexural stiffness [GPa]	flexural strength [MPa]
Dyneema/felt/glass	13,1	255
aramid/felt/glass	17,5	330
aramid/felt/carbon	22,9	279
aramid/felt/aramid	20,7	207
aramid/cork/glass	13,5	107
aramid/cork/aramid	14,0	113
aramid	26,1	251
aramid/felt/basalt	19,7	220
AL7021-T6	75,9	575

The aluminium reference was tested at a flexural modulus of 76 GPa and a flexural yield strength of 575 MPa. The aluminium stiffness and strength values are higher than any of the composite concepts as was already predicted in the theoretical approach chapter.

Several composite concepts do not perform well in this test. The Dyneema/felt/glass specimen and the two cork concepts have a significantly lower stiffness than the other composites. For the latter two, the low modulus of the cork core is the main cause of this effect as the similar felt concepts perform much better. The cork concepts also have a very low strength for the same reason. The Dyneema/felt/glass specimen has an acceptable strength.

The concepts that stand out are the aramid/felt/glass and full aramid concepts with a stiffness of 18 GPa and 26 GPa and a strength of 330 MPa and 251 MPa respectively. The concept with basalt fibres offers a slightly higher stiffness of 20 GPa than the aramid/felt/glass concept but has a substantially lower strength of 220 MPa. This is expected since Basalt fibres have a better stiffness but worse tensile strength, see section 4.1.

The aramid/felt/basalt and aramid/felt/aramid concepts do not offer worthwhile benefits over the aforementioned concepts, considering the fact that more expensive fibres are used in these composites.

Results

The combined results of the performed tests are given in table 4.7 and a summary of the results as discussed in this section is given below.

The aluminium design performs best in all of the tests. This is expected since the weight of the aluminium concept is twice that of the composite concepts. Saving weight is expected to result in a loss of mechanical performance but as long as it is sufficient for the application, this is not an issue.

The full aramid concept performed best compared to the other composites but has a high cost price of €251. The concept is light and offers good wear and point load resistance. Its wear resistance is 60 % of the aluminium which satisfies the requirement and it has a 92 % residual compression strength after point load damage which means that there is no detrimental impact to the mechanical performance. It offers a high stiffness and moderate strength.

The runners up are the aramid/felt/glass and aramid/felt/carbon concepts. Both have sufficient point load resistance with a residual compression strength of 71 % and 78 % respectively. Their wear is similar to the aramid concept since their wear layers are identical. The stiffness of both concepts is lower than the full aramid stiffness but the strengths are higher. The glass concept offers the best strength while the carbon concept offers a better stiffness. The glass concept is the cheapest concept at €122 while the carbon version is substantially more expensive at €164.

The aramid/felt/aramid and aramid/felt/basalt concepts do not offer worthwhile benefits over the aforementioned concepts. Their price is higher than the aramid/felt/glass concept but no notable performance increases are observed.

The Dyneema/felt/glass concept is not able to match the wear and point load resistance of the aramid concepts in general. Its wear resistance is only 25 % of the aluminium and severe delamination is visible after the point load test. The flexural stiffness is poor compared to the other composites.

The cork concepts did not bring anything new or interesting to the table. Their performance is poor over entire range of tests and will not be studied further.

Table 4.7: Results small scale testing

Sample	**Weight**	**Point load**	**Residual compressive strength**	**Flexural properties**		**Abrasion resistance**	**Price**
	[kg]	scale [1–10]	[%]	stiffness [GPa]	strength [MPa]	Weight loss after 1000 cycles [g]	[€]
Dyneema/felt/glass	7,4	5	-	13,1	255	1,28	140
aramid/felt/glass	7,0	7	71	17,5	330	0,51	122
aramid/felt/carbon	6,9	8	78	22,9	279	0,44	164
aramid/felt/aramid	6,9	6	-	20,7	207	-	149
aramid/cork/glass	6,7	5	-	13,5	107	-	122
aramid/cork/aramid	6,7	7	-	14,0	113	-	149
aramid	5,9	9	92	26,1	251	0,55	251
aramid/felt/basalt	7,6	6	-	19,7	220	-	145
AL7021-T6	14,1	10	-	75,9	575	0,33	65

5 Full scale approach

Chapter 4 gives the results of the small scale tests which can be used to further narrow down the number of concepts suitable for full scale testing. In the previous chapter, a list of small scale concepts was selected based on Chapter 3 and a testing program was set up. Composite specimens were made and run through all of the small scale tests.

The results are summarised in section 4.3 to allow for an easy comparison of the composites and aluminium test performance. Section 5.1 describes the concept selection process and lists the concepts selected for full scale testing. The selection is based on the data generated in chapter 4.

Section 5.2 discusses the full scale test program. The full scale composite specimens will be evaluated for their potential of application in air cargo containers based on these tests. Section 5.3 describes the process of producing the full scale plates and considers required changes in the assembly process of the plate compared to aluminium.

The final section will present the results of the full scale tests and the accompanying conclusion.

5.1 Full scale concept selection

This section discusses the full concept selection process. Data and insight gained from chapter 4 is used to make a decision on the test concepts and to shape the test program.

The small scale tests have three clear winners which makes this selection much easier. Two concepts will be selected for the full scale tests due to logistics.

The full aramid concept performed best compared to the other composites but has a high cost price of €251 which makes it impossible to use in air cargo containers from a business perspective.

The aramid/felt/glass and aramid/felt/carbon concepts scored comparably in the small scale tests but overall slightly worse than the full aramid concept. The glass concept is the cheapest concept at €122 which is comfortably less than the €150 cost price requirement. The carbon version is substantially more expensive at €164 which places it just outside of the requirement.

Considering all facets of the project, the aramid/felt/glass concept is the best potential candidate for application in air cargo containers and is to be tested in full scale. The second concept is full aramid which will serve as a composite best case scenario reference. If the aramid plate fails the full scale tests then a complete redesign of the composite is probably necessary. If one composite fails and the other does not, we can use this information to learn which property is critical and needs improvement.

5.2 Full scale test program

Because the small scale tests were set up to be comparative, it is difficult to assess the composites' real life performance. Instead, their performance was compared to the aluminium reference sample. The full scale tests make it possible to measure the real life performance by implementing the plates in a test container.

Representative tests that mimic actual container handling can then be performed. These show whether or not the composite floors are able to sustain the expected load cases encountered in a container's service life.

It is necessary to have a clear overview of the bottom plate costs in order to make decisions about the feasibility of the concepts. A model is created to estimate the cost of production of one plate as a function of the number of units produced per year and which production technique is used.

To show the benefits of a new composite bottom plate in air cargo containers, a comparative LCA is performed by a DSM professional. The composite plate is compared with the current aluminium plate to determine which is more damaging to the environment overall. The results of this study are analysed in section 5.4.

Performance tests

In this section the tests that shall be performed on the full scale prototypes are listed. Many full scale container tests are described in FAR (Federal Aviation Regulations), EASA (European Aviation Safety Agency) and IATA (International Air Transport Association) manuals. The tests that are deemed most critical to the container bottom plate are bundled in the test program. Nordisk and DSM have decided on these tests together as a representable selection for the actual container handling and loads.

Base strength test

This test shall be carried out to prove the ability of the container base to withstand the maximum operational loads that may be experienced during handling and transportation. The container under test shall rest on the aircraft loading system or its equivalent and the container floor shall be loaded to equal three times the container maximum payload of 1588 kg.

Cyclic test

This test shall be carried out to prove the ability of the container base to withstand the maximum operational loads that may be experienced during handling. The container under test shall be uniformly loaded to maximum gross weight and cycled one hundred (100) times over the aircraft loading system or its equivalent.

Bridging and Cresting test

This test shall be carried out to prove the ability of the container to traverse from one item of ground or aircraft handling equipment to another when the level of the conveyor surfaces are not in the same plane. At the point where the container balances on the end of the higher surface the entire load is supported by one row of rollers.

Base deflection test

This test shall be carried out to prove that when a fully loaded unit is traversed over ground handling equipment satisfying the requirements of AHM 911, no part of the underside of the container base shall make contact with the supporting structure, walkways, etc. on the ground equipment.

Requirement document

Similar to the small requirement document, a large scale requirement document is created. This states the tests, standards and applicable requirements that are agreed upon. This document can be found in annex C.

Price and production

In order to assess the viability of the two composite floors under consideration, a business case must be build for both. Performance tests like described in the previous section are vital but information regarding the production costs and possible production challenges are equally important.

A range of production methods is considered for both concepts and combined with different process parameters this makes it possible to reliably estimate the cost price.

LCA

The high cost price of the composites is compensated by their accompanied weight savings. This leads to containers with a lower tare weight which will allow airliners to increase their fuel efficiency. The result is beneficial to the environment and saves the airliner fuel costs. Both advantages will be considered for the composite plates compared the aluminium plate.

5.3 Prototype production and assembly

This section explains and shows how the composite full scale specimens were produced and what considerations were necessary to assemble the plates into a container to prepare for the full scale tests.

Prototype production

Vacuum infusion is used as the production method, this is a very flexible process suited for small series production. Only two plates are produced, making this a suitable process. Since the plates are flat, a glass plate can be used as a mould so that there is no need for expensive tooling. They measure 1,44 by 1,412 m and are just small enough to be produced on a 1,5 by 1,5 m glass plate. Below the required steps for the production of one plate will be summarised.

Production is started by cleaning the glass plate with acetone and applying Honey Wax. Several layers of wax are applied to ensure proper coverage and easy de-moulding. This will prevent the resin from sticking to the plate so that the product can be taken off easily without damage.

The next step is the positioning of the vacuum stack on the glass plate. This stack consists of all the materials required for an infusion: fibres, peel ply, flow mesh, tubes and vacuum foil. First, dry fibres are cut to size and laid down onto the glass plate in the right order. Then, a layer of nylon peel ply is placed which prevents the resin from sticking to the next layer: the flow mesh. The flow mesh helps the flow of the resin over the fibres so that impregnation through the thickness is possible.

Spiral tubes are placed on top of the mesh through the middle of the plate and on both edges, parallel to each other. To seal the package, a piece of vacuum foil is placed on top and is fixed at the mould edges with tacky tape. The centre spiral tube will form the inlet where the resin is sucked into the bag by the vacuum. The outer tubes are connected to the vacuum pump to reduces the pressure inside the bag so that all layers are compressed and the resin can be sucked in.

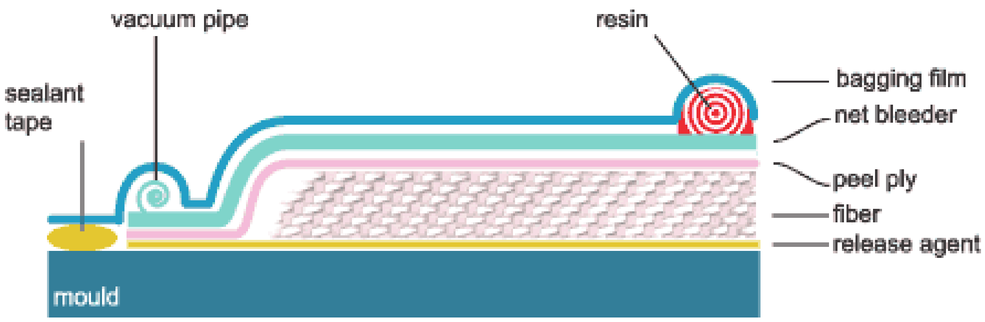


Figure 5.1: A schematic of the through the thickness vacuum infusion process used for the full scale prototype production.[1]

The resin is mixed and the can is placed near the inlets so that the hoses connected to the spiral tubes in the vacuum stack can be lowered in the can. The process is started by opening the inlet so that resin starts flowing through the mesh. The mesh will fill up with resin and subsequently will impregnate the fibres below the mesh through the thickness.

[1]Diatex SAS, 2016.

When the whole bag is full of resin, the inlet is closed and the vacuum level is decreased. This is done to prevent excessive resin extraction from the product, preventing the formation of dry spots. Also, small air or gas inclusions will decrease in size with an increasing pressure. The product is then left to cure overnight. The next day the vacuum foil, flow mesh and peel ply can be removed and the final product can be released from the glass plate.

Figure 5.2: Photo of the full aramid full sized test specimen produced in the DSM laboratories.

The weight of the full size plates is measured to compare against earlier weight data. The full aramid plate has a measured aerial weight of 3,03 kg/m^2 compared to 2,90 kg/m^2 from the small scale tests. The total weight of the plate cut to dimensions suitable for the prototype base is 6,2 kg.

The aramid/felt/glass concept has a measured aerial weight of 3,89 kg/m^2 compared to 3,44 kg/m^2 from the small scale tests. The total weight of the plate cut to dimensions suitable for the prototype base is 7,9 kg.

The aramid concept is 0,26 kg heavier than the small scale sample indicated and the aramid/felt/glass concept is 0,91 kg heavier than the small scale sample indicated.

Prototype assembly

Testing on the small scale prototypes was performed without any assembly structure. The full scale prototypes, however, will be tested while assembled in a container. This means that the composite plates have to be attached to the aluminium extrusion frame. The current aluminium bottom plate is fastened with rivets through holes in both the plate and extrusion frame.

Because drilling holes in the composite causes local stress concentrations which might jeopardize the structural integrity of the whole plate, it is preferred to use a bonded connection. Therefore, different bonding agents have been tested to determine their bonding strength and compare the results to the rivets that are currently in use.

Three types of adhesive are selected and tested based on availability in the labs. They are:

- Plexus MA425
- Loctite 9466
- Scotchweld DP410

Samples are created and tested according to the double lap-shear standard ASTM D3528[2]. A 5 mm thick glass composite is produced and cut into rectangular pieces. Two of these pieces are then butt joined together with a lap joint using two 1 x 1 inch aluminium samples. The aluminium and composite are sanded with a rough P80 grit sanding paper and cleaned with acetone. Then a square piece of aluminium is bonded on each side overlapping the butt joint of the two glass plates.

When the samples are fully cured, they are tested using a tensile test machine. The force on the sample is increased until failure occurs and the force and displacement are measured during the test.

Results of the double lap-shear test for the adhesives can be found in figure 5.5 and test data on the rivets can be seen in figure 5.6. Please note that for clarity only one (representable) sample data set is selected and plotted per performed test.

[2] ASTM International, 2008.

The adhesive surface area is $645mm^2$ and for the used bonding agents the maximum load is 9858 N 14 331 N and 16 969 N respectively. Calculating the shear strength with:

$$\tau = \frac{F}{A} \tag{5.1}$$

Gives us shear strengths of 15,3 MPa, 22,2 MPa and 26,3 MPa respectively. If we want to compare the bonding technique to the rivet technique, we have to determine the rivet spacing. Spacing of the rivets is 3 inches (76,2 mm) apart and the distance from the centre hole to edge is $10,5mm$.

From figure 5.6 on page 74 it can be seen that the maximum rivet load is 9175 N. This force works on an area of 76,2 mm by 21 mm equal to $1600mm^2$. Calculating the shear strength with formula (5.1) gives a shear strength of 5,7 MPa. Please note that this strength will increase if a smaller rivet spacing is used but since the spacing is fixed for this particular application, we can make the comparison between these numbers.

Since the shear strength of all tested bonding agents is higher than the rivet shear strength it is possible to bond the prototypes to the aluminium extruded frame without a loss in connection strength. An additional advantage of doing this is the better load distribution through the adhesive layer compared to the rivet connection. This will prevent stress concentrations at the edges of the composite plate.

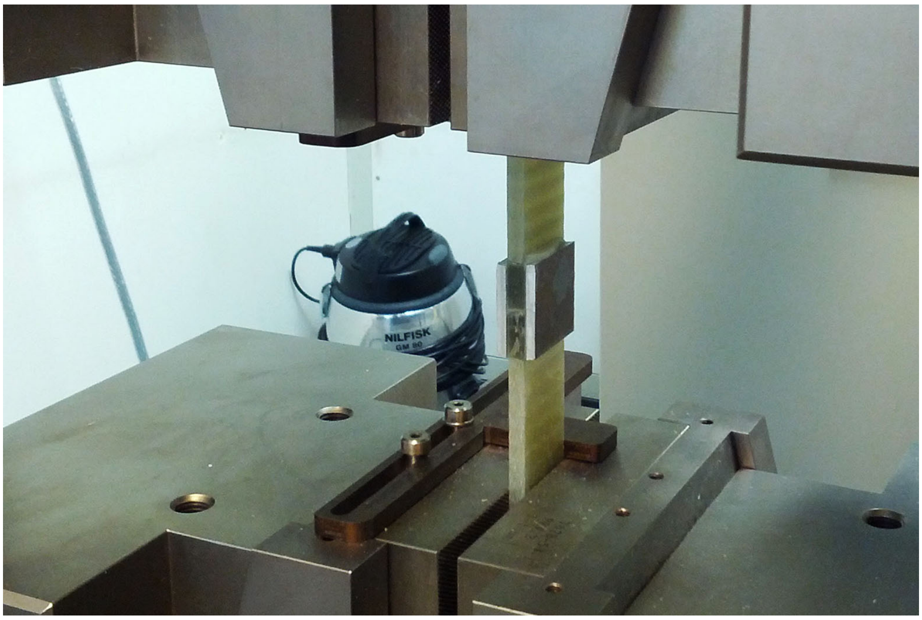


Figure 5.3: Lap shear specimen in test equipment before the test.

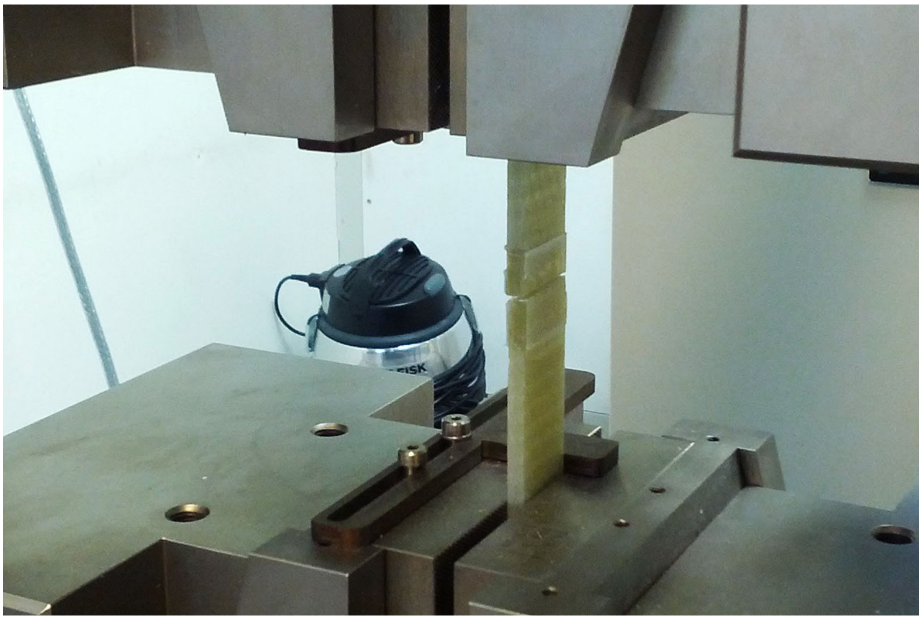


Figure 5.4: Lap shear specimen in test equipment after the test.

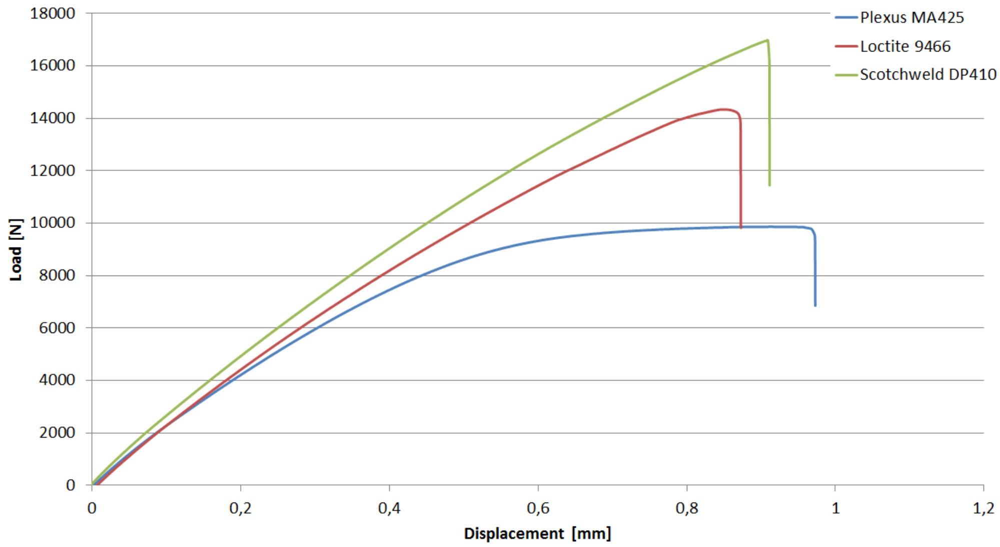


Figure 5.5: Double lap shear test data for bonded samples.

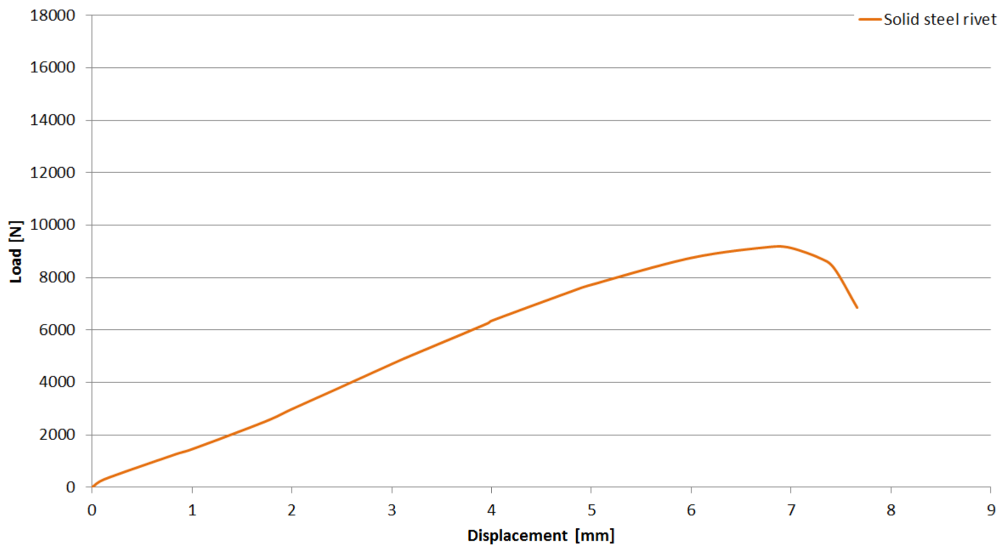


Figure 5.6: Lap shear test data for solid rivet sample.

5.4 Full scale test results

Due to time constraints not all of the performance tests are executed. The cyclic test is expected to be the most useful in the comparison between an aluminium base sheet and a composite version. Therefore this test is preferred above the other considered tests.

The full test document can be found in annex G on page 159. This document further explains the test equipment and methods used.

Also discussed in this section are important factors such as price, production methods and life cycle analysis. These are important considerations for a complete trade-off between the composites and the aluminium.

Cyclic test

The cyclic test is performed at the Nordisk site in Norway, where a special testing rig is designed and build by Christian Arnesen. A CAD drawing of this rig can be seen in figure 5.7.

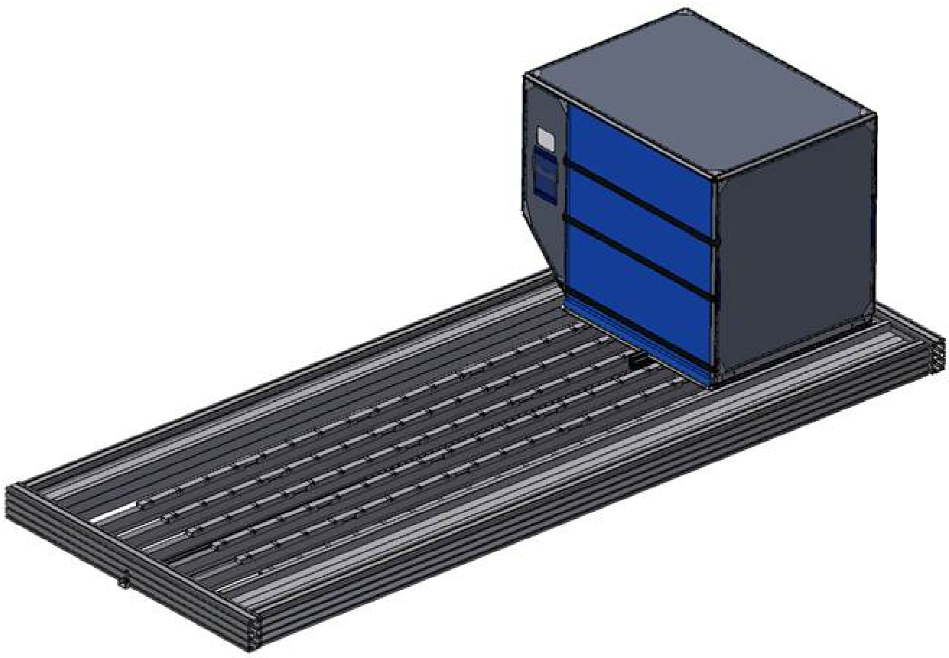


Figure 5.7: CAD drawing of the dynamic testing rig to simulate damage and wear on an air cargo container bottom plate due to transportation rollers used in aircraft.

A photo of the actual rig with an air cargo container placed on the rollers can be seen in figure 5.8. Since the upper structure is not needed to test the floor panels, a simpler base is used for the test. A photo of a prototype base on the test rig can be seen in figure 5.9.

Figure 5.8: Photo of an actual LD3 cargo container on the dynamic testing rig.

The full scale prototypes are produced in the DSM Composite Resins lab (see section 5.3). The plates are then shipped to Nordisk so that they can be assembled into a prototype base for testing.

In section 5.3, a bonding test is performed to check the bond strength between the aluminium and the composite when using different adhesives. For the connection in the prototype bases, a bonding agent is advised by DSM.

Cyclic test specifications

For the cyclic test a container base – without its upper structure – is fitted with a baseplate and loaded with a lifting bag filled with 1500 kg of sand.

Figure 5.9: Photo of a prototype base on the dynamic testing rig to simulate damage and wear on an air cargo container bottom plate due to transportation rollers used in aircraft.

This makes loading and unloading easy, see figure 5.9. The loaded base is then pulled 7,3 m over a roller floor similar to those found in aircraft. At fixed intervals the load is removed so that the underside of the base can be checked for damage.

The first base has a 2,5 mm thick solid aluminium sheet of alloy 7021-T6, the second base has a 2,3 mm monolithic Kevlar sheet and the third base has a 3,2 mm aramid/glass/Soric sandwich sheet. All edge rails were made of aluminium alloy 7003-T5/T6 and these were bonded onto the sheets using 3M DP410 as advised by DSM (see section 5.3).

The base is attached to a linear movement carriage to allow for an automated back and forth traversing motion over the roller bed. One cycle is defined as a complete forward and backward movement on the 7,3 m base.

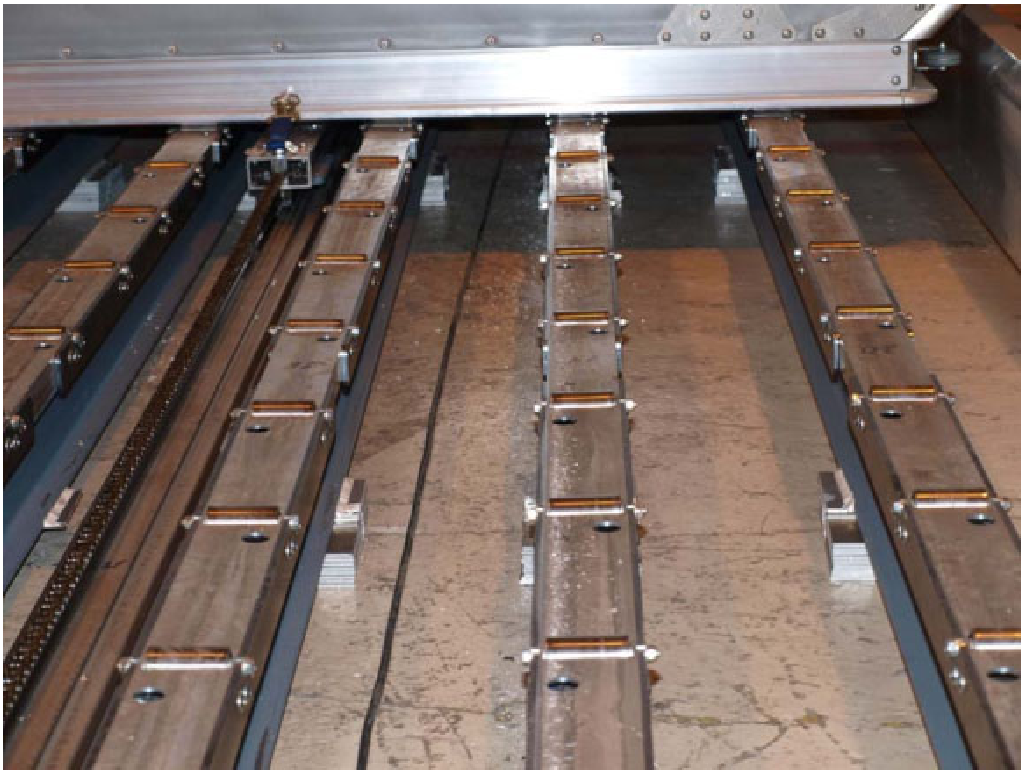


Figure 5.10: Close-up of the rollers in the test rig.

Aluminium 7021-T6

The reference aluminium base plate is put to the test first. The rig is cycled back and forth over the rollers and crack origination and growth is checked at repeating intervals. As the test progresses, the check up intervals are increased to speed up testing. Around 160 N of force was required to pull the container base over the roller system.

The first crack is detected at the 7854 cycle mark, it is 21 mm long and grows to 260 mm over the course of 5000 cycles. Through thickness cracks start to become visible around the 12 500 cycle mark and the test is stopped at 13 000 cycles due to the extensive damage. A total of five cracks have developed. The maximum measured indentation of the plate is 0,78 mm.

Nordisk indicated that the results from the reference test satisfy the expectations based on real life experience. This means that this test is suitable to compare the composite concepts to the aluminium reference.

Figure 5.11: Visible wear lines where the rollers and structure made contact with the aluminium plate.

Figure 5.12: Visible crack in the aluminium plate after testing.

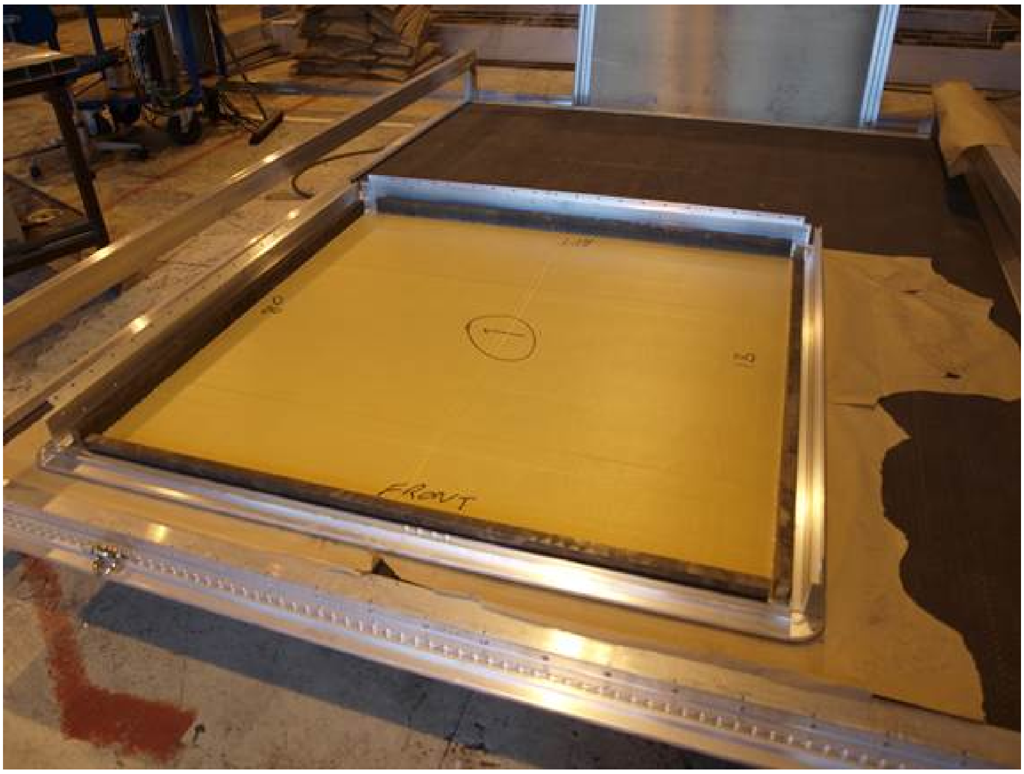


Figure 5.13: The aramid plate placed in the aluminium frame.

Full aramid

Figure 5.13 shows the aramid plate attached to the aluminium frame, ready for testing.

The aluminium plate in the previous test required 160 N of force to move the container base over the rollers. The aramid composite container requires two men to assist pushing it over the rollers so the required force is much greater. The stiffness of the plate is not high enough which caused the material between two rollers to deflect. It is hypothised that the plate hit the metal between the rollers due to the high deflections (see figure 5.10) which resulted in much higher friction forces.

The deflections between the rollers also make it more difficult to move the container due to continuous deformation of the plate and the resulting rising and lowering of the load locally. This is the reason why the plate shows thick black friction lines on the underside (see figure 5.14).

The monolithic aramid plate only lasted 600 cycles until an indentation of 0,71 mm was measured. Clear wear is visible on the locations where the rollers contact the plate in figure 5.15. Cracks are not expected in this material due to the tough nature of the fibres and were not observed indeed. However, local delamination and wear is visible in the plate.

It is clear that the difficulty of operation of this plate on the roller system makes it unsuitable for use in air cargo containers.

Figure 5.14: Visible wear lines where the rollers and structure made contact with the aramid plate.

Figure 5.15: Close-up of the wear due to the rollers and structure on the aramid plate.

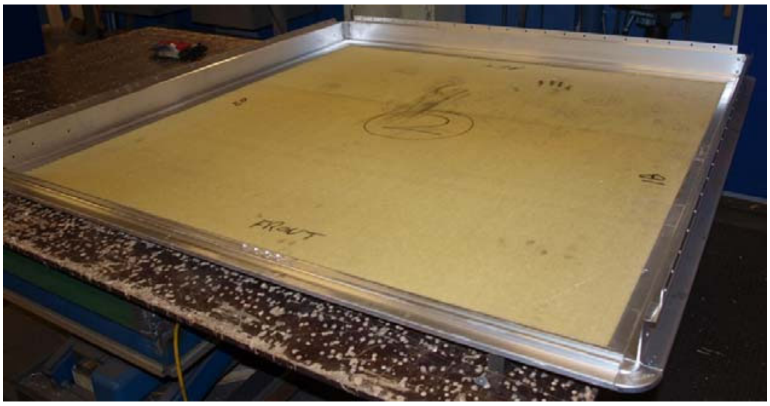


Figure 5.16: The felt plate placed in the aluminium frame.

aramid/felt/glass

Figure 5.16 shows the second composite plate – the aramid/felt/glass concept – attached to the aluminium frame, ready for testing.

This plate is tested up to 800 cycles. At 600 cycles the indentation is measured as 0,7 mm and the felt core is exposed due to local damage. Clear wear is visible on the underside of the plate similar to that of the full aramid concept.

The stiffness of this second composite is better than the aramid plate although not at the level of aluminium. The higher stiffness was expected to deliver better deflection performance on the roller system. Unfortunately, it is not sufficient to prevent the excessive deflection between the rollers.

This lead to the same problem that the full aramid plate experienced, making it difficult to move the container on the roller system due to the increased friction. This friction in turn caused substantial damage to the underside of the plate.

Like the full aramid plate, the difficulty of operation of this plate on the roller system makes it unsuitable for use in air cargo containers.

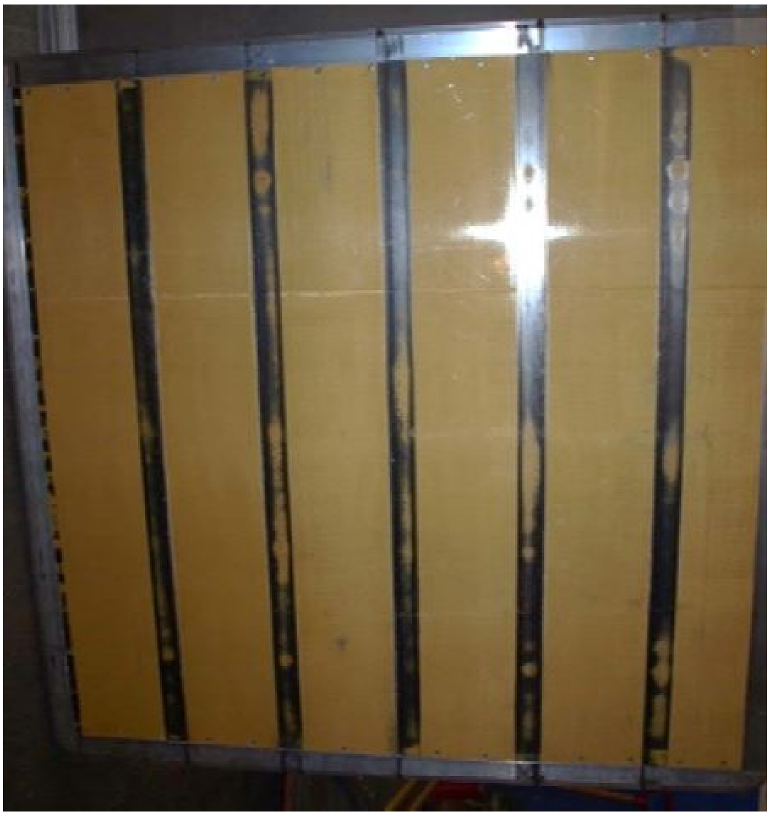


Figure 5.17: Visible wear lines where the rollers and structure made contact with the felt plate.

Figure 5.18: Close-up of the wear due to the rollers on the felt plate.

Figure 5.19: Five rivets were found to be missing after the test.

Price & production

In order to make an informed decision about the concepts, it is important that not only weight and performance are taken into account. The business case will determine whether a concept will be feasible for actual production. If the return of investment is too low, the airliner might not be interested in new containers.

Price

A critical factor is the cost price of a composite plate, which will directly impact the container sales price. The composite plates will be sold to Nordisk to be assembled into air cargo containers. The cost price of the bottom plate therefore directly influences the cost price of the container itself. Airliners are willing to invest in solutions that generate fuel savings but if the price is too high then the incentive is too small and the container will not sell well. The weight savings of the new container should be worth the additional costs for there to be a good business case.

In order to make a good estimation of the cost price per composite plate, an excel file is created with calculations to quickly determine the price of a certain concept. Input parameters are:

- Fibre lay-up
- Resin
- Number of units produced per year
- Production process
- Return of investment of the mould in years

With these parameters the price per plate is estimated. Next to this, the raw material price for the fibres and for the resin can also be noted. An example of the excel file can be found in annex E. The estimated price of the two selected concepts, aramid/felt/glass and full aramid, will be shown here as an example.

The aramid/felt/glass concept is build up out of the following plies: 170 g/m^2 plain woven aramid, 450 g/m^2 stitched glass, 450 g/m^2 woven glass and Soric TF-2. The fibre raw material price is €34,45 including waste and the resin raw material price is €15,22 including waste. The cost price per plate with the light RTM (Light Resin Transfer Moulding) production process and 500 produced units per year is €142,61.

For the full aramid concept, the used fibres are 170 g/m^2 plain woven aramid and 460 g/m^2 plain woven aramid. The fibre raw material price is €92,78 and the resin raw material price is €14,19. The cost price per plate with the light RTM production process and 500 produced units per year is €259,11.

Production

With the previously mentioned excel file, it is possible to determine which production method is the most favourable for this particular application. To do this, it is necessary to estimate the number of units that will be produced in one year and to decide the number of years that it will take before the mould costs are depreciated.

The following production methods are considered:

- Continuous processing
- Vacuum infusion
- Resin Transfer Moulding
- Light Resin Transfer Moulding
- Wet press

In general, the production methods that require a very expensive mould system (Resin Transfer Moulding, RTM, and wet press) are only suitable when the number of units produced is high and constant. This is because the mould costs are included in the cost price per unit and with a small number of units produced, the cost price is relatively high.

Also, the initial investment for such a mould poses a risk for companies. RTM moulds have to sustain high pressures and are therefore made from metal and quite heavy. The required equipment used in the RTM process and the fabrication of the metal mould itself are very expensive. Although the shape of the mould for this product is simple, the dimensions make it expensive nevertheless.

An example is considered where a RTM mould will depreciate after 5 years and 1000 units per year are produced. The depreciation per year is €300 000/5 = €60 000. Divided over one thousand units gives €60 000/1000 = €60 added to the cost price of each bottom plate.

This is only valid for five years of sales worth 1000 units per year. If the expected sales disappoint, the cost price will further increase and the margin will decrease. It is even possible that a loss is made on each plate sold. This poses a risk related to the high investments.

Therefore, in this particular case where the expected sales are not reliable, it is wise to go for a production technique with low initial investments. Light RTM is a good example of this, the required mould can be made from composite and is much easier to make than the metal RTM counterpart. Since light RTM works with vacuum and not with pressure, the forces acting on the machine are much smaller.

Life cycle analysis

To show the advantages of a composite bottom plate compared to the current aluminium plate, a life cycle analysis (LCA) was performed by Senior Life Cycle Consultant David Morris from DSM Corporate Operations. This shows the impact of each product on the environment taking into account the production of the used raw materials, manufacturing of the product itself, the use during the service life and recycling/disposing of the product at the end of life.

Two different techniques are used to calculate the results. The first is based purely on the amount of CO_2 released in the environment, focusing on the global warming potential of each solution. This is the carbon footprint method.

The second technique takes into account many more factors that influence the environment like fossil fuel depletion, climate change of ecosystems and climate changes influencing human health. This method is called the eco footprint.

A 7 year life time is assumed for the containers. It is assumed that a container will travel approximately 2,5 million km over its 7 year life time.

From the results of this study we can conclude that the weight saving associated with the DSM composite base plate when compared to the aluminium base plate has the most significant influence in reducing the carbon and eco footprints. The total reduction in carbon and eco footprints is 50 %. This reduction also qualifies the DSM composite base plate as an ECO+ product.

Although the results show a more favourable environmental impact for the DSM composite base plates, life cycle comparisons with specific products or product types in the public domain (publicly available comparative assertions) are not recommended until the assumptions and approximations used can be validated and the study approach verified by an independent 3rd party to accepted standards and guidelines.

In annex F, the full LCA report can be found for further reading.

Results

The requirements from chapter 3 give a minimum weight saving of 43 % compared to the aluminium bottom plate. With an aluminium weight of 14,1 kg this means that the composites should be lighter than 8,52 kg. The full aramid and aramid/felt/glass plates weigh 6,2 kg and 7,9 kg respectively so this requirement is met for both concepts. The aramid plate can even have additional material added and still satisfy this requirement.

Unfortunately, both composite sheets failed to meet the requirements of the dynamic roller test. They do not show sufficient durability on the roller playform to warrant further development of these two specific concepts. Both the monolithic aramid and the aramid/felt/glass plate are not able to match the performance of the aluminium design. The composite performance is less than ten percent of the aluminium in this particular test.

The maximum cost price requirement of €150 set in chapter 3 is only satisfied by the felt concept with a cost price of €142,61. The aramid plate is too expensive because the raw material price of aramid fibres is much higher than that of glass fibres. The total price for this concept is €259,11. The light RTM production process is found to be suitable for this product, allowing small production series without excessive product costs.

The life cycle analysis shows that a carbon and eco footprint reduction of 50 % is reachable if a composite floor is used. As CO_2 restrictions can be expected to become more severe in the future, such reductions are very interesting for companies dealing with cargo transportation.

The failure in the performance tests does not mean that it is impossible to design a composite bottom plate suitable for use in air cargo containers. The results tell us that the stiffness requirement is more important than initially thought and further designs should take this into account.

Having a floor with a high stiffness results in a flat area for the rollers to work upon which results in smooth operation and less wear due to friction.

Although local loads due to the rollers will still be relevant, the point load requirement might prove to be less important than the stiffness requirement.

6 Results, discussion and conclusion

This chapter summarises the obtained results for both the small scale and full scale tests. Then, the potential of the two full scale concepts for implementation in air cargo containers is discussed followed by the conclusion. Recommendations for further studies can be found in chapter 7 on page 97.

6.1 The problem statement

The problem stated is formulated in the literature study and forms the start of this thesis:

A composite floor for air cargo containers with comparable performance to aluminium floors can be designed to lower the Nordisk lightweight container tare weight. This results in improved sales for Nordisk, reduced fuel cost for airliners and lower prices for customers.

6.2 Summary small scale testing

The initial concept study, finite element calculations and adjusted requirements from the theoretical approach chapter are all used to set up the small scale concept list. Specimens of the concepts on this list are produced and subjected to a range of tests. The test program is set up such that all requirements are tested for:

- Weight
- Concept costs
- Wear and abrasion resistance
- Point load resistance

- Residual compressive strength
- Flexural properties

The aluminium alloys used in the Nordisk air cargo containers offer good mechanical properties such as high stiffness and strength. The aluminium alloy used for the floor is relatively hard which helps with abrasion and point loads. The raw material costs are low at €65 but the weight is high at 14,1 kg per bottom plate. The high weight is the reason why a composite bottom plate is under consideration by Nordisk.

Composites are at a disadvantage when local damage resistance is important. This followed – as expected – from the small scale tests. Composites are a combination of fibres and matrix and are therefore not homogeneous. The interface between the fibres and resin presents a weak area where cracks might initiate. The result is a material that is susceptible to damage if high local loads are applied as is the case with the roller systems in aircraft.

The results of the small scale tests show that none of the composite concepts reaches the same level of mechanical performance as aluminium. After discussions between Nordisk and DSM, it becomes clear that lower properties must be accepted to obtain the required weight savings. It is decided to pick the best performing composite concepts and continue to full scale testing.

The aramid/felt/glass, aramid/felt/carbon and the full aramid concepts show the best performance. Their stiffness and strength is not on the same level as aluminium but their damage tolerance and abrasion resistance is deemed satisfactory.

6.3 Summary full scale testing

Considering all facets of the project, the aramid/felt/glass concept is the best potential candidate for application in air cargo containers and is to be tested in full scale. The second concept is full aramid which will serve as a composite best case scenario reference.

A plate measuring 1440 mm by 1412 mm is produced at DSM composite resins for each concept. They are shipped to Nordisk in Norway to be assembled into a testable container base (see figure 5.9 on page 77).

Not all of the tests mentioned in section 5.2 are performed. Only the dynamic cyclic test is done, due to time constraints. Nordisk and DSM agreed that the cyclic test is the most demanding test that most closely resembles real life scenarios.

Section 5.4 on page 75 discusses the test result of the cyclic test for the two concepts compared to the reference. The aluminium plate can take roughly 13 000 cycles before the damage becomes excessive. Both composites do not nearly last as long and only reach 600 and 800 for the full aramid and aramid/felt/glass concept respectively.

Both composite containers require two men to assist pushing it over the rollers. The lower stiffness of the plates causes the material between two rollers to deflect. This caused the plates to touch the metal between the rollers which results in much higher friction forces and thus wear.

Both the monolithic aramid and the aramid/felt/glass plates are not able to match the performance of the aluminium design in the roller test. The composites do not satisfy the operational requirements for further development of these two specific concepts.

The weight savings of a composite bottom plate generate enough fuel savings to have a return of investment of two years. Comparing the two solutions with a life cycle analysis (section 5.4) shows a significant advantage for the composite. Both the composite production phase and the use phase generate less harmful substances although the total footprint is dominated by the use phase.

6.4 Discussion and conclusion of the test results

The problem statement reads that a composite floor is to be designed that offers comparable performance as the aluminium floor at a lower weight. Unfortunately the concepts designed in this thesis do not satisfy these criteria.

Both composite floor containers experienced a greatly increased friction on the roller system compared to the aluminium container. We know from the small scale tests that the flexural stiffness of the composite plates would be 25 % to 33 % of the aluminium plate. For thin composite plates it is not possible to match the aluminium stiffness while having both a lower weight and a limited cost.

The aramid prototype measures 2,3 mm in thickness compared to 3,2 mm of the aramid/felt/glass plate. Even though the aramid plate has a higher material stiffness, the bending stiffness is actually lower because of the lower thickness. Section 3.3 gives the impression that for thin plates the membrane stiffness is critical and the bending stiffness is not relevant. None of the involved parties (Nordisk, DSM Resins, and present author) anticipated that the bending between the rollers would be the critical design case, the problem never occured before. The full scale tests showed this flaw: the deflection between the rollers is severe which causes additional friction between the plate and the underlying steel frame.

There are some definitive advantages to using aluminium for this application. The aluminium grades used in the air cargo industry offer good stiffness and strength paired with a good hardness. This makes the material resistant to local loads and abrasion. The cost of an aluminium plate is low and the assembly process is easy due to the use of rivets.

The relatively high density of aluminium is a disadvantage which prevents Nordisk from decreasing the aluminium bottom plate thickness. Current containers experience plastic deformation of the floor due to cold working of the underside which makes the bottom plate bulge out. Decreasing the thickness of the floor would increase the amount of plastically deformed material and consequently worsen the damage as a result.

A decrease in thickness might also result in a lower bending stiffness that can cause problems with rollers systems. If the membrane and bending stiffness are not sufficient, the floor can hit the structure of the roller system possibly causing damage to the system and to the floor itself, similarly to what the composite plates experienced.

Composites in general have a lower density than aluminium and as such allow for a thicker structure for the same mass. This makes composites very suitable for this application. Quasi isotropic carbon fibre composites have a specific stiffness of 115 % of aluminium which makes these perfect for this application if the material would be lower priced. With 40 % weight savings this results in a composite plate 2,8 mm thick with 70 % of the aluminium membrane stiffness.

The cheaper glass fibres only have 31 % of the aluminium specific stiffness. This is further reduced with the 40 % weight savings and a maximum membrane stiffness of 18 % is expected. The full scale tests prove that this is not sufficient. The membrane stiffness and/or the bending stiffness must be increased to have a functional composite.

Another disadvantage of composites is the inherent weakness of the material to local loads and impacts. Air cargo containers are often subjected to such loads and this is not beneficial for a composite floor. During the project it became clear that the bottom plate of an air cargo container is a heavily loaded product that has to have sufficient stiffness and strength, abrasion, point load and impact resistance in order to function.

The full scale prototype tests show that the current concepts do not have these traits at a sufficient level. The current concepts show many shortcomings and it is necessary to take a few steps back and reconsider the future steps in the project which must be made. The following chapter outlines the next step in this project that are necessary to design a fully functioning composite floor that offers comparable performance as the aluminium floor for air cargo containers.

7 Recommendations

The research and tests that have been performed during this project give important insight in the application of composites in air cargo containers. It is an interesting and most of all difficult product to design and the selected concepts have not been able to meet the harsh requirements.

The most important learning points and recommendations are given in this chapter. This is useful for future design reviews of composite use in air cargo containers and for the possible continuation of this project. The shortcomings of the current prototypes are stated and ideas to tackle these challenges are given. Finally, some of the topics that are examined in this report are mentioned.

7.1 Learning points

The requirements for a composite floor in air cargo containers were not very clear at the start of the project. Some assumptions turned out to be correct while others proved to be false.

The maximum cost price was realistic but at the same time made it very difficult to use high cost high performance fibres such as carbon fibre. This is understandable, however, since the lightweight containers will not sell if they are priced too high.

The stiffness of the floor panel is critical for handling while this was not apparent initially. Roller systems appear to require a minimum membrane and/or bending stiffness of the floor to allow smooth operation. High deflections of the panel lead to increased friction on the floor which increases handling loads and wear damage.

A distributed load of 1588 kg on the bottom plate was used as the main load case. This occurs when the container is lifted on one side while the opposite side is still on the ground. The floor panel is then fully supported at the edges and should not fail. Such cases caused by improper handling were expected to be the primary cause of failure.

However, these situation are not likely to occur on a daily basis. Instead, a load case taking into account the roller system is expected to be more useful. Containers are transported over roller systems daily and it is likely that this is actually the primary cause of failure.

The wear resistance of composites equipped with an outer aramid layer is found to be sufficient. The point load resistance is deemed acceptable but further study on this subject is highly recommended.

7.2 Shortcomings

The shortcomings of the current full scale concepts are listed below. These challenges are explained further in their respective subsection and possible solutions are offered.

- Overall damage tolerance of composite is less than that of aluminium
- High deflection between rollers which has increased friction and wear as a result

Damage tolerance

The composite floors have an aramid wear layer that protects the material against wear. Abrasion tests indicate that the aramid layer performs this task quite good. Unfortunately, it doesn't help much to protect the composite against point loads. These local loads can cause resin cracking, fibre breakage, delamination and core crushing.

The small scale test results indicate that the strength loss after point loads in the composites is not detrimental. However, the aluminium experiences no loss in strength due to point loads which makes it the better performer. It would be interesting to find out whether this effect causes the composite compressive performance to degrade over time in service.

The full aramid sheet experienced the least damage of the two composites in the full scale and small scale tests. This is likely related to the use of tough aramid fibres throughout the thickness of the composite and because it is a monolithic laminate.

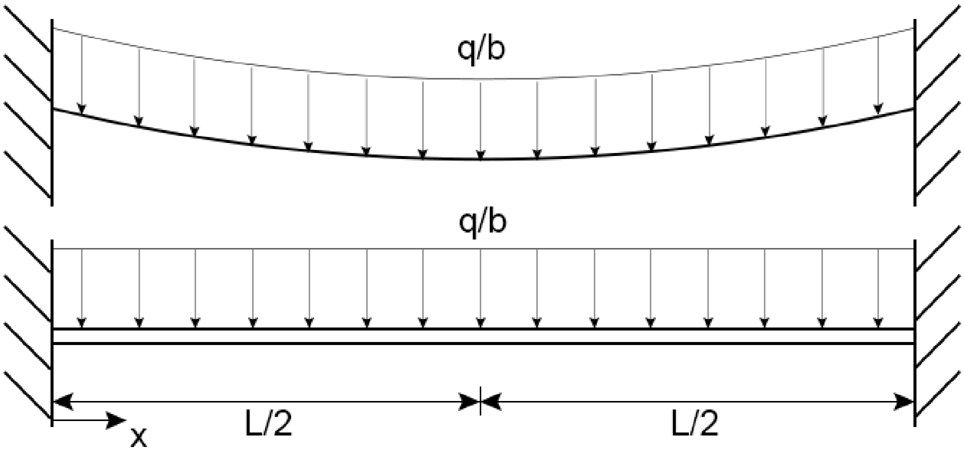


Figure 7.1: Schematic representation of a thin and thick bottom plate with a distributed vertical load.

The thin Soric core in the felt concept sustained and maybe also caused damage in the full scale and small scale tests. Additional local indentation might have caused the more severe fibre damage compared to the full aramid plate.

Deflection between rollers

The premature failure of both concepts is a result of the deflection between the rollers during the dynamic full scale test. The elimination of this excessive deflection is the most important recommendation for future projects that consider the replacement of air cargo container floor or pallets. In this subsection I will briefly consider the necessary changes to accomplish this.

We know that a container with an aluminium floor operates smoothly on roller systems. Therefore the aluminium deflection between two rollers is the reference which a potential composite concept must match.

Beam model

A simplified beam model is set up similar to the models in section 3.3 to approximate the deflection between two rollers. Figure 7.1 shows two beam models, one for thin plates and one for thick plates. The beam is assumed to be clamped.

The length L is equal to the maximum roller spacing which is 10 inch or 254 mm. The beams are considered per unit width, which means that all parameters that are dependant on the beam geometry are divided by the plate width $b = 1440$ mm.

Monolithic plate

For the monolithic concepts we assume the shear deflections are small and compare the membrane, bending and total deflection. The respective equations are given in equations 7.1[1], 7.2[2] and 7.3[3]. The first two can be used to check if the bending state or membrane state is predominant while the latter is used to determine the actual deflection. The equations can also be compared to each other to check whether the results are realistic.

Since the membrane and bending states are not fully separate, we cannot use super-positioning to combine the membrane and bending deflection. The two states have an overlap which means that the total deflection will always be smaller than either individual deflection.

$$w_{membrane} = L \left(\frac{3\frac{q}{b}L}{64\frac{EA}{b}} \right)^{1/3} \tag{7.1}$$

$$w_{bending} = \frac{\frac{q}{b}L^4}{384\frac{EI}{b}} \tag{7.2}$$

$$w_{max} + \frac{\frac{A}{b}}{16\frac{I}{b}} w_{max}^3 = \frac{\frac{q}{b}L^4}{4\pi^4\frac{EI}{b}} \tag{7.3}$$

In these equations, w is the maximum deflection in mm, $\frac{q}{b}$ is the distributed load per unit width in N/mm^2, L is the beam length in mm, $\frac{EA}{b}$ is the membrane stiffness per unit width in N/mm, $\frac{EI}{b}$ is the bending stiffness per unit width in N mm, $\frac{A}{b}$ is the cross-sectional area per unit width which is

[1] Young and Budynas, 2002.
[2] Zenkert, 1997.
[3] Young and Budynas, 2002.

equal to the plate thickness t in mm and $\frac{I}{b}$ is the area moment of inertia per unit width in mm^3.

Sandwich panel

For the sandwich panels we assume the bending state is predominant. Equation 7.2 is used in combination with equation 7.4[4] to account for the shear deformation in sandwich structures. The shear and bending mechanisms can be assumed to be separate which allows us to superposition them. This means that the total deflection is equal to the combined results of equations 7.2 and 7.4.

$$w_{shear} = \frac{\frac{q}{b}L^2}{8S} \tag{7.4}$$

Where S is the shear stiffness per unit width in N/mm given as:

$$S = \frac{G_c d^2}{t_c} \tag{7.5}$$

Here, G_c is the core shear modulus in MPa, d is the distance between the centroids of the faces $d = t_c + t_f$ in mm and t_c and t_f are the respective core and facing thickness in mm. See the shear element shown in figure 3.10 in section 3.3 on page 16.

Since the given equations are for beam calculations, the results won't be entirely accurate but for the purpose of this section sufficient. To account for the prevention of the lateral deformation in wide beams, $E/(1-\nu^2)$ can be used instead of E where ν is the Poisson ratio of the material[5].

Current concepts

To determine whether the deflection between the rollers is the cause of the premature failure of the composites in the full scale test, the deflection of the aramid/felt/glass and full aramid composites is compared to the aluminium deflection. Monolithic glass and carbon composites are added as a further reference to see how these materials perform in this load case. Since

[4] Zenkert, 1997.
[5] Young and Budynas, 2002.

Table 7.1: Properties of the materials under consideration.

Thin plate	E [MPa]	$\frac{EA}{b}$ [N/mm]	$\frac{EI}{b}$ [N mm]	t [mm]	*Weight* [kg]
Al7021-T6	76 000	213 220	111 052	2,5	14,1
Aramid/felt/glass	12 157	40 098	52 199	3,0	7,0
Aramid	24 672	63 705	24 377	2,3	5,7
Glass	20 132	37 584	11 356	1,7	6,6
Carbon	49 890	121 830	63 405	2,2	6,6
Sandwich	E_f G_c [MPa]	S [N/mm]	$\frac{EI}{b}$ [N mm]	t_f t_c [mm]	*Weight* [kg]
Glass IPHC sandwich 5 mm	18 260 21	139	195 730	0,8 5	5,6
Glass IPHC sandwich 10 mm	18 260 21	243	657 820	0,8 10	6,2
Glass IPHC sandwich 15 mm	18 260 21	348	1 392 500	0,8 15	6,9
Glass IPHC sandwich 20 mm	18 260 21	453	2 400 100	0,8 20	7,5

the stiffness requirement for the composite has become more important, a sandwich concept is also considered.

Table 7.1 provides the properties of the materials that are used for the calculations. E and $\frac{EI}{b}$ are obtained from Kolibri.

The results are given in table 7.2. For the thin plate concepts the separate membrane and bending deflections are given which can be compared to see which state is critical. If one of the deflections is a lot smaller than the other, this state is most likely critical. The total deflection where both states are taken into account is also given, this value is usually slightly lower than the lowest individual deflection since the membrane and bending states work together.

For the sandwich structures, the shear and bending deflections are given. These can be assumed to work separately and can be added to obtain the total deflection. For thick sandwich panels, the bending deflection will mostly determine the total deflection.

The results indicate that the felt and aramid composites have a deflection

Table 7.2: Deflection results of the materials under consideration.

Thin plate	$w_{membrane}$ [mm]	$w_{bending}$ [mm]	w_{max} [mm]
Al7021-T6	1,91	0,79	0,70
Aramid/felt/glass	3,34	1,59	1,36
Aramid	2,86	3,41	2,08
Glass	3,41	7,31	2,63
Carbon	2,31	1,31	1,09
Sandwich	w_{shear} [mm]	$w_{bending}$ [mm]	w_{max} [mm]
Glass IPHC sandwich 5 mm	0,44	0,42	0,87
Glass IPHC sandwich 10 mm	0,25	0,13	0,38
Glass IPHC sandwich 15 mm	0,18	0,06	0,24
Glass IPHC sandwich 20 mm	0,14	0,04	0,17

that is respectively two and three times as large as the aluminium sample. This may very well be the reason of the increased friction on the roller system. Although the stiffness of the aramid/felt/glass concept is not sufficient, these results do confirm that this concept has potential and that it's selection is valid. It appears that the aramid sample is critical in membrane and the felt sample is critical in bending. The aluminium sample is also critical in bending.

The full glass concept has a deflection that is four times as large as the aluminium sample, which does not make it an interesting concept. The full carbon composite, on the other hand, offers improved stiffness compared to the felt sample as is expected from section 3.4. The prohibitive costs of carbon make it infeasible as a solution for this application.

The 5 mm sandwich concept offers a comparable stiffness as aluminium at a good weight and cost. Thicker sandwich panels further lower the deflection at a small increase in weight. From these results a sandwich might seem to be the best solution but in section 4.1 we found that sandwich panels have issues with point loads and local damage.

Changed concepts

In the previous subsection the performance of the current concepts is analysed. In this subsection the concepts are modified to meet the deflection of the aluminium sample. This will give us an idea of the changes that are

Table 7.3: Deflection results of the improved composites.

Thin plate	w_{max} [mm]	t [mm]	*Weight* [kg]
Al7021-T6	0,70	2,5	14,1
Aramid/felt/glass	0,76	3,7	9,6
Aramid	0,67	3,7	9,2
Glass	0,67	3,8	14,5
Carbon	0,74	2,7	8,0

necessary to design a composite solution that is expected to perform good.

Additional material is added to the thin composite concepts to match the deflection of the aluminium sample. As a result the thickness and weight are also increased. The results are given in table 7.3.

As expected, the material that offers the same stiffness performance as aluminium at the lowest weight is the full carbon concept. In contrast, the full glass concept requires a higher weight than the aluminium to obtain the same stiffness.

Both concepts tested in full scale perform quite reasonable. The felt and aramid concepts achieve weight savings of 32 % and 35 % respectively, which is significant.

7.3 Alternative solutions

In the previous section two of the main causes for failure have been explained. Some possible changes or alternatives that might counter these issues will be briefly discussed now. These findings can be used in further research to guide the design process. Local damage and severe deflections between the rollers are both very important issues that need to be solved.

In general, sandwich structures are more susceptible to local damage due to point loads than monolithic structures. The local facesheet stiffness is often lower than a monolithic layup stiffness and the core is too weak to offer any out-of-plane load resistance. The felt composites experience comparable difficulties although to a lesser extend. Small scale tests indicate that the out-of-plane performance is acceptable but further testing is necessary. When considering point loads, a monolithic composite is probably the best choice.

Table 7.4: Deflection results of a Tegris composite.

Thin plate	w_{max} [mm]	t [mm]	*Weight* [kg]
Tegris consolidated sheet	0,73	6,0	9,5

The full scale tests show that the stiffness of the composites should be comparable to the aluminium stiffness to prevent excessive deflections between two rollers. Table 7.3 shows the deflection results of the modified composites with an improved stiffness. The weight savings are sufficient enough to initiate a discussion on the requested weight savings. During this project it has become clear that a decrease in floor weight of 40 % is unrealistic at best.

One solution might thus be a decrease in the requested weight savings to 30 %. This offers more flexibility in the design of a potential composite and we have seen that the current concepts are actually able to match the aluminium performance when more weight is permitted.

An alternative solution is a tough polymer composite like Tegris. Tegris is a polypropylene composite build from highly drawn polypropylene fibres encased in a lower melt polypropylene matrix. Products are manufactured from Tegris sheets while applying heat and pressure. Each sheet has an ABA layup where A is a low melt polypropylene and B is a higher melt highly drawn polypropylene fibre layer. The sheets are stacked and pressed to consolidate into thick, lightweight, impact resistant parts. See figure 7.2 for a part that is consolidated halfway.

Tegris has low mechanical properties, the consolidated sheet has a tensile stiffness of 5 GPa to 6 GPa but its density is very low at 780 kg/m^3.[6] Because of the low density, a higher material thickness is attainable which makes it possible to reach a sufficient bending stiffness. See table 7.4 for the between roller deflection calculations on a Tegris composite. One benefit of Tegris is the good impact resistance of the material which will help deal with point loads and abuse of the container.

Sandwich panels are also worth investigating further. The main challenge is the mitigation of damage due to point loads. A sandwich with a core that has better out-of-plane properties and thicker facesheets might help

[6] Milliken & Company, 2015.
[7] Milliken & Company, 2015.

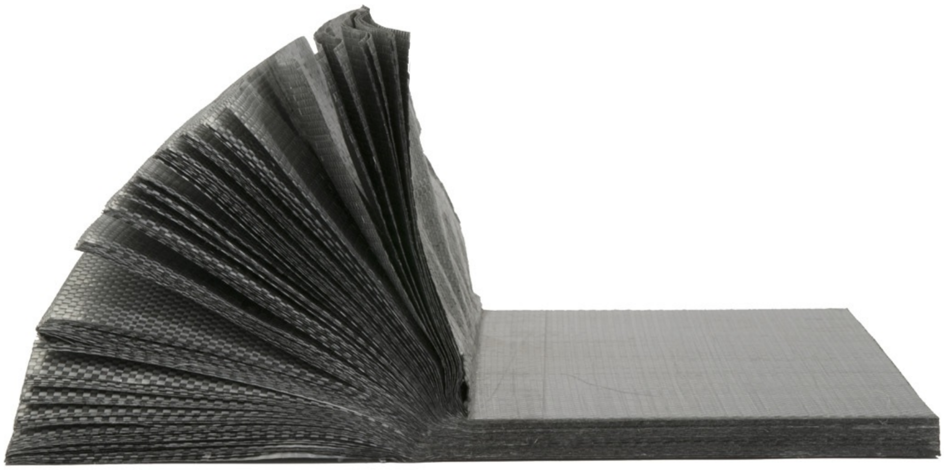


Figure 7.2: Halfway consolidated sheet of Tegris.[7]

with this.

When the carbon fibre price drops to €6,50 per kilogramme, a full or partial carbon fibre concept will also be feasible. This brings greater weight savings than possible with glass fibre based thin composites.

A final suggestion is to manufacture the entire bottom of the container in one composite part. This removes the critical bond interface between the floor plate and the aluminium frame and also results in a larger weight envelope for the composite which makes the design a lot easier. Such an integrated design allows more optimisation and I believe that it has a much higher chance of success for this application, based on this study.

7.4 Topics to be addressed

Several topics have not been discussed in this report while they may have an influence on test results or concept performance. They are identified as:

- More detailed research on the actual loadcase on air cargo containers
- Water absorption of aramid in a concept where aramid is used as an outer layer for wear protection.

- Creep of aramid in situations with a constant loading.
- Fire resistance of composites in air cargo applications
- More detailed research on the connection of the composite to the aluminium frame

Appendices

A Patents

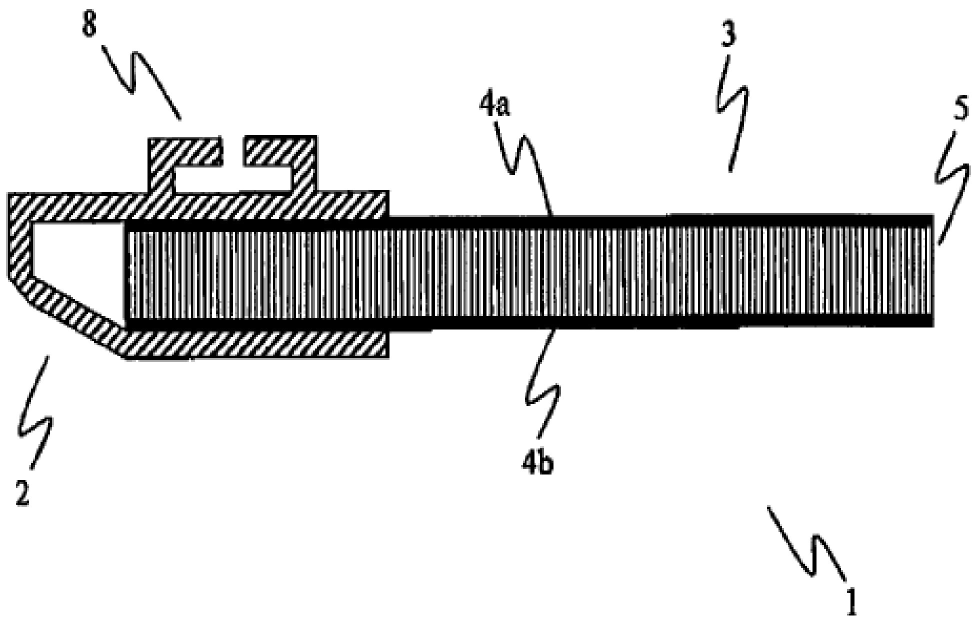


Figure A.1: Drawing extracted from patent EP2431302A1

A.1 EP2431302A1 (Figure A.1)

Applicant: German Aerospace Centre[1]

Grant date: 21-03-2012

Claims: Container for transporting goods with a basic structure that at least consists of a framework with a bottom plate attached. This bottom plate has at least a top skin and at least a bottom skin with in between a core material. The framework has a seperate upper framewall and lower framewall between which the bottom plate is fixed with bonding agent such that the plate is kept between the two framewalls.

[1]German Aerospace Centre, 2012.

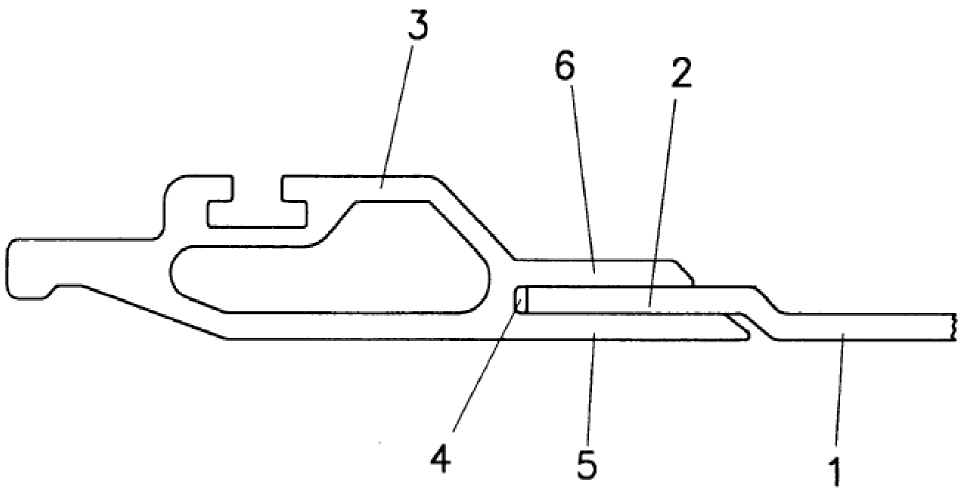


Figure A.2: Drawing extracted from patent EP0592940B1

A.2 EP0592940B1 (Figure A.2)

Applicant: DoKaSh GmbH[2]

Grant date: 07-10-1993

Claims: Pallet for transporting air freight, consisting of a sheet metal base which is surrounded by a frame of profiled edge strips. The lateral surfaces of the profiled edge strips facing the edges of the sheet metal base plate have a groove for receiving the plate. The base plate is offset in its edge region from the underside of the profiled strip by the distance of the groove.

[2]DoKaSch GmbH, 1996.

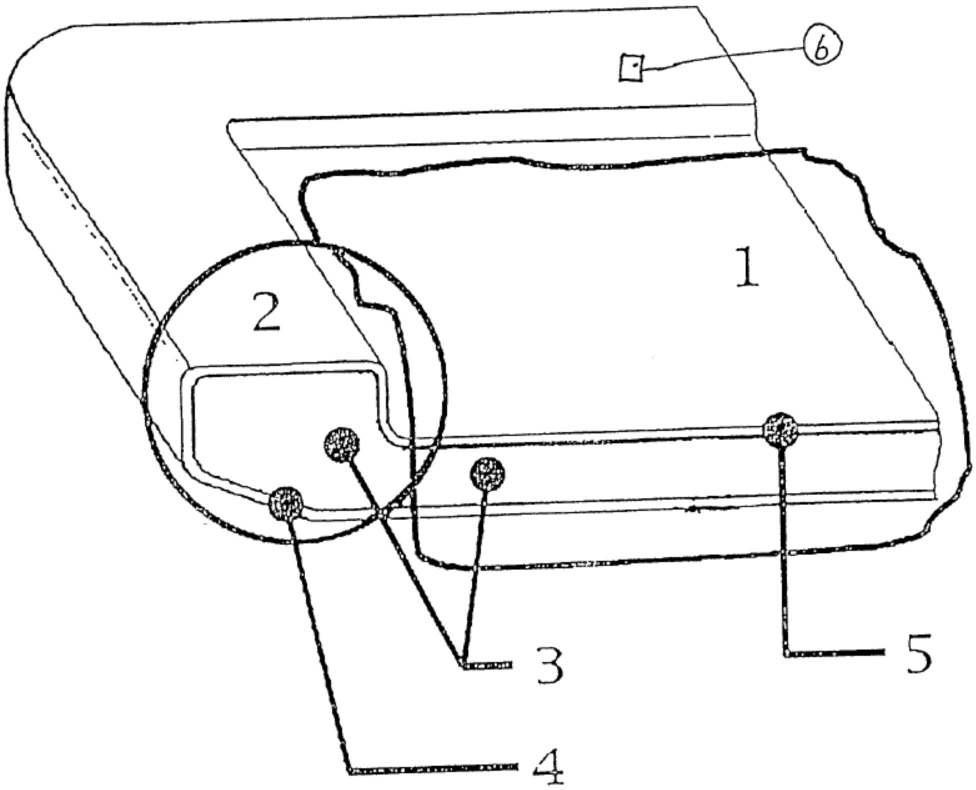


Figure A.3: Drawing extracted from patent WO2007090363A1

A.3 WO2007090363A1 (Figure A.3)

Applicant: Advanced Composites Engineering + Production[3]

Grant date: 18-08-2007

Claims: Air freight carrier with a bottom plate and attachable securing equipment to securely place the cargo on the device. The bottom plate is a sandwich construction with one or multiple layers consisting of a core material covered by a composite skin and has an integrated frame edge.

[3]Advanced Composites Engineering + Production GmbH, 2007.

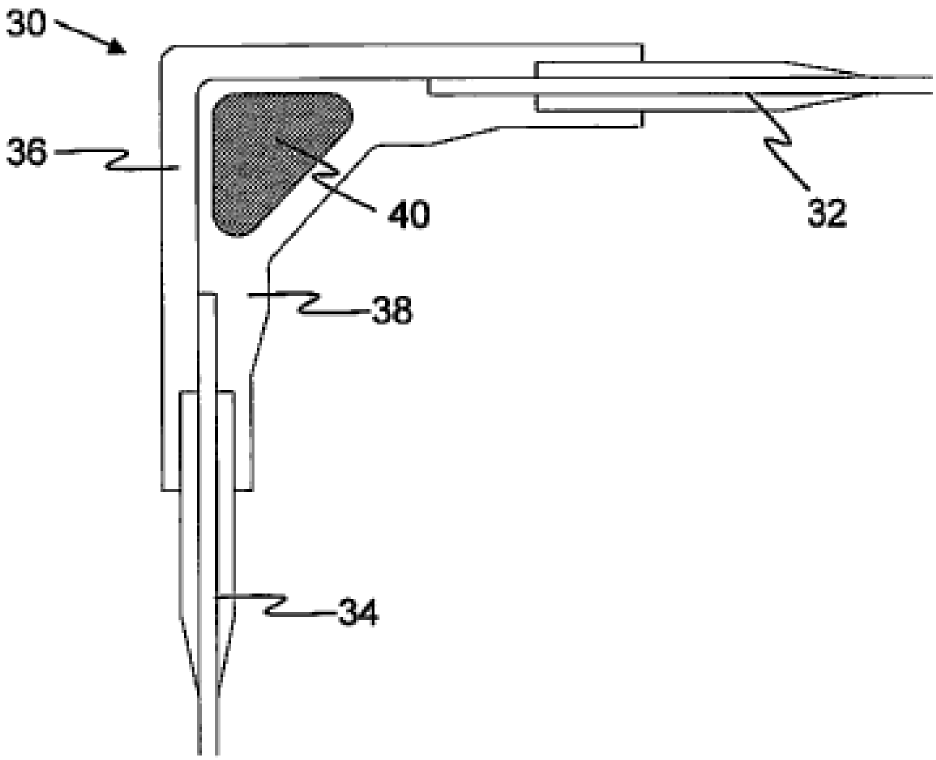


Figure A.4: Drawing extracted from patent WO2010045572A1

A.4 WO2010045572A1 (Figure A.4)

Applicant: Touchstone Research Laboratory Ltd.[4]

Grant date: 22-04-2010

Claims: A container comprising of composite sandwich panels connected by composite joints.

[4]Touchstone Research Laboratory Ltd., 2010.

B Small scale requirements document

Technical specification AKE container base - small scale tests

In this document the tests performed on the small scale concepts are listed and the results are given for the aramid/felt/glass and full aramid composites samples and where applicable, the aluminium sample. The document is meant as an overview of the composite properties for application in air cargo container baseplates.

Nordisk and DSM have worked together to set-up different test methods that are estimated to be most important/critical for this application. From the results of these tests, both parties have decided to continue with the aforementioned composite concepts in a full scale test. In these further tests, a full container with composite bottom plate is loaded with cargo and evaluated according to EASA, FAR and IATA requirements.

Roller indentation test

General

The container must be able to withstand the high point loads introduced by individual rollers in a roller floor. In some scenarios, a large portion of the weight of the container is concentrated on a single roller. To mimic this, a roller shaped piece of steel is pressed into the plate repeatedly. Visual inspection is used to evaluate the damage and the maximum indentation is measured.

Procedure

A 32 by 32 cm square plate is loaded perpendicularly with a steel roller 2” long and 1” in diameter with a 1mm radius. The exerted force is 3000N and is applied for 500 cycles.

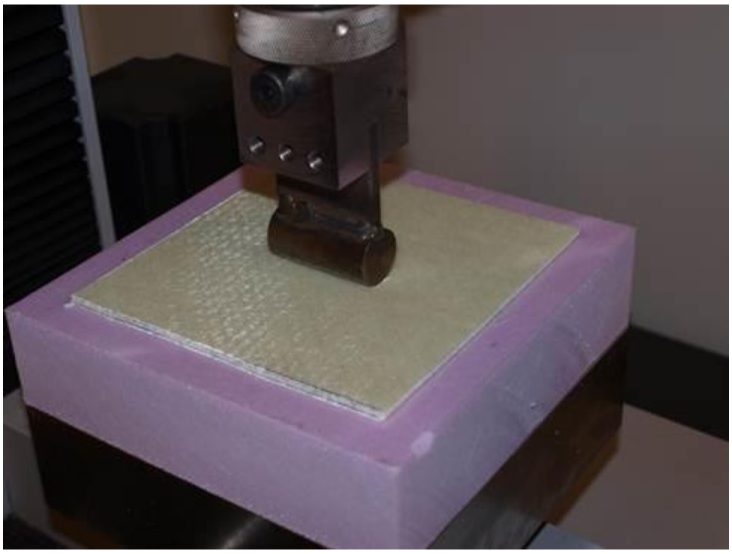


Figure: test set-up for the roller indentation test

Requirements

After testing, the plate shall show an indentation of less than 0.25mm.

Test

1. Plate to be placed on flexible underground in the testing machine.
2. Load the plate with a 2" long 1" diameter steel roller with a force of 3000N for 500 cycles.
3. After loading, check the front and backside of the plate against the aforementioned requirements.

Results

sample	Indentation [mm]
aramid/felt/glass	0,20
aramid	0,14

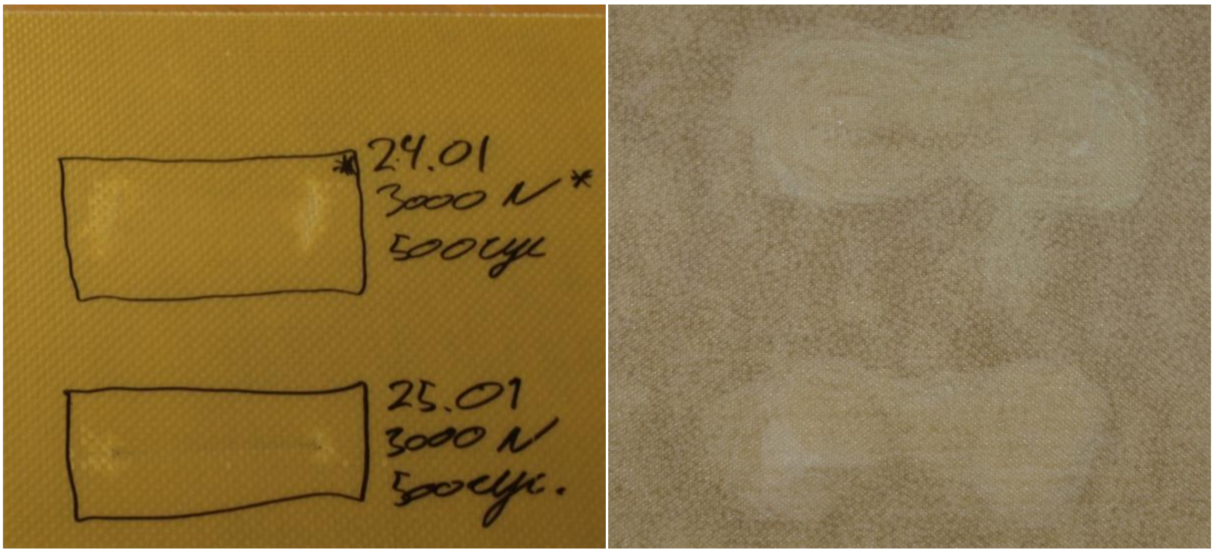


Figure: result of roller indentation performed on the aramid/felt/glass sample

Compressive strength after indentation

General

To evaluate the damage from the roller indentation test, compression samples are cut from the tested plate. Samples are cut from both the damaged area and from an undamaged area. The samples are tested in compression and the loss in compressive strength due to the damage is considered.

Procedure

A 32 by 32 cm square plate tested according to the "roller indentation test" has compression samples cut out according to the ASTM D6641 standard. A first series is cut from the damaged area; the second series is cut from undamaged material. The two series are tested in compression according to ASTM D6641 and the compressive strength loss is calculated.

Test

1. Cut damaged compression samples according to ASTM D6641 standard.
2. Cut undamaged compression samples according to ASTM D6641 standard.

3. Test the compression samples according to ASTM D6641 standard.
4. After testing, compare the two series and calculate the loss in compression stiffness and strength.

Results

sample	Compressive stress [MPa]	Compressive stress damaged [MPa]	Decrease in %
aramid/felt/glass	111,4	79,3	29%
aramid	106,7	97,7	8%

Stiffness and strength requirements

General
To verify that the composite material meets the strength and stiffness demands, flexural tests are performed on both the aluminium and the composite.

Procedure
Flexural test samples are cut from the composite plate according to ISO 14125 standard. These are then tested according to ISO 14125 and the results are compared with the reference (Al7021-T6).

Test
1. Cut samples according to ISO 14125 standard.
2. Test samples according to ISO 14125 standard.
3. Compare the test results with the aluminium reference results.

Results

sample	Modulus [GPa]	Stress at break [MPa]
aramid/felt/glass	17,5	330
aramid	26,1	251
Al7021-T6	75,9	575

Fire requirements

General
To verify that the container bottom plate does not pose a fire hazard, burn tests shall be performed. The container base sheet must be able to comply with EASA CS 25.853 Appendix F Part 1 (a)(1)(iv) and FAR 25.853 Appendix F Part 1 (a)(1)(iv) with maximum burn rate 64 mm (2.5") per minute when tested horizontally according to EASA CS 25.853 Appendix F Part 1 (b)(5) and FAA CS 25.853 Appendix F Part 1 (b)(5).

Procedure
From a previously produced plate cut samples according to EASA CS 25.853 Appendix F Part 1 (b)(5). The tests are then performed according to EASA CS 25.853 Appendix F Part 1 (b)(5).

Requirements
The maximum burn rate in the performed test is 64mm per minute.

Test
1. Cut sample according to EASA CS 25.853 Appendix F Part 1 (b)(5).
2. Test the sample according to EASA CS 25.853 Appendix F Part 1 (b)(5).
3. Measure the burn rate and compare with the requirements.

Results
No fire tests performed yet.

Abrasion requirements

General

To verify that the composite material can withstand the wear induced by handling of the container, an abrasion resistance test shall be performed.

Procedure

From a previously produced plate cut samples according to ASTM D4060 standard. The sample is weighed on an accurate scale and placed in the Taber Abraser machine. The vacuum level is set to 70% with a nozzle height of 4mm above the sample material. Rubber CS-0 wheels are used with P60 textile back sandpaper attached. Per wheel a 1kg weight is selected and the wheels are then placed on top of the sample material. The machine shall be set-up to do 500 cycles. The sample is weighed again and placed back in the machine. The wheels shall be cleaned and another 500 cycles is performed. Continue with same procedure until 2000 cycles is reached.

Requirements

Material should perform to at least 50% of Al 7021-T6 performance. A provision for adding some type of abrasion resistant coating should be taken if the sheets experience significant degradation due to abrasion.

Test

1. Cut samples according to ASTM D4060.
2. Test samples according to ASTM D4060.
3. Measure the weight decrease due to abrasion and compare with aluminium sample.

Results

sample	Sample weight [g]	Loss after 2000 cycli [g]
aramid/felt/glass	34,8	0,86
aramid	29,2	1
Al7021-T6	69,5	0,53

Interface/connection between sheet and edge rail:

General

An adequate connection between edge extrusion and base sheet is crucial. Depending on how well the sheet attaches to the edge extrusion there might be need for a flanged area at the perimeter of the sheet. A double lap shear test is performed to compare the bond strength to the strength of the rivets that are currently being used.

Procedure

A 5mm thick glass fibre composite plate is used as the composite sample material to make sure the failure is not in the composite. The composite is cut to size according to ASTM D3528 standard and sanded with coarse P80 grit sanding paper and cleaned with acetone. 2.5mm Al 7021-T6 is used to bond two composite samples together such that the bond between the aluminium and the composite is tested. The aluminium is cut to size according to the standard and sanded with coarse P80 grit sanding paper and cleaned with acetone. The aluminium samples are then bonded onto the composite. After bonding the samples are given a post-cure at 60 degree Celsius to make sure each bonding agent has the same cure. The samples are then tested in a tensile testing machine according to ASTM D3528.

Requirements

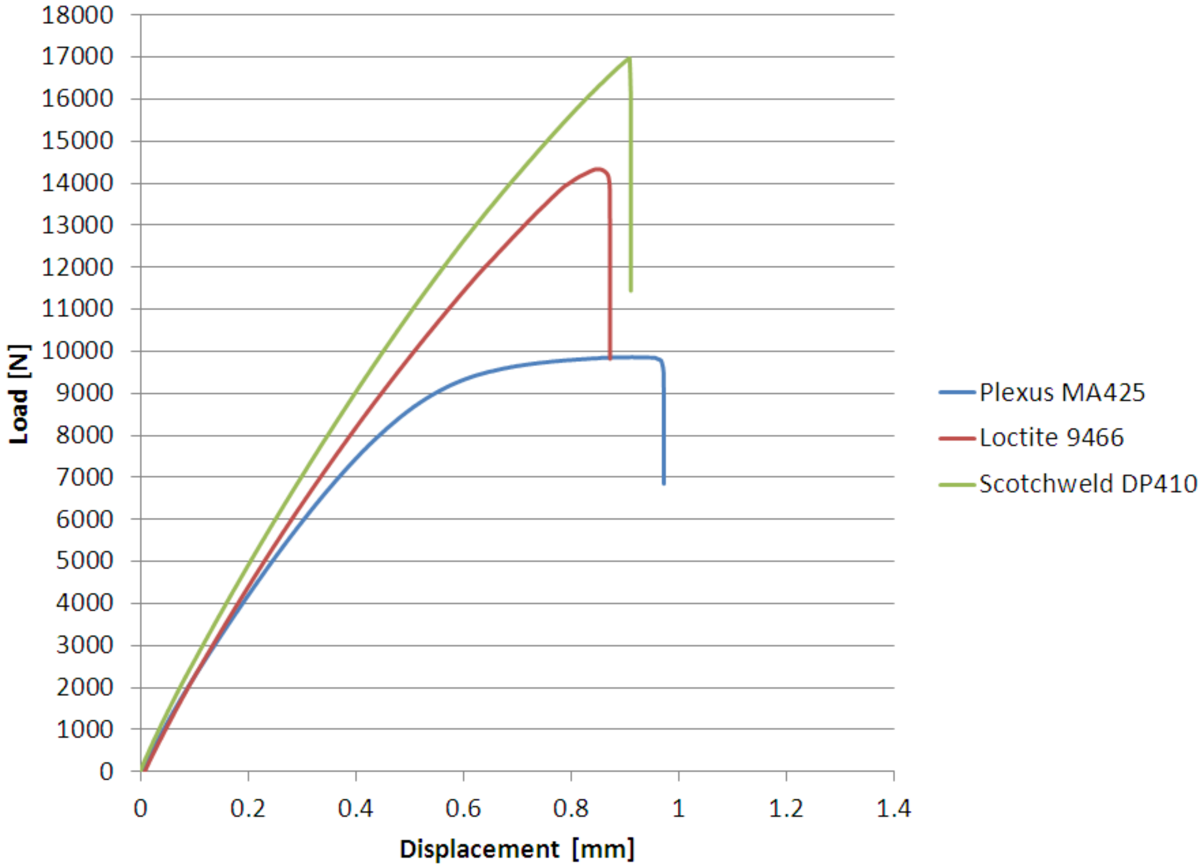
Bond with adhesive should provide similar or better adhesion strength compared to rivets.

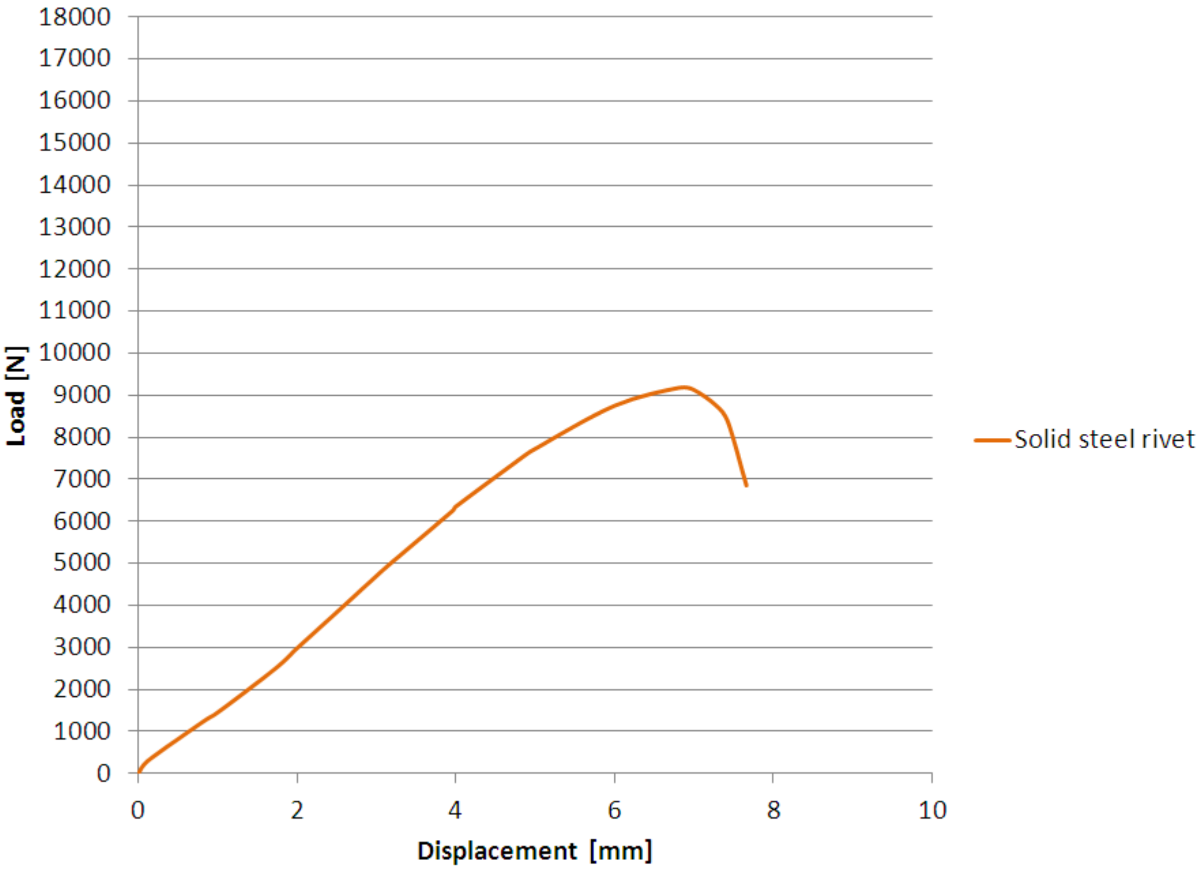
Test

1. Cut composite samples according to ASTM D3528.
2. Cut aluminium samples according to ASTM D3528.
3. Bond samples according to ASTM D3528.
4. Post-cure samples at 60 degrees Celsius.
5. Pull samples in tensile bench.
6. Compare bond data with available rivet data.

Results

glue	Maximum load [N]	Maximum displacement [mm]	Shear stress [MPa]
Plexus MA425	9850	0,97	15,3
Loctite 9466	14315	0,87	22,2
Scotchweld DP410	16893	0,90	26,2
Rivets used by Nordisk	9175	5,40	5,7


18000
17000
16000
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Load [N]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Displacement [mm]
Plexus MA425
Loctite 9466
Scotchweld DP410


18000
17000
16000
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Load [N]
0
2
4
6
8
10
Displacement [mm]
Solid steel rivet

Dimensional Requirements:

Base sheet must be producible up to the following size. 1562 X 1534 mm.

Conclusion

The aramid/felt/glass and full aramid concepts are going to be produced in full scale and will be tested accordingly. This has been mutually decided by DSM and Nordisk since both parties have enough confidence in the small scale tests to want to see the full scale test results. For reference, see "Technical Specification AKE container base full scale".

C Full scale requirements document

Technical specification AKE container base - full scale tests

In this document the tests to be performed on the full scale concepts are listed and when available the results are given for the aramid/felt/glass and full aramid composite samples. Where possible the results for the aluminium bottom plate will also be given as comparison.

Nordisk and DSM have worked together to form this specification document and it is meant as a comparison between the composite samples themselves and between the composite and the aluminium. The tests are subtracted from FAR, EASA and IATA manuals about air cargo containers and represent a good testing program according to Nordisk and DSM.

Certification test requirements:

- NAS 3610
- AS 36100

Does require full-scale test of the entire container.

Operational test requirements:

Base assembly with sheet needs to pass the General Purpose ULD – Standard Specification 50/4. Relevant tests for the base development being:

- Test No. 3. (Base strength)
- Test No. 4. (Cyclic test)
- Test No. 6. (Bridging and Cresting)
- Test No. 8. (Base deflection test)

Does require full-scale test of the entire container.

Fire requirements:

Container base sheet must be able to comply with EASA CS 25.853 Appendix F Part 1 (a)(1)(iv) and FAR 25.853 Appendix F Part 1 (a)(1)(iv) with maximum burn rate 64 mm (2.5") per minute when tested horizontally according to EASA CS 25.853 Appendix F Part 1 (b)(5) and FAA CS 25.853 Appendix F Part 1 (b)(5)

Dimensional Requirements:

Base sheet must be producible up to the following size. 1562 X 1534 mm.

Abrasion:

Abrasion resistance is not a stated requirement, but must be taken into consideration. Abrasion test according to ASTM D4060 Taber Abraser should be performed. Material should perform to at least 50% of Al 7021-T6 performance. A provision for adding some type of abrasion resistant coating should be taken, if sheets experiences significant degradation due to abrasion.

Interface/connection between sheet and edge rail:

An adequate connection between edge extrusion and base sheet is crucial. Depending on how well the sheet attaches to the edge extrusion there might be need for a flanged area at the perimeter of the sheet. General Purpose ULD – Standard Specification 50/4 Test No. 6 will be crucial to judge the connection between extrusions and sheet.

Service life test/Field test

General:

This test shall be carried out to prove the ability of the container to withstand all loads induced during operation of the container. Real handling and transportation might prove to cause different load cases than those tested for in the full scale prototype tests.

Procedure:

The container under test shall be added to the existing container fleet in order to ensure that the handling of the container under test is as much as possible equal to other containers.

Requirements:

Upon completion of the test, the container shall show neither detrimental permanent deformation nor abnormality which will render it unsuitable for use; and the dimensional requirements affecting handling, securing and interchange shall be satisfied.

Test:

1. Mount full scale composite prototype in container frame. If connection between plate and frame has proved to be sufficient in previous full scale tests then the same connection technology can be used. If this is not the case, a new technology should be developed.
2. Find airliner that is interested in having prototype containers in its container park.
3. Have a small quantity (<10) of containers in use.
4. Carry out periodic checks on container.
5. Check container for detrimental permanent deformation or abnormalities that will render the container unsuitable for use, securing and interchange.

Results:

Illustration:

Conclusion:

Requirement	Passed	Failed	Comment
NAS 3610			
AS 36100			
50/4 Test No. 3.			
50/4 Test No. 4.			
50/4 Test No. 6.			
50/4 Test No. 8.			
Dimensions			
Abrasion			
Interface sheet and extrusions			

List of enclosures:

General Purpose ULD – Standard Specification 50/4.

- Test No. 3. (Base strength)
- Test No. 4. (Cyclic test)
- Test No. 6. (Bridging and Cresting)
- Test No. 8. (Base deflection test)

Test No. 3: Base strength

General:
This test shall be carried out to prove the ability of the container base to withstand the maximum operational loads that may be experienced during handling and transportation.

Note:

Procedure:
The container under test shall rest on the aircraft loading system or its equivalent as defined in Specification 50/0. The container floor shall be loaded to 5860kg/m² (1200 lb/ft²). The load shall be applied to an area 1,524mm (5 ft) wide centered in the container, and the load shall equal but not exceed three times the container maximum payload.

Requirements:
Upon completion of the test, the container shall show neither detrimental permanent deformation nor abnormality which will render it unsuitable for use; and the dimensional requirements affecting handling, securing and interchange shall be satisfied.

The doors shall open and close with no prevalent binding, and the locks shall engage and disengage with ease.

Test:
1. Container to be placed on aircraft cargo loading system or equivalent as defined in Specification 50/0 in IATA ULD tech. Manual.
2. Load the container according to description I “Procedure”
3. Unload the container.
4. Check container for detrimental permanent deformation or abnormalities that will render the container unsuitable for use, securing and interchange.
5. Check that the door opens normally and that the locking mechanism engages and disengages with ease.

Results:

Illustration:
Test setup
Fully loaded
Inspection

Conclusion:

Test No. 4: Cyclic Test.

General:

This test shall be carried out to prove the ability of the container base to withstand the maximum operational loads that may be experienced during handling

Note:

Procedure:

The container under test shall be uniformly loaded to maximum gross weight and cycled one hundred (100) times over the aircraft loading system or its equivalent as defined in Technical Standard Specification 50/0, with a maximum speed of 0,3m/s (1ft/s). Maximum displacement of roller tops on the test system from a theoretical plane should be varied randomly to a maximum of +-0,7mm (+-0,03 in). Each cycle shall be equal to at least twice the container length.

Requirements:

At test speed, draw bar pull shall be recorded during the first and last cycles. Maximum allowable draw bar pull shall be 3% of container gross weight. Maximum variation of draw bar pull from the first cycle to the last cycle shall not exceed 0,5% of container gross weight.

Upon completion of the test, the container shall show neither permanent deformation, nor abnormality which will render it unsuitable for use and those dimensional requirements affecting handling, securing and interchange shall be satisfied. The doors shall open and close with no prevalent binding, and those locks shall engage and disengage with ease.

Type of container	
Tare weight	
Max Gross weight	
Total test load	

Test:

1. Load container to maximum gross weight. The load shall be uniformly loaded
2. Cycle the container a minimum of twice the container length with a gauge to measure draw bar pull on the first and last cycle. Do not exceed speed 0,3 m/s (1ft/s)Load Total test load in container ensuring a evenly distributed load against the sides described in section 2.
3. Cycle the container 100 cycles
4. Inspect

Results:

Draw bar pull first cycle	
Draw bar pull last cycle	
Variance in percentage	

Illustration:

Test setup
Draw bar pull first cycle
Draw bar pull last cycle
Inspection

Conclusion:

Test No. 6: Bridging and Cresting.

General:
This test shall be carried out to prove the ability of the container to traverse from one item of ground or aircraft handling equipment to another when the level of the conveyor surfaces are not in the same plane. At the point where the container balances on the end of the higher surface the entire load is supported by one row of rollers.

Note:

Procedure:
The container loaded to maximum gross weight, with a central c.g. position, shall be traversed on a roller system compatible with the minimum requirements of International Standard ISO 4116 (IATA AHM 911 is equivalent), and made to pass across a stepped junction with another similar roller system, with the height difference at the junction being not less than 152 mm (6 in). At the point balance (cresting) on the edge of the higher platform, hold the container in this position for a minimum period of 5 seconds. The rear end of the container shall then be allowed to drop from the higher platform onto the lower roller platform.

Requirements:
Upon completion of the test, the container shall show neither permanent deformation, nor abnormality which will render it unsuitable for use and those dimensional requirements affecting handling, securing and interchange shall be satisfied.

Type of container	
Max Gross weight	

Test:
1. Load container with max. gross weight on upper platform
2. Push container on upper platform to the point of balance (cresting)
3. Keep the container in cresting position for 5 seconds
4. Allow the rear end of the container to drop (bridging) from upper platform to lower platform
5. Perform inspection.
6. Unload container and perform inspection on empty container.

Results:

Illustration:
Test setup

Container at cresting
Container at bridging
Container during inspection

Conclusion:

Test No. 8: Base Deflection Test (Applicable Only to Units with Overhanging Contours C, E, F, G, H and U)

General:

This test shall be carried out to prove that when a fully laden unit is traversed over ground handling equipment satisfying the requirements of AHM 911, no part of the underside of the container base shall make contact with the supporting structure, walkways, etc. on the ground equipment.

Note:

Procedure:

The container under test shall be loaded to its maximum gross weight. The overhanging portion of the container shall contain its volumetrically proportional share of the total payload, which shall be completely independent of the remaining payload. The center of gravity of this load shall be coincident with the center of area of the overhanging portion when viewed from the long side of the unit, and the load shall be evenly distributed across the width of the unit. Where the container contour has an overhang at each end, both ends shall be similarly loaded. The remaining payload shall be uniformly distributed over the base of the unit. The container shall be positioned on battens or rollers with the base at the contoured end unsupported over a length of 25.4 cm (10 in), i.e. cantilevered.

Requirements:

The maximum deflection of the base shall not exceed 9.5 mm (3/8 in).

Type of container	
Max Gross weight	
Test load (overhang portion)	
Test load base	
Total test load	

Test:

1. Place container on battens or rollers with the base at the contoured end unsupported over a length of 25,4cm (10in)
2. Measure base at the end (on the contoured side)
3. Load container with the specified load
4. Measure base deflection

Results:

Measurement: Container unloaded	
Measurement: Container loaded	
Difference/Deflection of base	

Illustration:

Test setup

Deflection unloaded

Deflection loaded

Conclusion:

D Solid rivet testing document

Nordisk AVIATION PRODUCTS	Date:	15.10.2010
	Revision:	0
	Report No.	MT-21302

MATERIAL TEST

Stainless steel rivets for pallets/Jiangyin Hongseng

Prepared by:	Jon Teyler	Date:	2010-10-15

1 Test Setup

Set up as Test report TR-20838

2 Test Results

	Tensile	**Shear**
Results	6004 (N)	9175 (N)

3 Conclusion

The test results execs the results from our existing vendor

Testometric materials testing machines

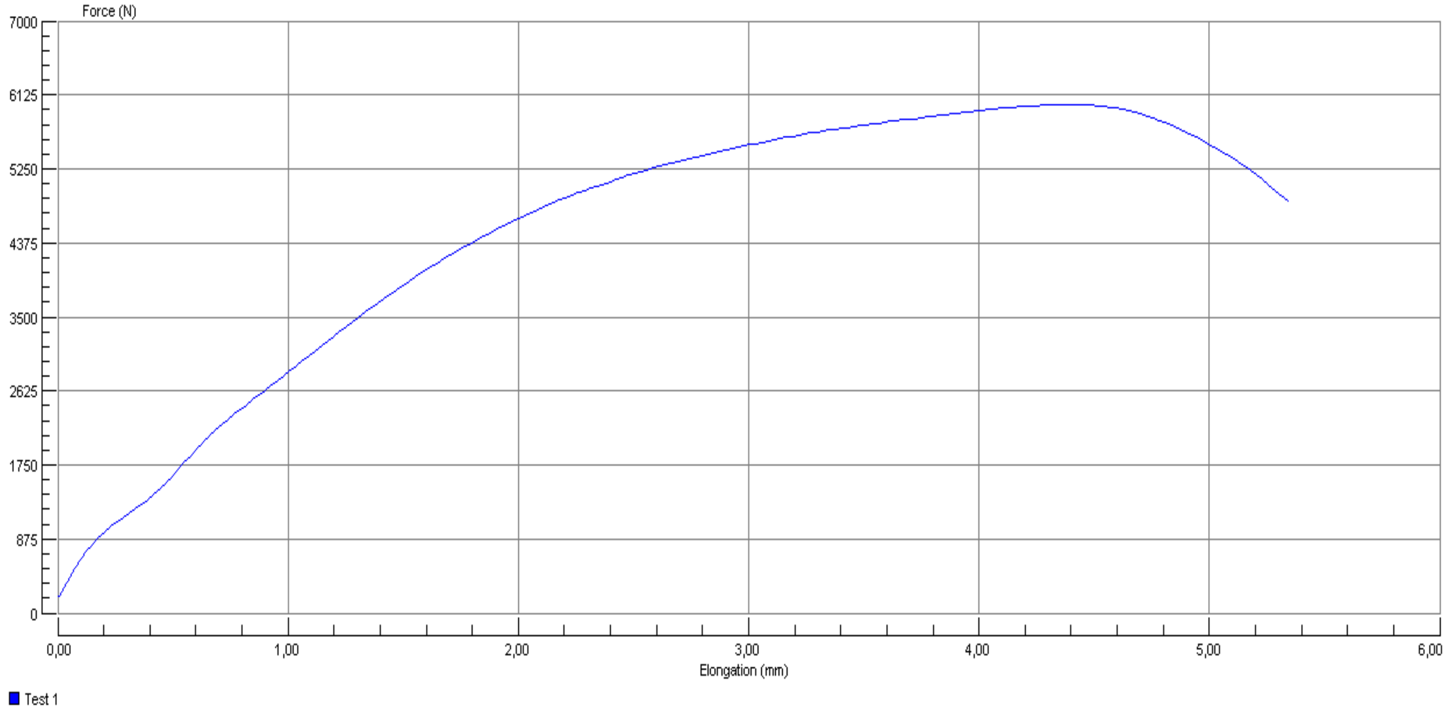
winTest™ Analysis

Tensile strength test of sheet edge riveting.

Report No.: :
Material: : Steel rivets /pallet
Manufacturer: : Jiangyin Hongseng Co
Test standard: :
Sample drawing: :

Test Name : Sheet Riveting Test
Test Type : Tensile
Test Date : 15.10.2010 13:16
Test Speed : 50,000 mm/min
Pretension : Off
Sample Length : 100,000 mm

Test No	Age:	Force @ Peak (N)
1	Tensile	6004,000



Unit 1 Lincoln Business Park Lincoln Close,
Rochdale, Lancashire, England OL11 1NR

Tel: (44) (0)1706 654039 Fax: (44) (0)1706 646089
Email: info@testometric.co.uk website: www.testometric.co.uk

Testometric
materials testing machines

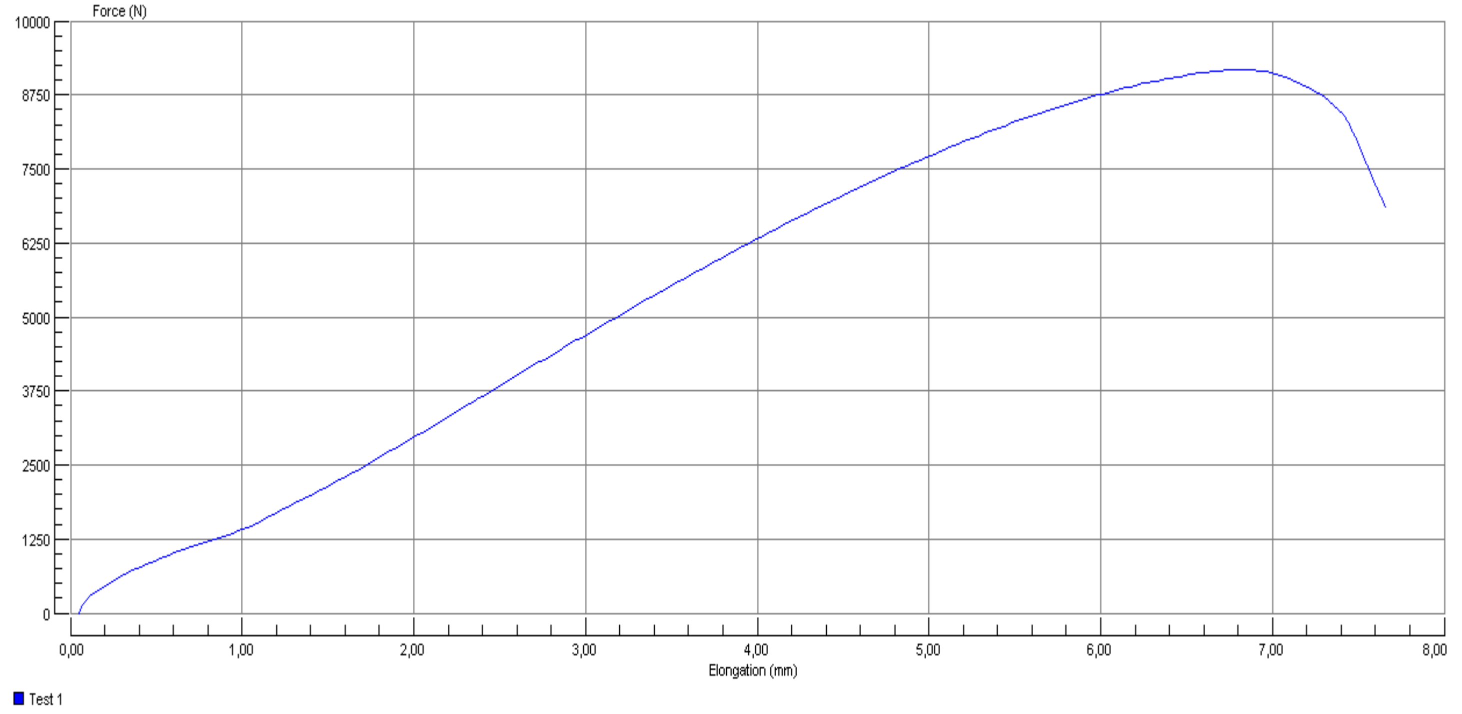
winTest™ Analysis

Tensile strength test of sheet edge riveting.

Report No.: :
Material: : Steel rivets /pallet
Manufacturer: : Jiangyin Hongseng Co
Test standard: :
Sample drawing: :

Test Name : Sheet Riveting Test
Test Type : Tensile
Test Date : 15.10.2010 13:20
Test Speed : 50,000 mm/min
Pretension : Off
Sample Length : 100,000 mm

Test No	Age:	Force @ Peak (N)
1	Shear	9175,000



Unit 1 Lincoln Business Park Lincoln Close,
Rochdale, Lancashire, England OL11 1NR
Tel: (44) (0)1706 654039 Fax: (44) (0)1706 646089
Email: info@testometric.co.uk website: www.testometric.co.uk

E Business case

Price calculations bottom plate

Plate costs calculation

Number of units:	500	units	input
Production method:	Light Resin Transfer Moulding		output
Return of investment mould	5	years	
Plate length:	1.44	m	
Plate width:	1.412	m	
Plate area	2.03	m2	

Investments			
mould		€ 5,000.00	
Raw material cost per plate			
raw materials	170gsm Aramid	€ 9.11	/m^2
	170gsm Aramid	€ 9.11	/m^2
	450gsm Glass stitched	€ 1.87	/m^2
	Soric TF2	€ 4.76	/m^2
	450gsm Glass stitched	€ 1.87	/m^2
	450gsm Glass woven	€ 3.24	/m^2
		€ -	/m^2
		€ -	/m^2
		€ -	/m^2
		€ -	/m^2
		€ 34.45	/m^2
resin	Daron 41	€ 7.50	/kg
		2.03	kg/m^2
		€ 15.22	/m^2
Variable cost per plate			
consumables		€ 2.03	/plate
3rd party costs		€ 29.57	/plate

Cost per unit

margin DSM

Selling price DSM

Selling price Nordisk

Value composite bottom plate

ROI

enter applicable parameters
xls sheet gives output

€ 10.00	/plate	

	Weight	
	0.17	kg/m2
	0.17	kg/m2
	0.45	kg/m2
	0.115	kg/m2
	0.45	kg/m2
	0.49	kg/m2
	0	kg/m2
	0	kg/m2
	0	kg/m2
	0	kg/m2
	1.845	kg/m2
composite	7.1	kg
aluminium	14.2	kg
savings	7.1	kg	50%
value per kg	27	€/kg/year

€ 101.01	/plate	
€ 31.60	/plate	
€ 142.61	/plate	
€ 107.39		75%
€ 250.00	/plate	
€ 375.00	/plate	
€ 190.95	/plate	
2	years	

F Life cycle analysis

Report

Confidential

DSM Corporate Operations & Responsible Care
Funtional Excellence - Operations
LCA Department

Het Overloon 1
6411 TE Heerlen
P.O. Box 6500
6401 JH Heerlen
Netherlands

Phone 0044 7798724830
Email dave.morris@dsm.com

Date
April 12, 2012

From
D Morris, FE Ops

To
W Bode, DRS

cc
Y Rahardjo, FE Ops

LCA Air Cargo Containers Base Plate Comparison – Composite vs. Aluminium

1. Management Summary

In this report the final results of the Cradle to Gate LCA study for the air cargo base plate comparison are presented. The purpose of the study is to assess the environmental impact of the production and use of an air cargo base plate produced from DSM composite compared to standard aluminium base plates. This has been done using 2 methods. The 1st method (IPCC 2007 GWP 100a) assesses the carbon footprint (CFP) of the process in terms of emissions of greenhouse gases expressed as kg of CO_2 equivalent. The 2nd method (ReCiPe Europe H/A) assesses all environmental impacts across categories that relate to human health, natural resources and eco-system quality.

The carbon footprints of the 2 competing materials are shown in the table 1 below as kg CO_2 eq / base plate. This includes the production of the materials, the manufacture of the base plate and the impacts related to disposal. Use phase impacts are shown in table 2.

Table 1 – Carbon footprint expressed as kg CO_2 eq / base plate

	DSM Composite plate	Aluminium plate
Production of raw materials	29.8	65.3
Manufacture of base plate	8.6	33.7
Disposal / recycle at end of life	16.4	3.3
Total	54.8	102.3

Table 2 below compares the carbon footprint of the life time use phase impacts of the 2 base plates. This is based on the reduction in GHG emissions and other atmospheric impacts from aviation fuel due to the weight reduction of 7.2kg when using the DSM composite base plate.

Table 2 – Carbon footprint of the life time use phase

	DSM Composite plate	Aluminium plate
Global warming potential (kg CO_2 eq / base plate)	4445	9018

The use phase impacts are significantly higher than those associated with production and disposal of the base plates. The carbon footprint of the production, use and disposal of the DSM composite base plate is approximately 50% lower than that of the aluminium plate.

The graph below (figure 1) shows the eco footprint for each of the base plates. This includes the production of the materials, the manufacture of the base plate and the impacts related to disposal. Use phase impacts are shown in figure 2.

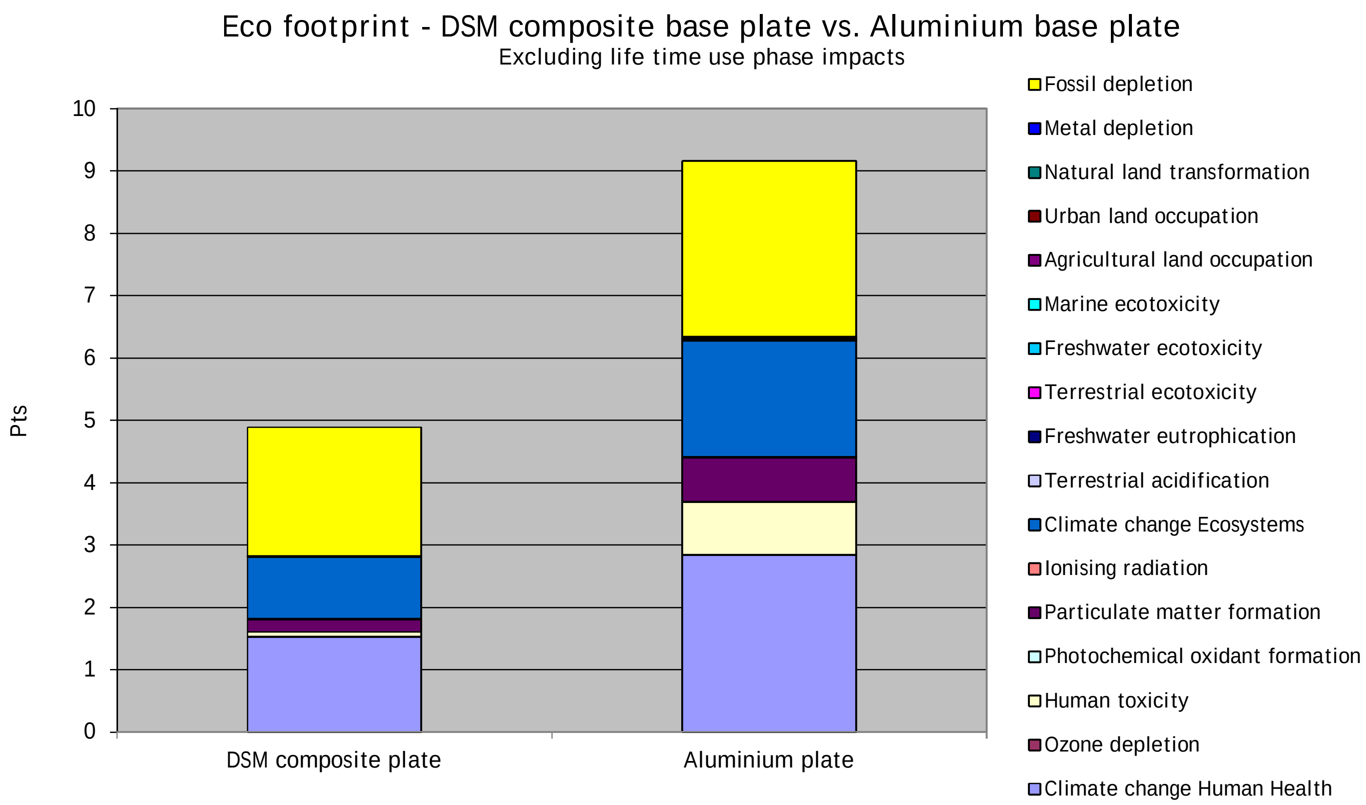


Figure 1

Figure 2 shows the eco footprint of each base plate including the life time use phase impacts. As the use phase impacts are related only to the global warming effects of CO_2 emissions from direct fuel usage and other factors such as the impact of ozone and water vapour the eco footprint is dominated by climate change impacts.

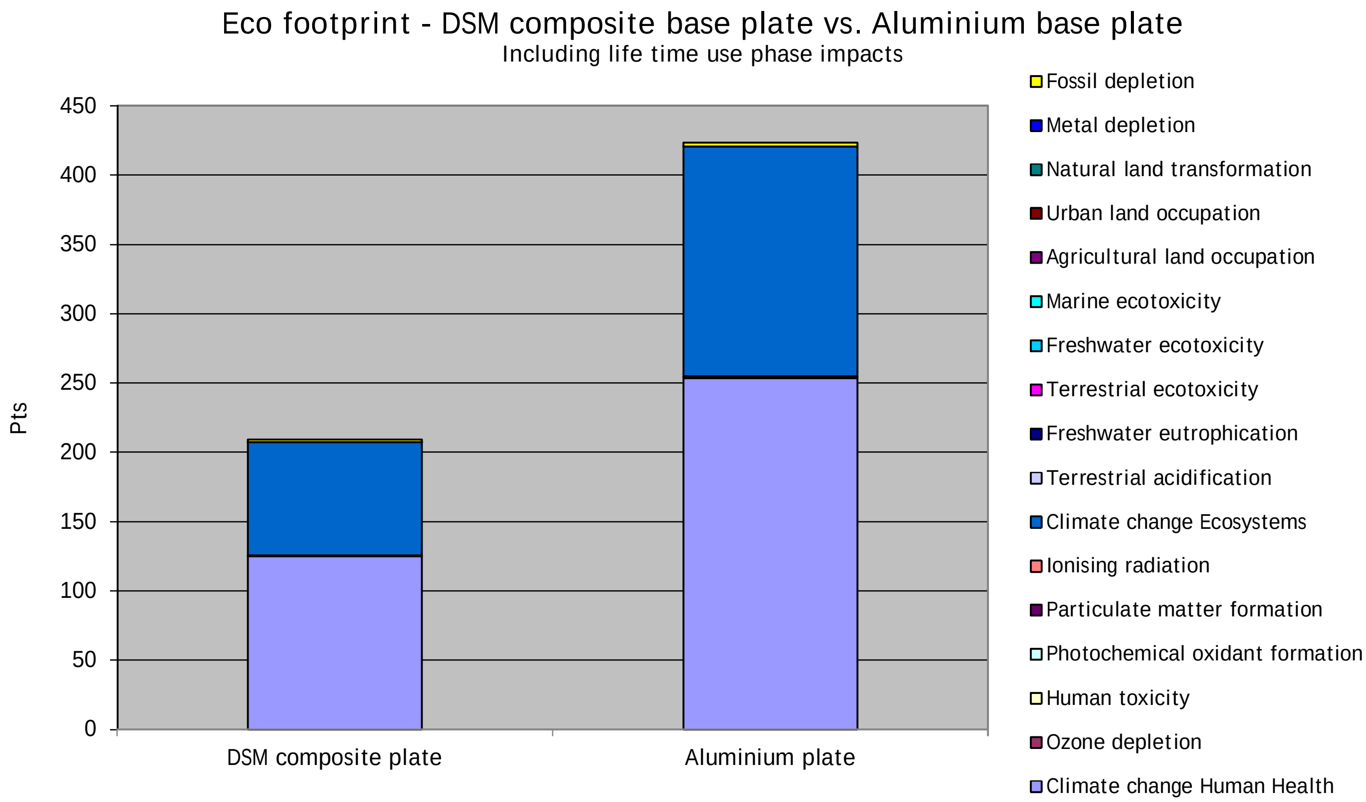


Figure 2

As for the carbon footprint the use phase impacts are significantly higher than those associated with production and disposal of the base plates. The eco footprint of the production, use and disposal of the DSM composite base plate is approximately 50% lower than that of the aluminium plate.

Due to the significantly lower impacts in human health and ecosystem categories the DSM composite air cargo base plate can be considered an ECO+ solution. ECO+ solutions are superior profitable products and services that have more ecological benefits than the mainstream competing solutions unless mainstream is the most favourable solution. The ecological benefit can be created at any stage of the lifecycle – from the raw material, manufacturing, use, to potential re-use and end-of-life disposal. ECO+ solutions create more value with less environmental impact.

The criterion used is that the ECO+ solution scores significantly better on at least 2 out of the 3 main categories of environmental impact (human health, ecosystems and resources), and on the weighted sum of the three categories. The graphs below show the ECO+ determination for the DSM composite base plate with and without life time use phase impacts.

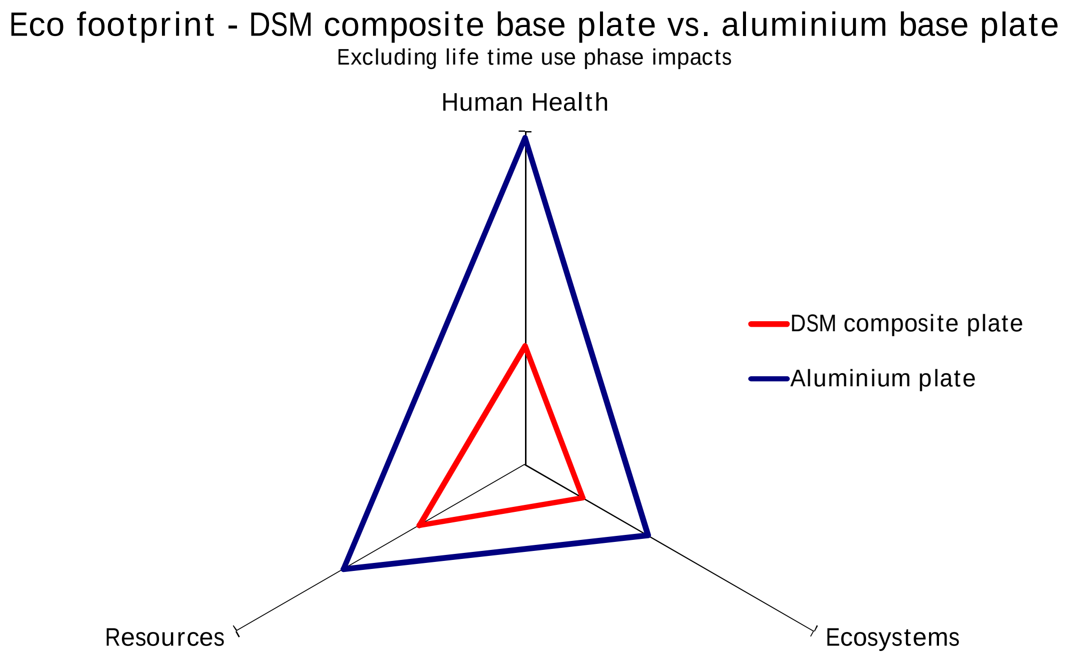


Figure 3

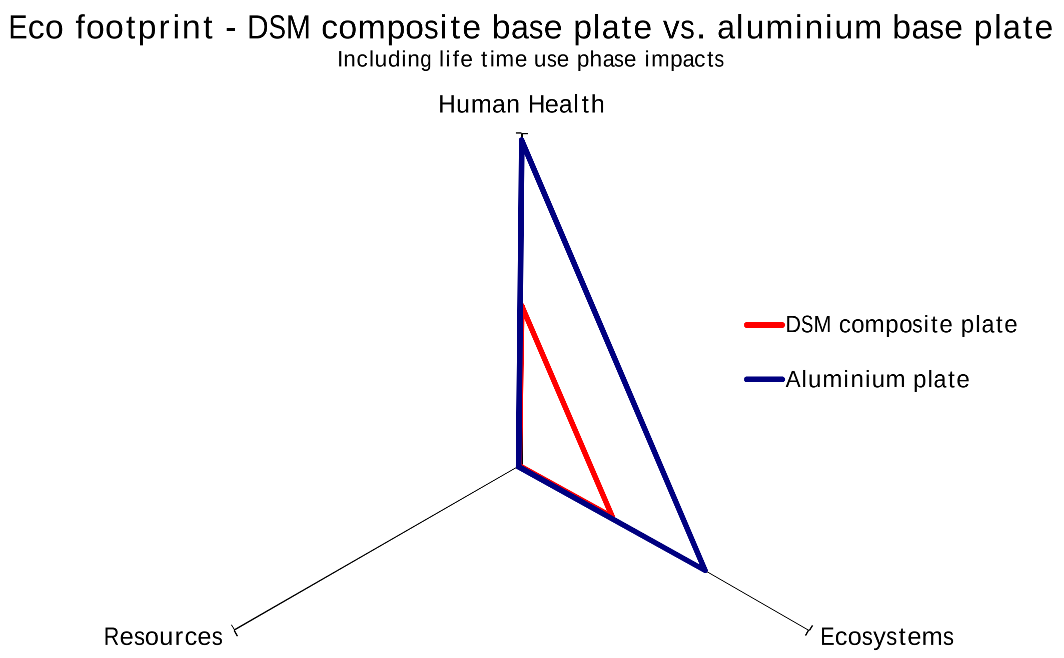


Figure 4

2. Introduction

DSM Composite Resins are investigating the replacement of aluminium air cargo container base plates with suitable composite materials. The aim is to have a lighter container while maintaining its strength and durability. They have commissioned this study to assess the environmental impact of a DSM composite base plate and compare it to the impacts of the existing aluminium base plate. These results are intended to support the progression of the project from a sustainability stand point; taking into account the benefits in the use phase of a lighter container as well as any manufacturing (cradle to gate) benefits.

3. Goal and Scope

The aim of this study is to establish the life cycle carbon and eco footprint of a DSM composite air cargo container base plate and to compare this against a competing aluminium base plate.

Methodology
The carbon footprint (CFP) is calculated using the IPCC 2007 GWP 100a assessment method and the results are expressed as kg CO_2 equivalents; using the associated characterization factors for the relevant greenhouse gases.

An eco footprint assessment has also been made using the ReCiPe v1.06 2011 endpoint (H/A) method investigating impact categories related to human health, ecosystem quality and resource depletion.

The LCA software SimaPro 7.3.3 has been used for this study. The software contains the Eco-Invent v2.2 database which details the environmental profile of many chemical processes and substances. We have used data from this database where possible and defined our own where necessary.

System Boundary
The system boundary includes all raw materials and energies required for the production of the base plate raw materials, production and assembly of the base plate, use phase impacts related to fuel consumption and weight saving, and end of life disposal/recycling.

Assumptions and approximations
The following assumptions and approximations have been used in this study:

1. The functional unit studied is 1 air cargo container base plate – 1.4m x 1.412m
2. Weight benefit DSM air cargo container base plate: 7.2kg
3. Two materials of construction are investigated: DSM composite and aluminium (alloy 7021-T6 according to EN AW-7021)
4. The production process for the DSM composite is vacuum infusion
5. As only limited information is available on the production of the aluminium base plate, a standard EcoInvent database entry for average aluminium product manufacturing via average metal working processes has been used as an approximation.
6. The emissions and energies for transportation of raw materials are assumed to be similar between the aluminium plate and the DSM composite plate.
7. The viability of end-of-life recycle scenarios for the DSM composite are not known so a worst case scenario of incineration has been assumed for end of life. This has been modeled using the standard EcoInvent database entry for incineration of average plastics as an approximation.
8. It has been assumed that the aluminium containers will be recycled at end-of-life and so a standard EcoInvent database entry has been used to model the impact of the production 'Old scrap' aluminium.
9. The CO2 equivalent emissions contributing to global warming potential (GWP) from the use of aviation fuel related to the weight of the containers throughout their life time has not been studied here as this has been investigated previously by DRS / DSM Dyneema. This assumes factor of 3.15 to convert fuel use to CO_2 emissions and a factor of 6 to convert fuel use to full

environmental impact of CO2 emissions plus emissions of other greenhouse gases, O_3 and the impact of contrails.[1]

10. A 7 year life time is assumed for the containers. It is assumed that a container will travel approximately 2.5 million km over its 7 year life time: average distance travelled by 1 plane in 7 years is 12.6 million km; assumed 1 containers travels for 20% of this. [2]

4. Data inventory

Average European production has been assumed for all materials used where geographically specific data is not available. Input data for raw materials and energy has been taken from the EcoInvent 2.2 database for modeling purposes when available. For those processes without standard EcoInvent 2.2 database entries approximations have been used, typically based on literature information. Further details on data inventory can be found in Appendix 2.

5. Results

The results of the assessment and details of the models used will be discussed in this chapter. Information regarding mass balances can be found in Appendix 1.

5.1. Carbon footprint

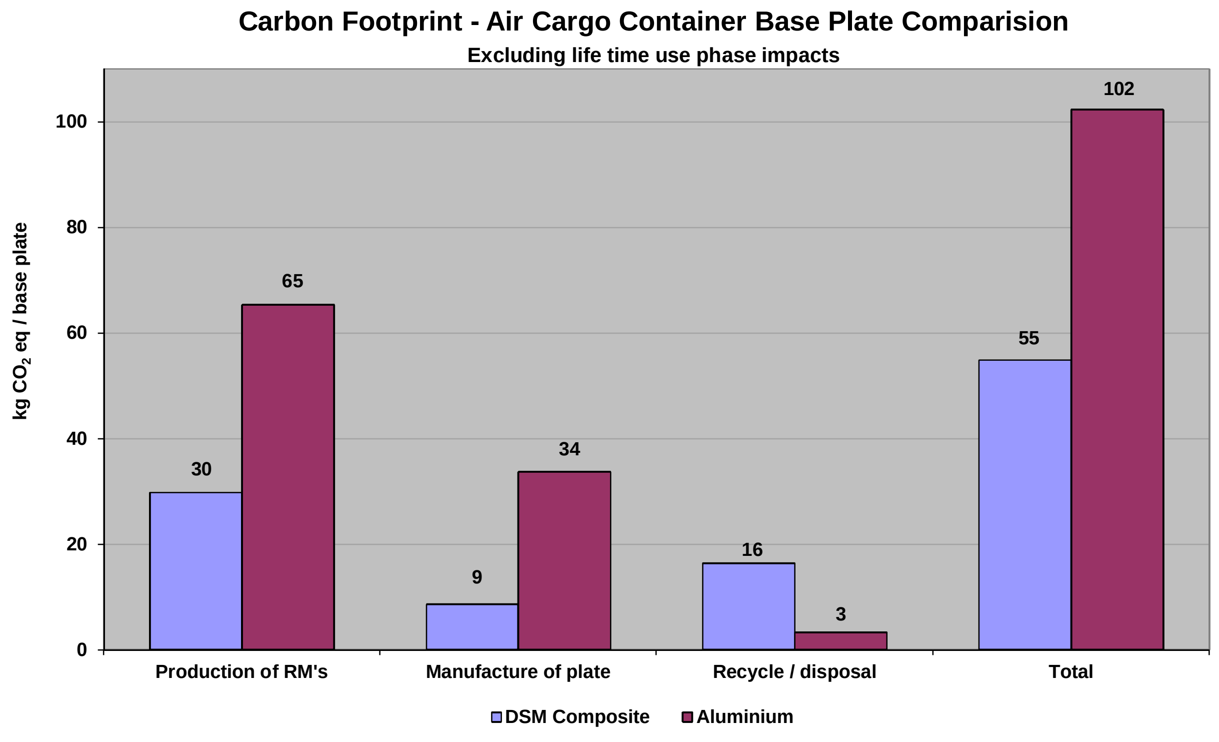


Figure 5

Figure 5 shows the carbon footprint for both base plates broken down into 3 areas; production of materials, manufacture of the base plate and end of life disposal / recycle.

The production of the aluminium alloy for use in the aluminium plate has a much higher CFP than the production of the composite resin and fibres used in the composite plate. The energy used to produce

---

[1] Emission and fuel consumption figures based on Climate care Aviation Emissions & Offsets. Part 1; Dr. C.N. Jardine; Environmental Change Institute, Oxford University Centre for the Environment, Oxford

[2] 100115 CO2 and fuel reduction by Light weight containers - Study and calculations by Ingrid Damen DSM Dyneema January 2010

the primary aluminium is a significant contributor as is the use of magnesium in the final alloy. For the composite resin the use of bisphenol A as a precursor for bis [4-(2-hydroxyethoxy) phenyl] propane and styrene monomer has the largest contribution to the CFP. The production of fibres accounts for approximately 40% of the CFP at this stage.

As mentioned earlier under assumptions and approximations the manufacturing of the base plates has been approximated using standard EcoInvent database entries for extrusion and average aluminium product manufacture. This results in a higher CFP for the aluminium base plate as its production process uses significantly more energy.

At end of life it is assumed that the composite is incinerated and the aluminium is recycled for use in lower grade applications. For this life cycle stage the incineration of the composite has a higher CFP than the energy used in the recycling process of the aluminium.

The life time use phase impacts of the base plates are the most significant and are not shown in figure 5 so the other impacts remain visible. The life time use phase impacts are calculated by assuming a reduction in fuel use and a reduction in associated the global warming potential of air travel due to the weight saving of the lighter composite base plate. Data from previous studies assumes a total global warming impact of 635 kg CO_2 eq / kg over the life time of the base plate assuming it travels 2.5 million km. Therefore, as the DSM composite base plate is 7.2kg lighter than the aluminium base plate its global warming potential in the use phase is 4573 kg CO_2 eq lower than that of the aluminium base plate.

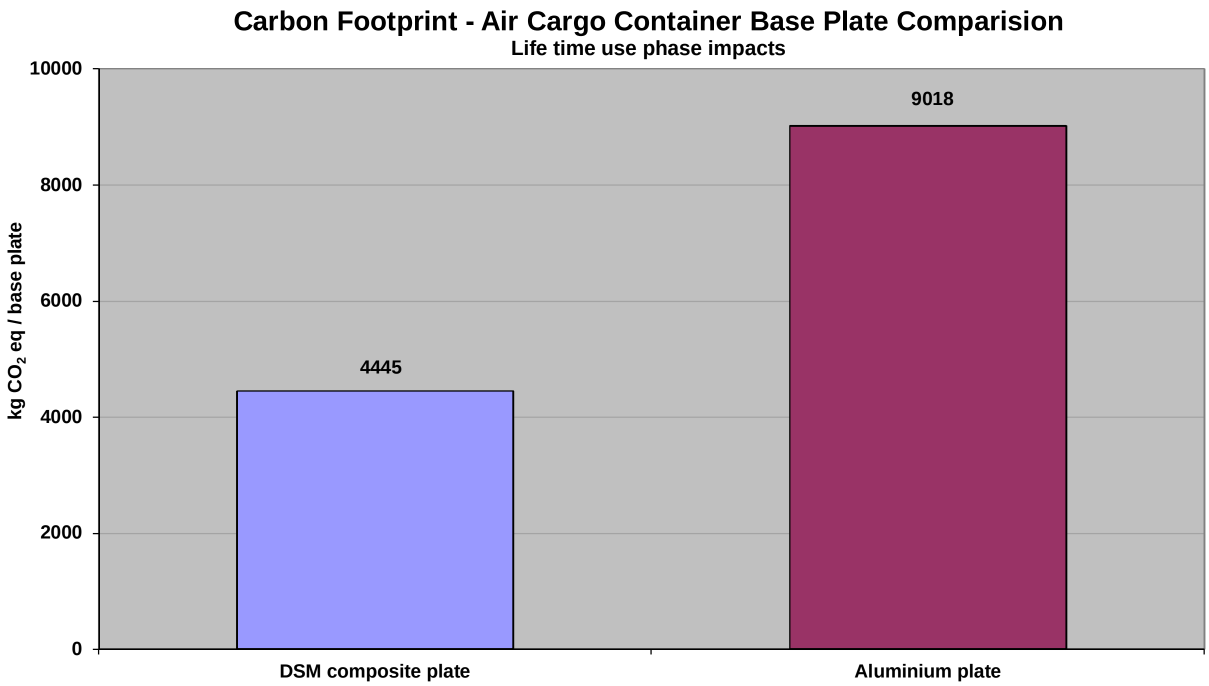


Figure 6

5.2. Eco footprint

For all life cycle phases excluding the use phase the eco footprint for both the DSM composite and the aluminium base plate is dominated by climate change impacts, the use of fossil fuels and in the case of the aluminium base plate human toxicity related to the production of aluminium and zinc used in the alloy. As shown in figure 1 above the eco footprint trend is in line with that for carbon footprint; the DSM composite base plate footprint is approximately 50% lower than the aluminium base plate.

When the impacts of the use phase are added the climate change impacts dominate the entire eco footprint. This can be seen in figure 2 above.

6. Estimate of completeness

The accuracy of the models for raw material production is expected to be within the range of ±10-20% as it is based on plant specific recipe and energy data and known processes for which standard database entries could be modified to improve accuracy.

The models for the base plate manufacturing processes and disposal/recycle scenarios are much less accurate as approximations have had to be made due to the lack of specific or primary data. However, lack of accuracy here does not alter conclusions as the use phase impacts are significantly higher.

The use phase assumptions are in line with published peer reviewed data on the global warming potential of air travel. However, there is a great deal of uncertainty generally in this area as to which factors are most representative or actually play a part in radiative forcing. As the same assumptions have been applied to the DSM composite base plate and the aluminium base plate the % difference is still valid even if the absolute values for carbon and eco footprint are affected by the assumptions used.

7. Conclusions

From the results of this study we can conclude that the weight saving associated with the DSM composite base plate when compared to the aluminium base plate has the most significant influence in reducing the carbon and eco footprints. The total reduction in carbon and eco footprints is 50%

This reduction also qualifies the DSM composite base plate as an ECO+ product.

Although the results show a more favourable environmental impact for the DSM composite base plate life cycle comparisons with specific products or product types in the public domain (publicly available comparative assertions) are not recommended until the assumptions and approximations used can be validated and the study approach verified by an independent 3rd party to accepted standards and guidelines.

8. Summary of changes

This is the 1st version of the report.

Appendix 1 – Mass Balances

Composition of DSM composite base plate
Dimensions: 1.42m x 1.412m; Weight: 7.0 kg; Thickness: 3 mm

Material	Weight (kg)
Daron 41	3.4
450gsm stitched glass fibre	0.9
450gsm stitched glass fibre	0.9
115gsm Lantor Soric TF2 felt	0.23
450gsm stitched glass fibre	0.9
170gsm woven Twaron 2200 Aramid	0.34
170gsm woven Twaron 2200 Aramid	0.34

Composition of aluminium base plate
Dimensions: 1.42m x 1.412m; Weight: 14.2 kg; Thickness: 2.5 mm

Material	Weight (kg)
Aluminium alloy - Al7021-T6	14.2

Appendix 4: Approval sheet

This document was reviewed, validated and approved by:

Subject	Role	Name	Date	Signature
Data used				
Footprinting calculations	LCA Expert	D Morris	09/05/13	
Review of calculations	LCA Reviewer			
Presentation of results				
Commercial use				

G Full scale test results

	Date:	2013-09-23
	Revision:	0
	Report No.	TR-26631

TEST REPORT

Dynamic Roller Load Tests of bases

Tests were performed at NAP Holmestrand the 2013.

Prepared by:	Christian Arnesen	Date:	2013-09-23
Signature:			

Approved by:	Frode Eriksen	Date:	2013- -
Signature:			

Revision	Amendment	Issue Date	Eff. Date
0	First edition	2013-09-23	2013-09-23
1			
2			
3			

Test(s) were witnessed by:

Christian Arnesen NAP Engineering

Contents

1 Purpose of test

2.5 mm aluminum base sheet was first tested to establish an initial reference for composite material suitability for use in K-size base application.

The composite base sheets were then tested to determine the their potential as replacements for aluminum sheets.

2 Container description

General characteristic:

Base size: 60.4” x 61.5”

Construction:

- 2.5 mm aluminum sheet.
  - Standard “K” size base with single solid aluminum sheet and extruded edge rails attached to base sheet using glue (3M DP8005).
- 2.3 mm Monolithic Kevlar sheet.
  - Glued connection (3M DP 410)
- 3.2 mm Kevlar/glass/Soric sandwich sheet.
  - Glued connection. (3M DP 410)
  - Riveted connection using CSK steel rivets (after failure of glued connection).

3 Loads

3.1 Test loads

1500 KG of evenly distributed sandbags.

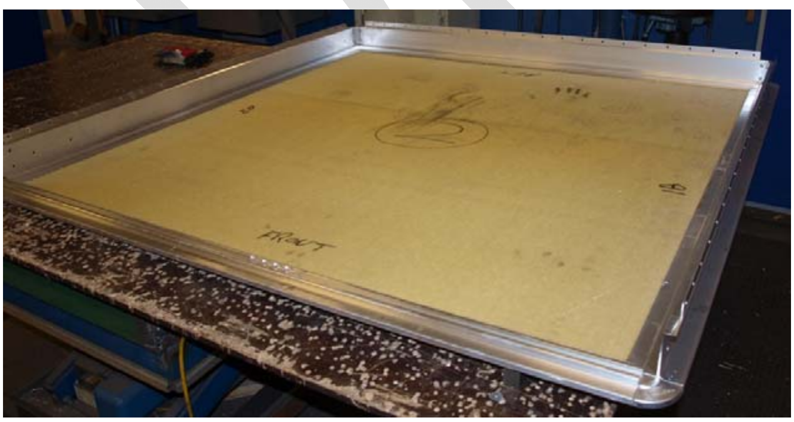
Sandbags are stacked inside a lifting bag, to support loading and unloading.

Picture 1:

4 Test specimen

Three K-size bases were made

- Base nr 1 was made of a 2.5 mm thick solid aluminum sheet of alloy 7021-T6.
- Base nr 2 was made of 2.3 MM Monolitich Kevlar sheet
- 3.2 MM Kevlar/glass/soric sandwich sheet
- Base edge rails were all made of alloy 7003-T5/T6.
- Extrusions were glued onto the sheets using glue from 3M



Picture 2:

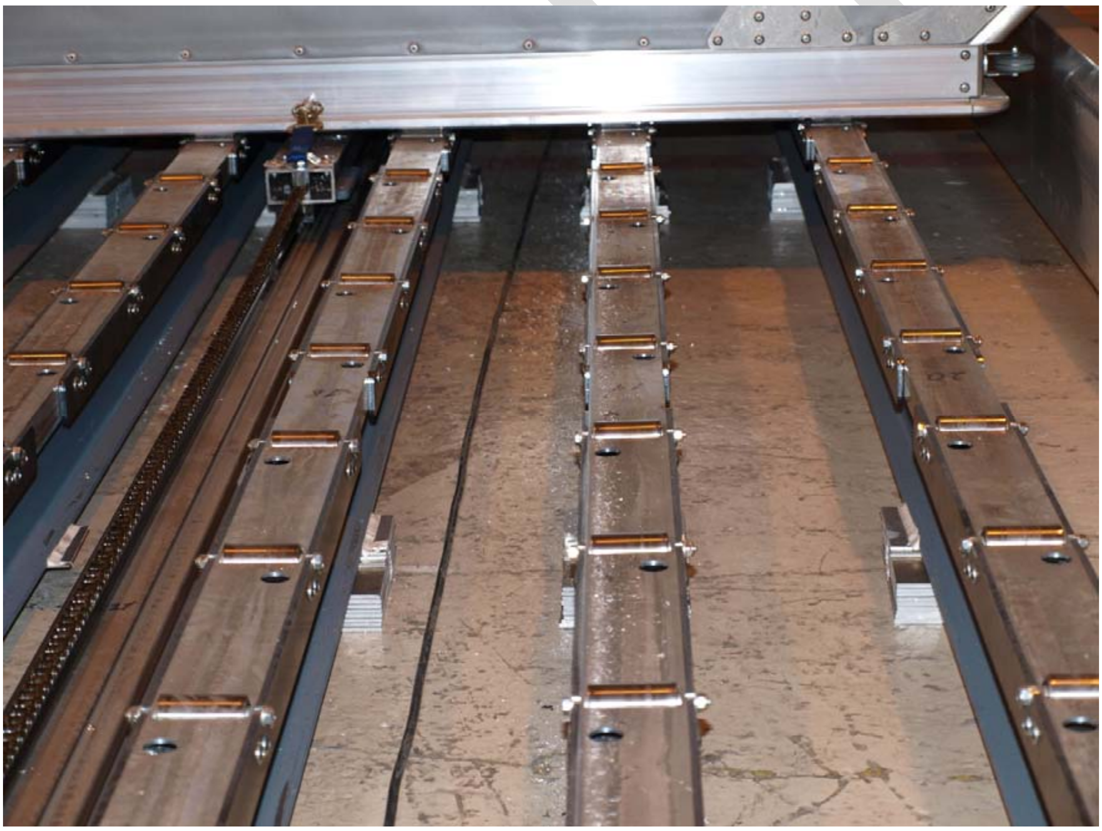
5 Test performance

5.1 Equipment

- Custom made 1400X1400mm Lifting bag
- Control weighted Sandbags, 25 kg each
- Automated roller-bed machine.

5.2 General methods

The base is attached to a linear movement carriage. The base is then traversed in a linear movement back and forth over a roller bed. The base is unloaded and inspected after a certain number of cycles. (1 cycles is defined as complete forward and back movement of the base, which for K-size is 7,3 meters)



Picture 3:

6 Test results

6.1 2.5 mm monolithic aluminum sheet

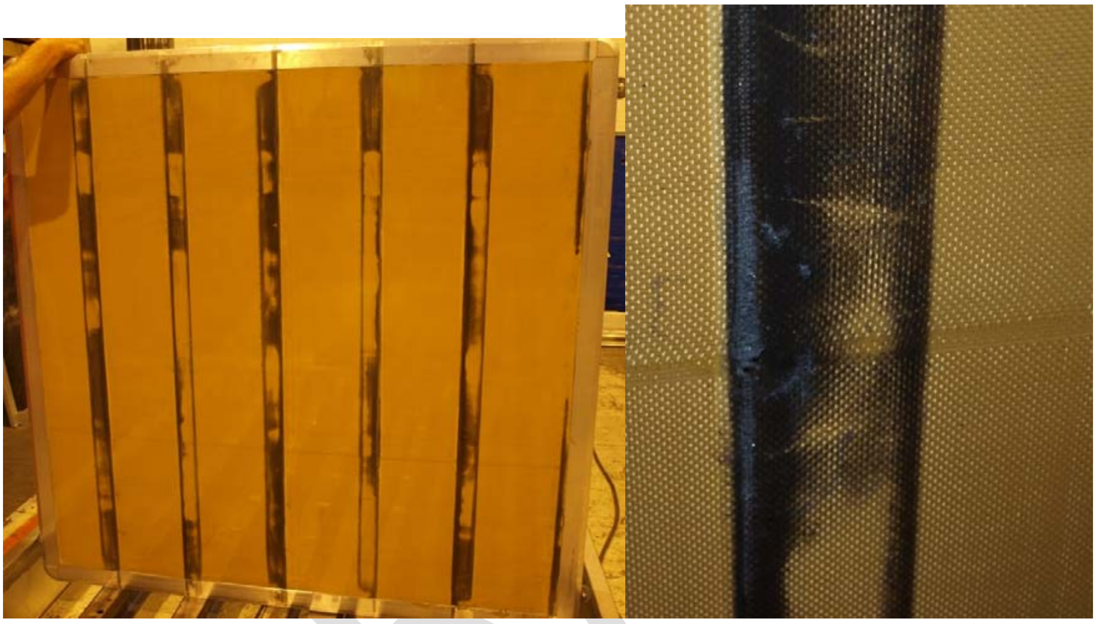
The base was checked according to the following inspection intervals.

2,5 mm Aluminum				
cycles	Measured indentation (mm)	Number of cracks (mm)	Length of cracks (mm)	Notes
100	0,15	0		Visible wear from rollers.
200	0,3	0		Some deformation in one section of the sheet.
300	0,19	0		Deformation on two sections of the sheet.
400	0,19	0		Visible deformation in edgerail extrusion.
500	0,13	0		
600	0,14	0		
700	0,13	0		
1000	0,14	0		
1300	0,18	0		
1600	0,17	0		
1900	0,24	0		
2200	0,24	0		
2500	0,2	0		
3000	0,23	0		
4000	0,22	0		
6000	0,2	0		
7854	0,25	1	21	Edge rail glue attachment failed. Crack detected in sheet.
8354	0,4	1	29	
9000	0,4	1	130	
9500	0,45	1	150	
10000	0,6	1	185	
10500	0,6	1	185	
11000	0,6	1	185	
11500	0,65	1	205	
12000	0,65	1	205	
12500	0,9	3	260	Cracks start to become visible in topp of sheet.
13000	0,78	5	260	Test aborted due to amount of damage

Picture 4-5: 2.5 mm aluminum

6.2 2.3 mm monolithic Kevlar sheet

2.3 mm solid Kevlar				
cycles	Measured indentation (mm)	Number of cracks (mm)	Length of cracks (mm)	Notes
200	0,4	0		Visible wear from rollers. Some deformation in one section of the sheet
400	0,65	0		Deformation on two sections of the sheet.
600	0,71	0		Visible deformation in edgerail extrusion.



Picture 6-7: monolithic Kevlar sheet

6.3 3,2 mm Kevlar/Glass/Soric sandwich sheet

3.2 mm soric sheet				
cycles	Measured indentation (mm)	Number of cracks (mm)	Length of cracks (mm)	Notes
200	0,15	0		Visible wear from rollers.
400	0,3	0		
600	0,7	0		soric exposed
800	1	0		5 rivets missing

Picture 8: Kevlar/Glass/Soric sandwich sheet

Picture 9-10: Kevlar/Glass/Soric sandwich sheet

7 Conclusion

The two composite sheets that were tested in the full scale roller bed jig did not satisfy the operational requirements for further development of these two specific concepts. Both the monolithic Kevlar sheet and The Kevlar/Glass/Soric sheet were not able to match the performance of the 2.5mm aluminum sheet. The performance was under with at least a factor of 10.

7.1 Monolithic 2.5 mm Aluminum sheet:

This sheet was tested in order to obtain a benchmark for the composite sheets. Pull bar test revealed that it took approximately 16 KG in order to move it over the roller. Testing was stopped at 13 000 cycles, since it was deemed unserviceable. It had then developed 5 visible cracks in the sheet.

7.2 Monolithic Kevlar sheet:

This sheet was measured to 2.3 mm thick. The lacking stiffness of this sheet was evident, due to the fact that it was extremely hard to move the loaded base over the roller. 2 men were needed to push it along the rollers, since it deflected greatly over the rollers. Pull bar test was not preformed. Damage to the underside of the sheet was early evident.

7.3 Kevlar/Glass/Soric sheet:

This sheet was 3.2 mm thick and had improved stiffness characteristics compared with the monolithic Kevlar sheet, but it performed worse than the 2.5 mm aluminum sheet. The glued connection between sheet and edge rails failed after 153 cycles. Edge rails were reattached using stainless steel rivets for 3 sides, and testing resumed. Pull bar test was not preformed. The Soric core shoved clear signs of being collapsed by the passing rollers. Damage to the underside of the sheet was early evident.

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