LASS, Lightweight Construction Applications at Sea

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Fire Technology

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Abstract

The LASS project– **Lightweight construction applications at sea** – aimed at improving the efficiency of marine transport and increasing the competitiveness of the Swedish shipping industry. The target was to accomplish this through the development and the demonstration of practical techniques for using lightweight materials for ship construction.

The consortium behind the project consists of representatives from the shipping industry, material manufacturing industries, universities and research institutes as well as public authorities and classification societies. The project started in January 2005. LASS is sponsored by VINNOVA (www.vinnova.se), participating industries and other partners. This report contains a description of some of the accomplishments made.

Key words: lightweight, ship building, composite, aluminium, fire safety at sea

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Table of contents

1 Introduction

In 2003 the Swedish Governmental Agency for Innovation Systems, VINNOVA, made a call for research applications within the area of "Lightweight Materials and Lightweight Design". The aim was to support a transition from high density construction materials to more sophisticated lightweight materials and to create networks of organisations (industry, research, authorities...) into a Technical Platform of various and complementary knowledge and know-how that could both support and sustain the said transition.

A disadvantage of lightweight materials is the lowered fire resistance compared to high density materials and a lightweight construction development therefore requires fire safety engineering in order to maintain the same level of safety as for traditional material. In response to the VINNOVA call, the Department of Fire Technology at SP Technical Research Institute of Sweden contacted different industries to identify areas for developing new lightweight constructions where fire science and fire safety engineering would be of particular value. A Swedish group of maritime industries were quick to respond and also very enthusiastic about the idea of developing lightweight constructions for shipbuilding. The driving force for this was the need to lower fuel costs by using lightweight ships but also the need for constructions that would enhance ship stability. Using more lightweight materials in the upper parts of the ship will lower the ship's centre of gravity and thereby increase its stability.

The combination of a strong industrial interest and the need for fire safety design was the basis for SP Fire Technology to prepare and send an application to VINNOVA entitled "Lightweight construction applications at sea" (LASS). The core task described in the application was to investigate technically and economically four different vessels where appropriate parts had been re-designed using lightweight materials. The target was to be able, after the finished project, to provide practical solutions for how to actually build a lightweight ship using either aluminium or fibre reinforced polymer (FRP) composite as construction materials. Constraints were that the weight reduction should be at least 30 % where new materials were used and that the total cost should be at least 25 % lower based on a life cycle cost analysis (LCCA).

The objects for study were:

1. A 24 m all composite passenger HSC (high speed craft)
2. An 88 m aluminium high speed catamaran with an FRP composite superstructure
3. A 199 m RoRo vessel with an aluminium deck house
4. A 188 m RoPax vessel with an FRP composite superstructure.

The application was accepted by VINNOVA in the autumn of 2004 and the kick-off meeting was held in Borås in January 2005. The project officially ended the 30th of June, 2008.

The LASS-project originally gathered twenty industries and organisations and had a budget of 22.1 MSEK (~2.4 M€) of which 50 % was funded by VINNOVA and the rest provided by the participating partners as direct financial support or as support in kind. The partners, including ship owners, ship designers, ship organisations, ship yards, material manufacturers, authorities and researchers, represented a highly qualified Technical Platform for the given task of investigating lightweight ship construction.

In addition, nine more industries later joined the group as associated LASS members in order to strengthen the important area of insulation expertise but also support two new objects that were introduced into the project:

5. An 89 meter dry cargo freight vessel with parts in FRP composite
6. An offshore living quarter (LQ) module in aluminium.

Due to support from the associated new industries but also due to a stronger support than planned from the original group of industries, the final financing of the LASS project has been over 25 MSEK (> 2.75 M€).

When the time has come to summarise what has been achieved, it turns out that this is quite a complicated task as so much has been done by so many people. In this report, we have chosen to describe the most central and important parts of the project. A long list of separate reports is available providing more details of the full research program. These reports are provided as appendices to this main report and can be downloaded from the LASS website: www.lass.nu.

The project will continue in different forms, e.g. in a new project "LASS-c" where parts of a large cruise vessel will be re-designed in FRP-composite, but also through ongoing co-operations between the LASS-group and the EU projects SAFEDOR (Integrated Project), "De-Light Transport" (STREP) and SURSHIP (Eranet). New developments will continuously be reported on the LASS website.

In summary, the LASS project has been very successful and all project targets have been reached. More than 30 scientific/conference papers or articles in important scientific journals have been published together with a number of short texts or notes in different papers. Six Masters theses and one Licentiate thesis have been produced in co-operation with different Swedish universities.

Central to the project has been to demonstrate certified fire safe composite constructions, e.g. for 60 minutes fire resistant deck and bulkhead constructions. Before the LASS project there were, to our knowledge, no certificates at all for composites[i] and over a dozen construction certificates have been produced within LASS using new lightweight insulation materials. These certificates make it possible to actually build a high speed craft (HSC) in FRP-composites in accordance to the HSC-code and also provide a basis for composite constructions in SOLAS vessels. A methodology for demonstrating fire safety on lightweight SOLAS vessels has also been developed together with a DNV[ii]-led subgroup within SAFEDOR and several commercial projects are ongoing or planned based on the LASS-results. Last but not least, a large number of people have learnt a lot about lightweight constructions through the LASS project. The core group within the LASS research team is given in Table 1-1 but many more has worked directly or indirectly on the LASS project.

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[i] Some laminate based certificates existed but none based on ceramic or mineral wool materials

[ii] The Norwegian classification society "Det Norske veritas"

Table 1-1 LASS research team

ORGANISATION	MAIN RESPONSIBILITY	CONTACT	WEBSITE
SP Fire Technology	Co-ordination, fire safety	Tommy Hertzberg	www.sp.se
SICOMP-Swerea	Composite HSC	Kurt Olofsson	www.sicomp.se
Chalmers Naval Architecture and Ocean Engineering	Aluminium catamaran	Anders Ulfvarson	www.chalmers.se
SSPA	RoRo vessel with aluminium	Peter Gylfe	www.sspa.se
Kockums	-RoPax and dry cargo vessels with composite	Henrik Johansson	www.kockums.se
Emtunga	Off-shore LQ	Peo Svärd	www.emtunga.com
KTH Machine Design	LCCA and LCA	Anna Hedlund-Åström	www.kth.se

Two conferences were held presenting LASS results. The first, held in Borås in October 2007, gathered 150 people from more than 10 countries. The second, held at the Kockums yard in Karlskrona, May 2008, assembled more than 50 people. The second conference was organised in co-operation with EU project ”De-light Transport”.

Finally, working together with a very skilled group of researchers and at the same time working and interacting with a highly motivated team of industrial and other partners in the LASS group has been a pleasure and a privilege.

Borås, 090131
Tommy Hertzberg

Figure 1-1 Studied objects in LASS

2 Background

When lightweight materials are discussed as an option for new ship constructions, one should bear in mind that it is necessary to overcome not only technical and fire safety issues but also the long empirically-based tradition of ship building. This is a conservative business and new technologies do not easily appear until thoroughly tested and proven economically sound. Also, both the IMO regulations and the design rules given by the classification societies provide obstacles necessary to overcome in the process.

Shipbuilding is regulated by national authorities (the flag state) as well as international organisations, in particular the IMO (International Maritime Organisation). In the end, the flag state has to accept the ship design if the ship shall be allowed to sail but usually the flag state leaves this task to a classification society (DNV, Lloyds, Bureau Veritas....) in terms of requirements for mechanical properties and design. However, the flag state usually provides general safety regulations for the ship, including fire safety, and these regulations are based on the IMO code SOLAS[1] (Safety of life at sea). The IMO also has a particular set of regulations for high speed crafts provided in the HSC-code[2]. Such crafts are defined by a minimum speed/displacement quotient but also by requirements for land based safety support. Until recently, SOLAS prohibited the use of lightweight construction materials by requiring (Chapter II-2 reg.11):

> "The hull, superstructures, structural bulkheads, decks and deckhouses shall be constructed in steel or equivalent materials....." [iii]

In July (2002) a new SOLAS regulation 17 (part F), “Alternative design and arrangements” appeared that made it possible to use a functionally based safety design instead of the earlier design based solely on prescriptive rules. This new regulation opens up for the possibility of using any construction materials provided the same level of safety can be demonstrated as if the standard materials defined by the prescriptive regulations had been used for ship design. A problem, however, is that no safety level is defined in SOLAS, i.e. the code provides a set of prescriptive rules but no measure of what the usage of these rules means with regards to safety. Therefore, not only will it be necessary to demonstrate safety of the new design but also to develop a methodology for demonstrating safety equivalence with a prescriptive-based design.

SOLAS also defines (Ch X) high speed crafts (HSC’s) with safety regulation given by the HSC-code that does allow non-steel construction materials provided that they are “fire restricting”. This means that they must pass a large scale fire test according to ISO 9705[3] with tough requirements on the amount of heat released and smoke produced by the material when submitted to the heat from a gas burner. The HSC code first appeared in 1994 and has further evolved in response to the need for regulations concerning this particular craft and is perhaps more modern than many other parts of SOLAS, at least with regards to the possibility to use new construction materials.

Another area with a strong need for fire safety requirements at sea is the offshore industry. The IMO regulation for offshore construction is the MODU (Mobile Offshore Drilling Units) code[4] (which first appeared in 1979) and it can be seen that many requirements for fire safety on offshore constructions resemble the requirements for ships. However, in the code (Ch 9.1.2.) it is stated that: “Units constructed of other

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[iii] “Steel or equivalent” means first of all ”non-combustible” construction materials, which in principle is the same as inorganic materials. This phrase was originally put in the SOLAS code to prevent the use of wood for ship building

materials" (than steel) "may be accepted provided that in the opinion of the administration they provide an equivalent standard of safety".

Table 2-1 Fire-hazard management at sea SOLAS, Chapter II-2

SOLAS	Area
Part A	General
Part B	Prevention of fire and explosion
Part C	Suppression of fire
Part D	Escape
Part E	Operational requirement
Part F	Alternative design and arrangement
Part G	Special requirements

The fire safety chapter in SOLAS consists of seven different parts (see Table 2-1). In the new part F it is stated that the general demands for fire safety objectives and functional requirements defined in part A should be fulfilled when the prescriptive regulations in B, C, D, E or G are deviated from and further that the design has to be analyzed, evaluated and approved in accordance with the regulation. The information given in part F on how to accomplish the analysis is very brief but the IMO provides a document, MSC/Circ. 1002[5], that give an idea of a methodology to use when demonstrating equivalence in safety. A schematic view of the methodology is given in Figure 2-1.

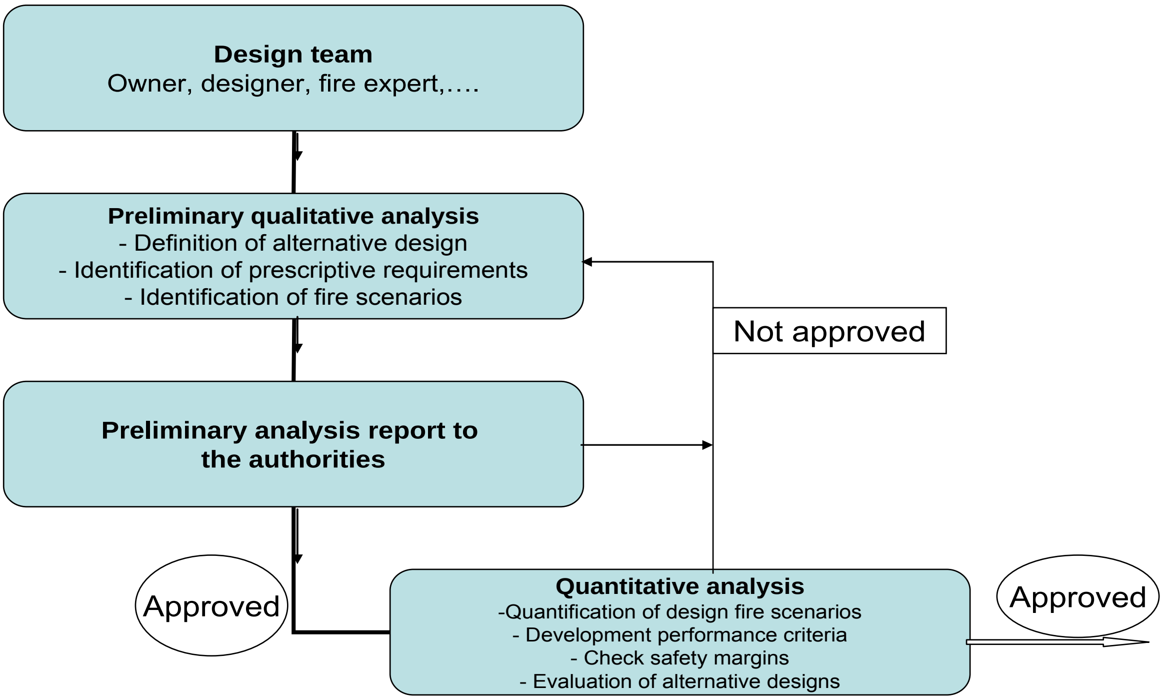

Figure 2-1 Flow scheme of the methodology given by MSC/Cirk 1002 to fulfil regulation 17 in SOLAS.

It is not self evident how to e.g. identify suitable fire scenarios or how to make a trustworthy quantitative analysis but at least the flow scheme provides a structure for such work.

2.1 Appendix-reports

A number of studies have been made as part of the LASS-project and much information will for practical reasons be presented in the form of separate reports, so called “appendix-reports” throughout this document. All these reports can be downloaded from the project website: www.lass.nu.

The first such work to be published was an interesting study of Swedish shipowner attitudes towards lightweight ship construction. This study was conducted as part of a Masters Degree project, run by two students at the Linköping Technical University. Their work (in Swedish) is documented in the appendix-report: “Degree project - Shipowner lightweight attitudes”.

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[1] *The International Convention for the Safety of Life at Sea: SOLAS*, 4th ed., International Maritime Organization, IMO publications, London 2004

[2] *International Code of Safety for High-Speed Craft, 2000: HSC Code*, International Maritime Organization, IMO publications, London 2001

[3] International Standard – Fire tests -- *Full-scale room test for surface products*.
ISO 9705:1993(E) International Organization for Standardization, Geneva, 1993

[4] *Code for the Construction and equipment of Mobile Offshore Drilling Units: MODU code*, International Maritime Organization, IMO publications, London 2001

[5] *Guidelines on alternative design and arrangements for fire safety*, MSC/Cirk.1002, International Maritime Organization, IMO publications, London 2001

3 Lightweight at sea

The use of more advanced and lightweight materials might be a very powerful method to increase technological depth and add value to a product, which in turn might provide significant competitive advantages. However, the old system will most likely be well known and tested whereas the change of material and/or construction methods will require new techniques and add unexplored hazards to the design. Indeed, these simple truths carry the seed for the three main obstacles for lightweight constructions at sea:

Technical difficulties. New types of constructions and mixing of materials with different mechanical properties will raise questions such as: how to mix construction materials with different mechanical properties, how to actually make a new design when there are no rules or guidelines for using the material or at least existing rules and guidelines are not optimised to take full advantage of the new material.. The most critical task to solve is, however, how to make and how to demonstrate that the new ship design using lightweight materials is fire safe.

1. **Tradition.** There is a general lack of knowledge concerning lightweight materials in the marine business (ship owners, ship yards, classification societies, national authorities etc.). There also seems to be a generally conservative attitude in the business, perhaps supported by the fact that any new type of ship construction might be an expensive experiment.

2. **Cost.** More advanced materials are usually more costly and if the ship owners look at initial costs only, lightweight construction will perhaps not be considered interesting. However, if a life cycle cost and environmental impact analysis is made, lightweight materials become more interesting.

The economic advantages from lightweight materials could be estimated from different aspects. Either one could calculate cost reduction per ton-km based on fuel savings or based on increased load capacity. The bunker fuel savings could be substantial, however, it is usually much easier to get a short pay-back time by using the weight savings to increase load capacity, even though this might change as bunker price increases further. Other things to incorporate in the cost comparison are maintenance/aging/recycling, engine power requirement (i.e. less power requirement translates into less expensive engines), etc.

Tradition and conservatism in the ship building industry is probably best tackled by demonstrating that lightweight constructions at sea are possible and economically beneficial. However, there might presently be an additional obstacle due to the fact that ship building at the moment (2008) is the seller's market. The demand for new ships is high and a ship owner might have to wait several years to obtain a new vessel. A yard that is used to making steel constructions might therefore be reluctant to invest in lightweight know-how as long as there are customers fully satisfied with conventional steel constructions. However, the economic and ecological benefit of lightweight materials will probably induce sufficient momentum for a change to take place sooner or later.
What is needed for the transition is practical examples of how to make lightweight constructions, the main objective of the LASS project.

3.1 The LASS project

The project “Lightweight construction applications at sea”, LASS, has between January 2005 and June 2008, been focused on developing practical methodologies for using lightweight constructions partly or wholly for the design of six different objects: five ships and one offshore living quarter module. Originally, the LASS project group consisted of twenty parties from different fields: ship owners, ship yards, material manufacturers, ship designers, military marine industry, different ship organisations and a research group from universities and institutes. However, the LASS group later expanded to include a total of twenty-nine organisations (see Figure 3-1).

Figure 3-1 The LASS consortium.

Somewhat more structured, the consortium is described by organisation-blocks in Figure 3-2. Kockums, the Swedish ship yard situated in Karlskrona on the Swedish east coast, was an important part of the research group as they were responsible for two of the total of six work packages that studied redesigned lightweight objects. They are, however, for clarity of organisations situated in the ship yard block in Figure 3-2.

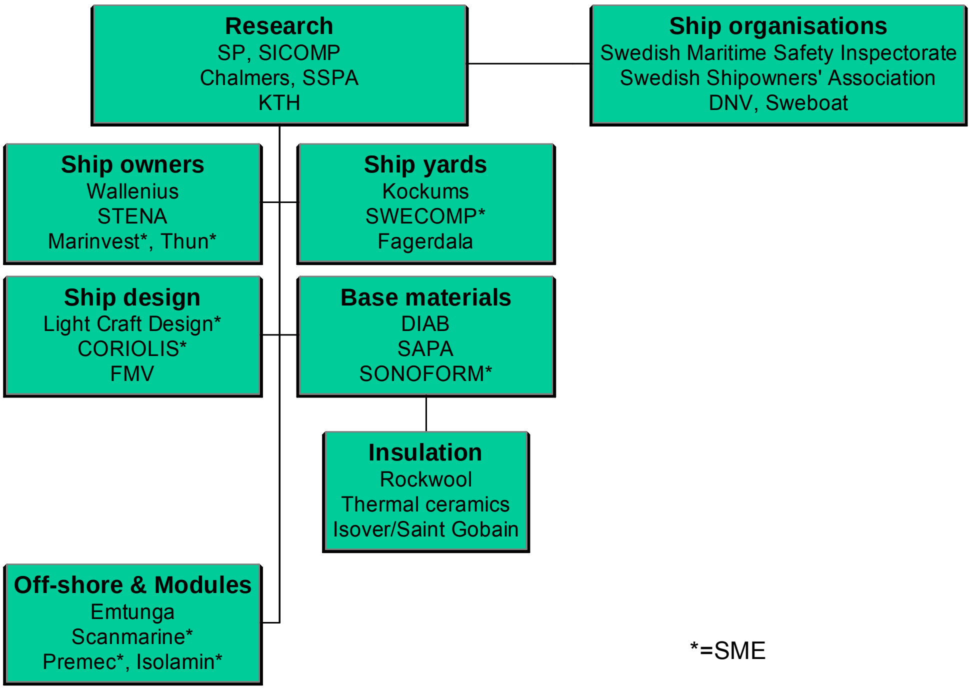


Figure 3-2 The LASS consortium

3.2 Lightweight materials used in LASS

The lightweight construction and insulation materials used in the project are briefly described below.

3.2.1 Construction materials

The lightweight construction materials used in LASS are

1. aluminium, with the possibility of forming structured elements
2. sandwich construction material consisting of two fibre-reinforced polymer (FRP) laminate on each side of a core of lightweight PVC foam (see Figure 3-3).

The sandwich material is the more controversial of the two materials in ship building as it is combustible. The drawback of aluminium compared to steel from a fire perspective is its relatively low softening and melting temperature; ~200 °C and 660 °C, respectively. Softening temperature of steel is 400-500 °C and melting could be 1400-1500 °C.

The weight quotient between aluminium and steel is ~1/3, steel having a density of ~7800 kg/m^3 and aluminium a density of ~2600 kg/m^3. A steel plate having a thickness of 7 mm (a typical thickness for a RoPax superstructure) therefore weighs almost 55 kg/m^2. A similar aluminium plate weighs 18.2 kg/m^2. The weight of a composite differs depending on the density of the core material and the thickness and fibre content of the FRP laminate. Typically the core material used has a density between 60 and 200 kg/m^3 and a thickness of 25-100 mm. The laminate is at least 1 mm thick and has a density of about 2000 kg/m^3. A composite construction consisting of a 50 mm core surrounded by two 2 mm laminates (a construction that from a strength perspective could very well replace a 7 mm steel plate) would then have a weight of 12 kg/m^2, i.e. the composite-steel quotient would be ~1/5.

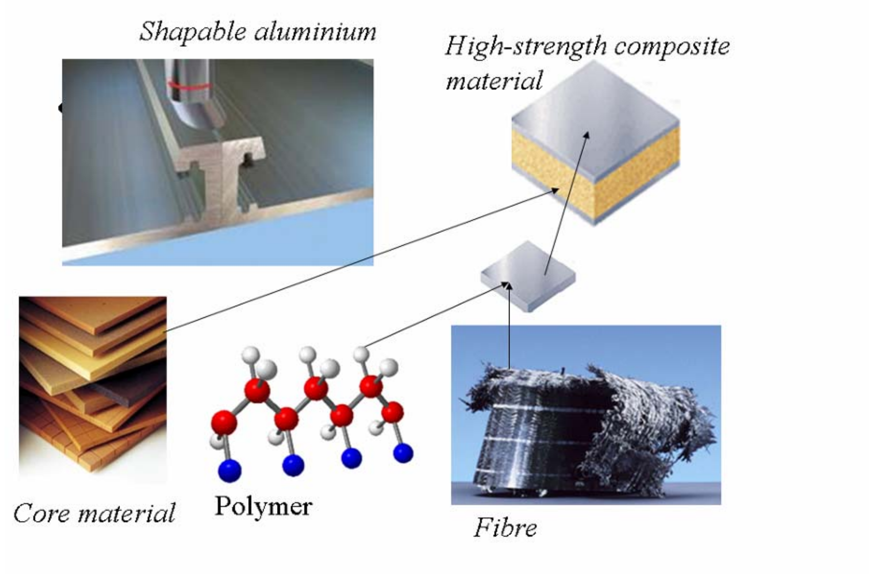


Figure 3-3 Lightweight materials used in LASS

3.2.2 Insulation materials

Three insulation producing companies were involved in the LASS project and in particular two of them, Thermal Ceramics and Saint-Gobain/ISOVER, made important contributions to the project by certifying their most advanced lightweight insulation material on various composite constructions (“Ultimate” from Isover and “FireMaster Marine plus” from Thermal Ceramics). Before the project started, existing certificates were scarce but as a result of the fire tests made within LASS, it will be possible to make wholly HSC using composite constructions in accordance with the IMO regulations.

3.3 LASS construction objects

The main target for investigation was originally conceptual studies of the four different vessels, depicted in

Figure 3-4.

The original ships used were (from top left in

Figure 3-4):

1. A 199 meter, RoRo vessel
   Objective: Switch the steel deck house to an aluminium construction

2. An 88 meter, high speed catamaran
   Objective: Exchange this wholly aluminium construction into an aluminium construction with an FRP composite superstructure

3. A 188 meter, RoPax vessel
   Objective: Exchange the steel for FRP composite in the superstructure

4. A 24 meter, Swedish troop carrying vessel
   Objective: Transform the aluminium troop vessel into an FRP composite passenger HSC

RoRo vessels and container ships are the dominant form of intermodal transport today. RoRo traffic can be divided into traffic with load carriers (trucks, trailers and semi-trailers) and transport of (newly-manufactured) vehicles and also passengers (RoPax). Coastal Ro-Ro traffic is exposed to considerable competition from road and rail in terms of quality, transport time and cost. It is difficult for ship transport to compete in terms of transport times, and so it tends to compete on the basis of the combination of load capacity and transport time. Reducing the superstructure weight of Ro-Ro vessels increases their cargo capacity, reduces the need for ballast and reduces fuel costs, which in turn improve competitiveness. In addition, and by no means least, a lightweight superstructure is expected to reduce maintenance costs. Many modern RoPax vessels are also constructed close to the stability limit and therefore there is an interest in a lighter superstructure.

The RoRo vessel used in this study is a “Panamax” type of vessel, i.e., it has a maximum width that enables the ship to pass through the Panama channel. A lighter superstructure could provide the possibility to increase the number of decks, without inducing stability problems. A particularly interesting part of this study was the use of extruded aluminium profiles for the construction.

The catamaran, STENA Carisma, used in the study is already an advanced lightweight craft and it was when constructed in the 1990’s, the world’s largest aluminium vessel. The main interest now was to investigate if a further weight reduction would be possible using FRP composites in the superstructure.

The passenger HSC vessel is interesting as there is a need for new, lightweight HSC for passenger transport in Europe. New rules within the EU for passenger ships require higher leak stability than before, which will force ship owners to invest in new vessels.

Figure 3-4 Ships used for investigation of lightweight constructions in LASS

It was previously mentioned that the LASS consortia expanded with nine additional members after initiation. The reason for the expansion was the introduction of complementary expertise from the insulating material industry, but also to be able to expand the conceptual study to include:

5. An 89 meter dry cargo freight vessel
   Objective: exchange steel superstructure and hatches for FRP sandwich

6. A 350 ton steel offshore living quarter (LQ) module construction
   Objective: exchange steel construction for aluminium

The expansion with two new concept objects took place in 2006. The main reasons for the expansion were interest from the industry and the fact that the structures are very interesting targets for a lightweight construction concept.

The cargo vessel is a typical ship used for in-land channel transport. Often such vessels cannot use their full load capacity due to restrictions from channels and sluices. Their geometry might very well be size-optimised based on the smallest sluice on the expected route of travel. The dry cargo vessel used in the project was a “Troll-max” type of vessel, i.e., was optimised to pass through the Trollhätte channel. Any weight saving of the ship structure could therefore potentially be directly exchanged for pay load.

The offshore LQ module is interesting since many technical obstacles and fire requirements are similar for the offshore and ship industry and hence, there is a potential for technology exchange. There is also an increased concern from the offshore industry about platform weights[1]. This is related to the need for more active components on the platform, e.g. drilling equipment, as it has become economically viable to drill deeper than before. Therefore, when new platforms are made or old ones are being reconstructed, lightweight construction material is asked for.

It should be noted that the only two LASS concepts that need to tackle the new SOLAS regulation 17 is the RoPax ship and the freight ship as HSCs are allowed to use combustible materials as long as they are “fire restricting”. However, as mentioned earlier there was a lack of certified construction elements prior to the LASS project. Aluminium is allowed on SOLAS vessels as they are part of the family “steel or equivalent material”.

Figure 3-5 Added concept studies for the 2006 expanded LASS project

3.4 Project targets

Main targets for the project were:

1. Design of six lightweight objects used at sea
2. Demonstration of technical solutions for <u>30% lighter</u> objects at <u>25% lower</u> total cost compared to a conventional steel constructions
3. Demonstration of practical methodologies for using lightweight constructions at sea.

Point no 2 in the list above is somewhat impractical to use since “total cost” implies cost for the entire life time of the object and conventional steel at sea has a life length of 20-35 years whereas sandwich composite will last much longer. A better and more realistic requirement for the industry partners was given by ship owners in the LASS group who stated that a pay-back time of 5-8 years was what we should aim at.

3.5 An overview of the structure for work

The project included the following Work Packages (WP’s):

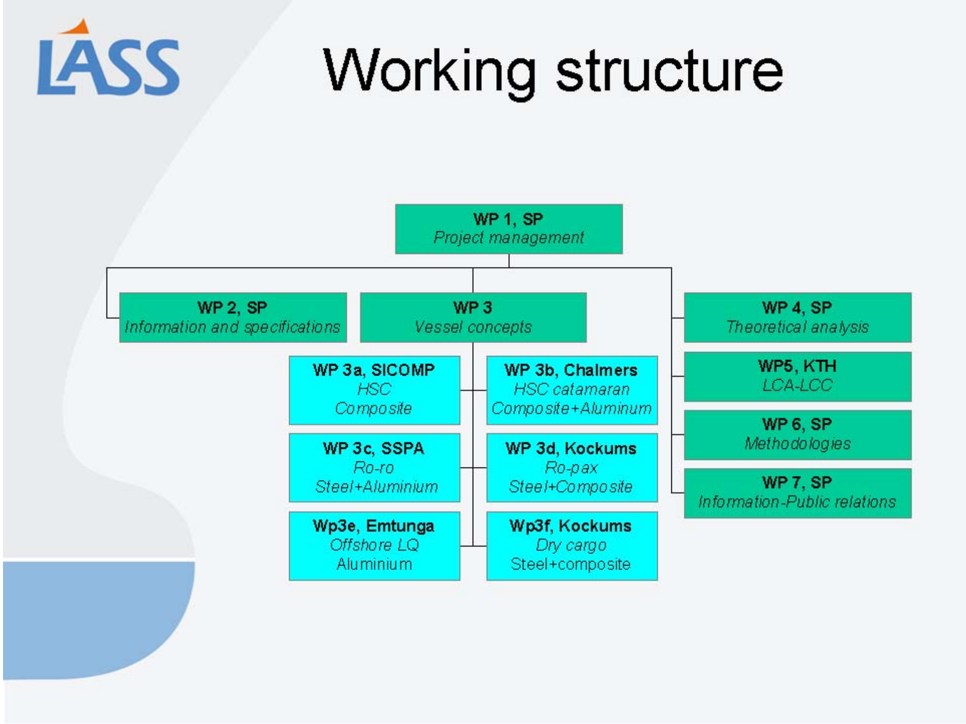
WP1: Project management
WP2: Information acquisition and preparation of requirement specifications

WP3: Concept studies:

- *A* Composite passenger HSC
- *B* Aluminium HSC catamaran with composite superstructure
- *C* RoRo vessel with aluminium deck house
- *D* RoPax vessel with composite superstructure
- *E* Off shore living quarter module in aluminium
- *F* Dry cargo freight vessel with composite parts

WP4: Theoretical analysis, design calculations
WP5: Development of LCA/LCC tools
WP6: Methodology for SOLAS acceptance of lightweight vessels
WP7: Information dissemination

The WP-structure with responsible organisation is given in Figure 3-6.



LASS

Working structure

WP 1, SP
Project management

WP 2, SP
Information and specifications

WP 3
Vessel concepts

WP 3a, SICOMP
HSC
Composite

WP 3b, Chalmers
HSC catamaran
Composite+Aluminum

WP 3c, SSPA
Ro-ro
Steel+Aluminium

WP 3d, Kockums
Ro-pax
Steel+Composite

Wp3e, Emtunga
Offshore LQ
Aluminium

Wp3f, Kockums
Dry cargo
Steel+composite

WP 4, SP
Theoretical analysis

WP5, KTH
LCA-LCC

WP 6, SP
Methodologies

WP 7, SP
Information-Public relations

Figure 3-6 Working structure for the LASS project

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[1] *BP Groans under weight of Valhall- Heavy topsides pose problems for installation on Norway field*, Upstream news:18, pp 19, August 2006

4 Fire at sea

A fire that is out of control is always an unpleasant event and even more so if it is difficult for people to get away from the fire such as on a ship at sea. Fires cause ten percent of all casualties at sea and fire is, after grounding and collision, third in place with regard to insurance costs from accidents at sea. Hence, nobody is interested in lowering the level of fire safety at sea.

For any new construction, whether it is a building, a train, a car or a ship, there are requirements for its properties with regards to resistance to fire. SOLAS, the HSC code and the off-shore MODU code, all rely on standardised empirical fire tests and certificates for ship constructing elements. These tests are defined in the IMO FTP (fire test procedures) code[1] and they provide tested building elements for decks, bulkheads, cabin walls, flooring materials, etc, where the tests involves a given well defined fire or heat exposure together with well defined criteria for acceptance. These tests are made at fire laboratories all over the world and, normally, the laboratory provides a client with a test report that can be sent to a classification society, which will provide a certificate in accordance to the IMO regulations. Similarly, the fire protection systems (sprinkler etc) used onboard ships are submitted to fire tests and certified. In areas of the ship where fire hazards are relatively large, such as in connection to the machinery space, the requirements for fire safe construction elements and fire protection systems are more severe than, e.g., a standard corridor building element. The fire tested and certified products represent a base for the IMO prescriptive coding of ship building.

Obviously many non-fire related technical difficulties need to be addressed and solved if lightweight construction and materials shall be useful for ships and offshore constructions. However, without a sufficient level of fire safety, no lightweight ship or offshore construction will be made regardless of how efficient or economically interesting the developed the concept might be.

4.1 Theory: lightweight fire hazard

A solid material subjected to a fire is influenced by heat in three different ways: through radiation from hot areas, through convection where hot gases get in contact with the solid and through conduction where heat is transported by the solid material. In a fire, the main heat transport comes from radiation.

The dynamic equation for heat conduction in a one dimensional solid is given as:

$$\frac{\partial T}{dt} = \frac{k}{\rho C}\frac{\partial^2 T}{dx^2} = \alpha \frac{\partial^2 T}{dx^2} \qquad (1)$$

where k is the coefficient for thermal conductivity of the material, ρ is the material density and C its thermal capacity. The variables T, t and x represents temperature, length and time respectively.

Given appropriate boundary conditions, it is possible to solve the above equation analytically. For a thick[iv] solid exposed to a heat flux q (W/m^2) at x=0, the boundary condition is defined by:

[iv] "Thick" here means "semi infinite", i.e. the thermal wave moving inwards from the heated surface will not be reflected back from the cold side of the specimen

$$-k\left.\frac{\partial T}{\partial x}\right|_{x=0} = q \qquad (2)$$

If the initial temperature of the solid is T_0, the analytical solution for the 1-dimensional heat equation is given by:

$$T(x,t) = T_0 + 2q\frac{\sqrt{\alpha t\pi}}{k}\exp\left(\frac{-x^2}{4\alpha t}\right) - \frac{qx}{k}\left(1 - erf\left(\frac{x}{2\sqrt{\alpha t}}\right)\right) \qquad (3)$$

Looking at the boundary temperature only (i.e. at x=0) leads to

$$T(0,t) = T_0 + 2q\frac{\sqrt{\alpha t\pi}}{k} = T_0 + 2q\frac{\sqrt{t\pi}}{\sqrt{k\rho C}} \qquad (4)$$

The last equation provides a critical parameter with regards to fire safety, i.e., the surface temperature[v]. The piloted ignition temperature for most solid materials is 250-450ºC and auto ignition somewhat higher (>500 ºC). Obviously, the rate at which these levels are approached is highly important for fire safety.

In Table 4-1 is collected some material data and results from calculating the surface temperature based on these data and equation (4) when q is 1000 W/m^2. It is found that a low density material will obtain critical temperatures more quickly than a high density material.

It can be seen from the data that the thermal conductivity coefficient, k, diminishes at the same time as the density, ρ. This is not an artefact created from a particular choice of materials in this table but a general truth. Further, the heat capacity, C, is almost constant; it is within a factor of 2.5 from a standard value= 1000 J/Kg K for all materials in the table. It is therefore logical that a low density material in general will increase the fire hazard since it is seen from equation (4) that

$$T(0,t) \propto \frac{1}{\sqrt{k\rho C}} \qquad (5)$$

i.e., the surface temperature will increase faster for a low density material than for a high density material.

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[v] It should be understood that the surface in question is considered inert; i.e. that no melting or other material transition is taking place due to heat absorption.

Table 4-1 Material thermal characteristics and calculated surface temperatures

Material	k W/mk	ρ Kg/m^3	C J/KgK	1/(kρC)$^{0.5}$ m^2/s	Calculated surface temp. at t=120 s by equation (4)
Steel	46	**7800**	460	7.8E-05	**28**
Concrete	1.2	**2300**	880	6.4E-04	**65**
Brick	0.69	**1600**	840	1.0E-03	**65**
FRP-laminate	0.52	**1600**	1125	1.0E-03	**50**
PVC floor covering	0.17	**815**	1810	2.0E-03	**103**
Oak	0.17	**800**	2380	1.8E-03	**93**
Plywood	0.12	**580**	1215	3.4E-03	**159**
cork	0.04	**120**	1800	1.1E-02	**443**
PVC-foam	0.05	**80**	2250	1.1E-02	**434**

The conclusion of the above discussion is that the development towards lightweight constructions will also impose a need for more fire safety measures. This was a major argument in the LASS project description to the VINNOVA call "Lightweight materials and lightweight constructions" and it has also been a major theme throughout the project.

4.2 Fire Safety at sea

The combustibility of the composites materials must be handled properly in order to obtain a high degree of fire safety. Basically, two methods are possible:

1. A passive fire protection of the material, e.g. by covering the composite surfaces with a proper non-combustible material.
2. An active fire protection system such as a sprinkler or a water mist system.

Obviously the two methods might be combined. However, even if the combustibility hazard is eliminated, there is still the problem of high temperature behaviour. Both FRP composites and aluminium are less temperature resistant than steel but all materials need a fire insulating material in order to comply with SOLAS requirements for fire resistance. Aluminium looses its structural strength at about 200ºC and the interface between the PVC core and the FRP laminate in the composite sandwich used in LASS (see Figure 3-3) softens at ~100ºC[vi] where as steel starts to deform at 400-500 C°. To ensure fire safety on a ship that uses these materials it is therefore essential to maintain the material at a low enough temperature. It is clear that the low density materials used will require more insulation than standard steel in order to have the same fire resistance. As an example, in the WP3c task of redesigning a RoRo vessel with an aluminium deckhouse, it was found that the insulation weight increased by a factor of ~1.7 compared to the required steel insulation. For a composite deck or bulkhead construction the insulation weight could increase by a factor of 2-3 due to it's low temperature resistance but also due to the fact that a composite bulkhead construction will need insulation on both sides (unless it is an outer wall construction) whereas a steel bulkhead, according to the FTP code is sufficiently protected with one-sided insulation. Obviously, it is not good if so much extra insulation is needed that the weight advantage of the low density materials disappears. In the project therefore, advanced lightweight insulation materials have been used when fire safe constructions have been certified.

[vi] It is possible to use more temperature resisting polymers (~150-200ºC) with the disadvantage of a higher material cost and more difficult processability. Also more fire resisting core materials are possible but they have usually disadvantages from a mechanical point of view.

4.3 Fire tests according to SOLAS

SOLAS defines different classes of ship construction materials according to its use:

- A-class divisions; typically used for deck and bulkhead constructions in areas such as engine room, escape routes, stair cases, bulkheads separating fire zones and areas with high fire risks. The construction must withstand a 60 minute large scale furnace fire test (see
- Figure 4-3) without flames or hot gases penetrating to the back side. The division might also have temperature restrictions (temperature increase < 180ºC max and < 140 ºC average) on the backside; A-X implies a temperature restriction for X minutes (X=0, 30, 60). The construction material must further be non-combustible.
- B-class divisions; typically used in cabins or corridors. Must withstand a 30 minute large scale furnace fire test (see
- Figure 4-3). Might also include temperature restrictions for X minutes (temperature increase < 225ºC max, < 140 ºC average); B-X implies a temperature restriction for X minutes (X=0, 15). Non-combustible materials must be used for the construction; however, a combustible veneer might be allowed.
- C-class division; used in low risk areas. The only requirement is to use non-combustible materials for the construction.

Fire testing is performed according to the Fire Test Procedure (FTP) code. To obtain a certificate for A-, B- or C-class division, the material used must, except the above mentioned tests, pass the non-combustibility test according to ISO 1182 (see Figure 4-1) where the material is heated to 750 ºC. The only materials that will pass this test are basically inorganic.

The large scale furnace tests required for A- and B-class division are defined by IMO Res.A(754). A temperature profile, the so called “standard temperature curve” (see Figure 4-2) is created in the furnaces by gas burners and the A or B class construction is exposed to the heat. The furnace is shown in
Figure 4-3 (left) and the fire exposed insulated side of an FRP sandwich bulkhead with different penetration constructions, is shown in the same figure (right).

4.4 Fire safety philosophy in LASS

It is possible to ignore all prescriptive SOLAS code and then try to “compensate” for this by means of adding e.g. more active fire protection systems or whatever other safety measures could be imagined. However, it is easy to foresee that such an approach would lead to a heavy burden with regards to proving safety equality of the design, as required by the new SOLAS regulation 17. An easier approach, used in LASS, is to try to fulfil the functional requirements for fire resistance given by SOLAS through A, B and C class divisions.

As stated before, the HSC-code permits constructions for 60 and 30 minutes fire resistant division (FRD) that do not need to pass the difficult ISO-1182 non-combustibility test, provided that they are “fire restricting”, which means that the construction must pass the IMO fire test MSC.40(64). This test is basically the same as the ISO 9705 Room-Corner test (see Figure 4-4), which is a corner stone for fire testing of surface lining materials for buildings in the European classification system. The IMO test, however, also has special requirements for heat and smoke evolved during the test.

In this test, a gas burner is ignited in a corner of the room where the walls and ceiling have been covered with the material being tested. The gas burner provides 100 kW for 10 minutes and then 300 kW for an additional 10 minutes. The maximum allowed peak heat released from the tested material is 500 kW and the average heat released should not be more than 100 kW. There are also requirements for the maximum amount of smoke produced. This is a severe test of the construction material but any combustible material will pass the test provided a “sufficient” amount of insulating material (mineral wool, ceramic wool) covers its surface.

Once a material has been accepted as a Fire Restricting Material (FRM) it can be tested for the HSC functionally-equivalent construction of the SOLAS A class division, which is the FRD 60 (Fire Resisting Division 60 minutes) and B class division, which is the FRD 30. The same type of large scale furnace test is required as for the A and B class material (see
Figure 4-3) using the same standard heating curve (see Figure 4-2). An additional requirement for many FRD constructions is that they are tested with predefined loads.

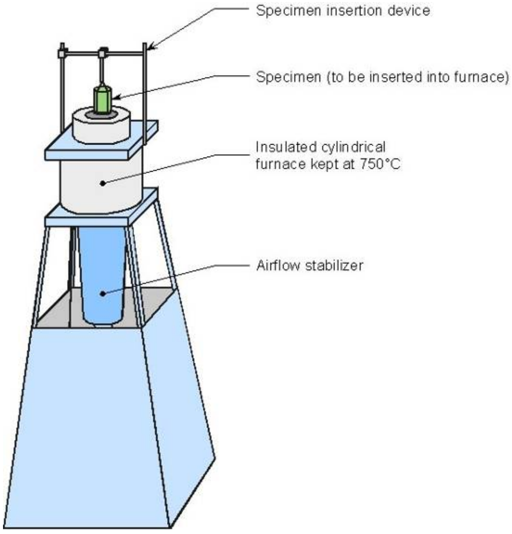

Figure 4-1 Non combustibility test equipment according to ISO 1182

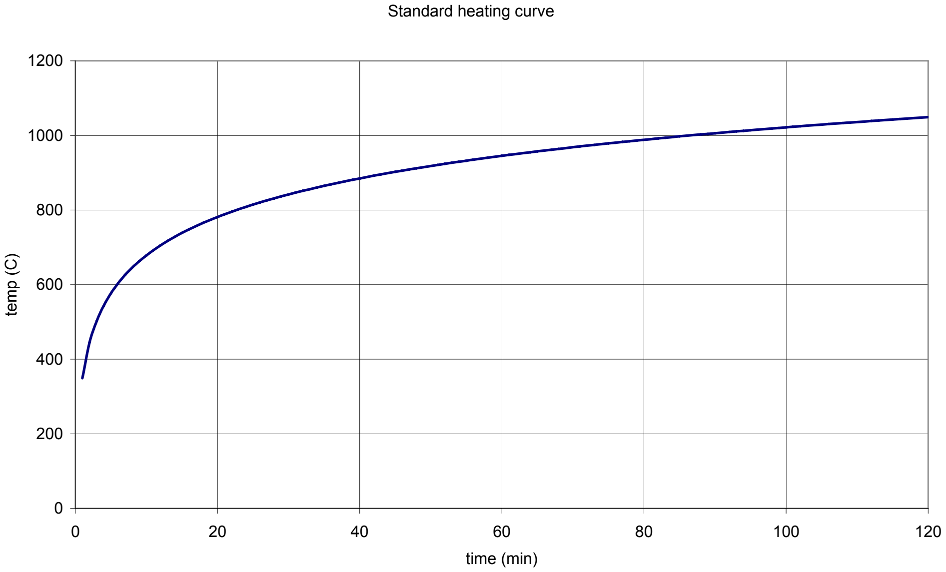

Figure 4-2 Temperature in the bulkhead and deck large scale furnace test

The approach taken in the LASS project is therefore to ensure that on SOLAS vessels, the same *functional requirement* can be obtained with composites as with steel. Through this approach a "functional equivalency" is obtained as summarised in Table 4-2.

Table 4-2 Summary of suggested functionally equivalent construction elements

SOLAS prescriptive code requirement	Functionally equivalent construction, based on HSC-requirement
A class division	Fire resistant division (FRD) 60
B class division	Fire resistant division (FRD) 30
C class division	Fire restricting material (FRM)

Figure 4-3 Large furnace used for bulkhead test (left) and fire exposed side of a sandwich composite bulkhead construction after successful bulkhead penetration tests in the furnace (right)

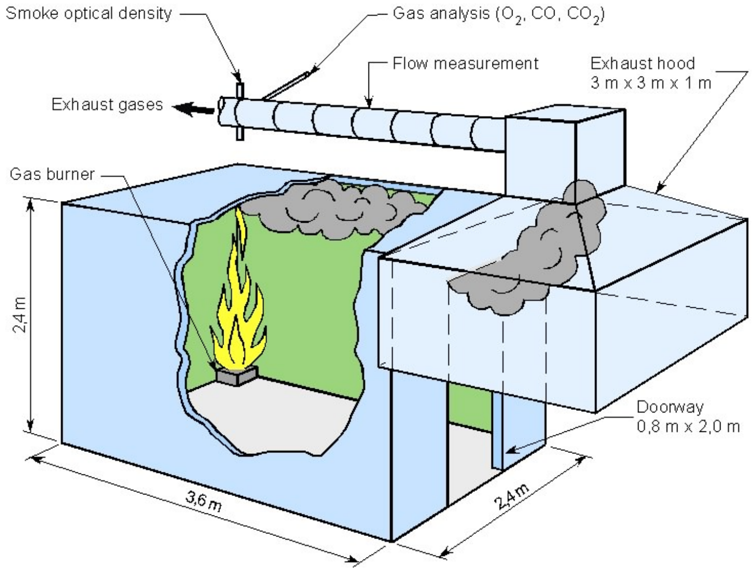

Figure 4-4 Schematic view of ISO 9705 Room-Corner experimental set-up

When performing deck or bulkhead tests on a sandwich composite, the FRD temperature requirement for the unexposed side (maximum 180ºC temperature increase for FRD 60) is not important since the critical issue for the construction, as mentioned earlier, is the temperature between the core and the laminate facing the fire, which should remain below 100-110 ºC (see footnote vi). A sandwich composite is an excellent thermal insulator and the backside temperature is therefore more or less at room temperature when the critical interface temperature at the fire exposed side is reached. This also means that in a real fire, there are fewer problems with heat transfer from one compartment to the other compared to a steel construction, which also means that more heat is kept within a fire enclosure, i.e. temperatures will be higher in the fire compartment.[vii]

If the suggested equivalency in Table 4-2 was accepted by the authorities, the switch to using combustible materials on a SOLAS vessel would be easy enough. However, the complete fire safety philosophy of the prescriptive code in SOLAS is not necessarily covered by the explicit requirements for A, B and C class construction materials; using combustible construction materials still violates the functional requirement in Ch II-2 part A for "restricted use of combustible materials". There is an implicit, empirically founded safety level given by the experience of using steel constructions at sea for many years, written, so to say, between the lines in SOLAS and it is this safety level that it is difficult to define and to compare to. The methodology used in LASS to make the comparison of safety levels obtained is based on risk analysis and risk management methodologies. The specific procedure used was developed in cooperation with a DNV-led subgroup of the EU project SAFEDOR.

4.5 Fire tests run within LASS

A large number of fire tests have been run within the LASS project. The objective of each test has always been one of the following three:

1. To investigate basic material fire properties
2. To obtain data for simulations
3. To prepare for or to certify fire safe constructions.

A particular difficulty is that the IMO do not define constructions to test in the large scale furnace (
Figure 4-3) other than those made of steel or aluminium. This would also be a problem, e.g., for an insulation company that wishes to obtain a certificate for a composite deck or bulkhead FRD construction. The philosophy used in LASS was always to test a "worst case" construction in order to create a situation where a, from a fire safety perspective, "better" construction could be accepted without testing. Through such an approach, the obtained certificates can be used for many types of constructions which will facilitate the building of composite ships.

4.5.1 Small scale fire tests

Small-scale tests were run in the Cone Calorimeter which is used in the standardised ISO 5660 test (Figure 4-5) where a 0.01 m^2 specimen, horizontally positioned, is subjected to irradiation from electrically heated surfaces above the tested material. Irradiation levels used are typically in the range of 25-75 kW/m^2. This test is used mainly for investigating ignitability and HRR (Heat Release Rate) for a given material. In Figure 7 the HRR curve for such an experiment with a carbon fibre based FRP is shown. Time integrating the

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[vii] This also induces a modified methodology for fire fighting; instead of cooling the backside of e.g. a bulkhead construction in a fire event, normally done to prevent fire spread to adjacent rooms, it will be necessary to cool the exposed side of the construction, that is, to cool the fire enclosure directly.

HRR signal, provides the total heat release (THR), which is another important characteristic for a material as it shows the tendency to sustain and add energy to a fire.

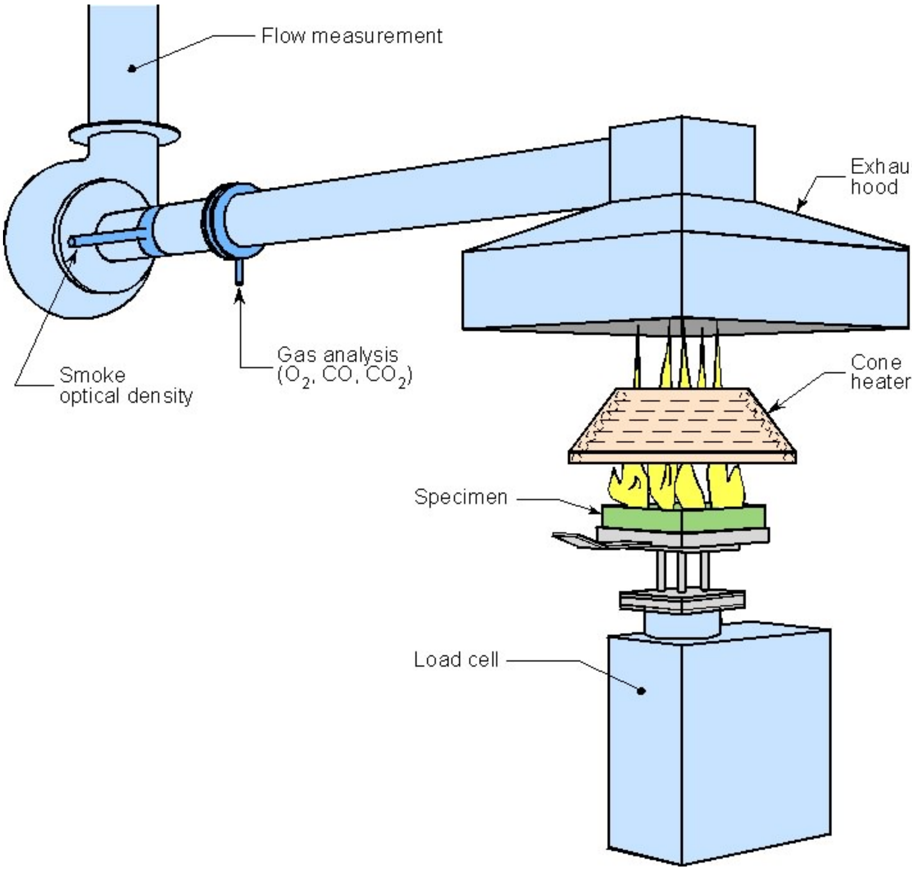

Figure 4-5 Schematic picture of a Cone Calorimeter

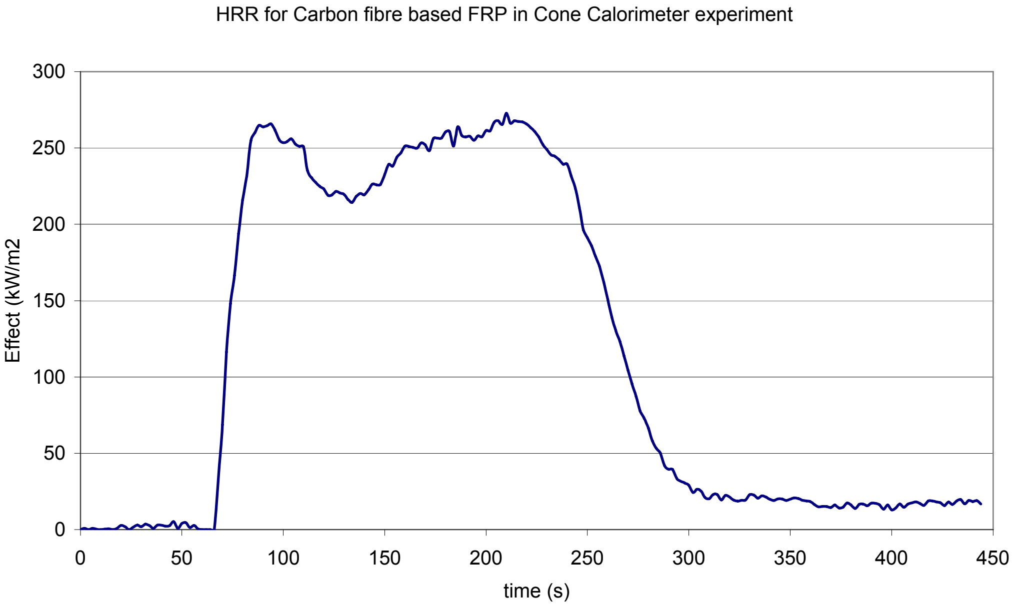

Figure 4-6 Cone Calorimeter HRR results from FRP material at 50 kW/m^2 radiation level

The Cone Calorimeter is also a useful tool for measuring material temperatures as a result of a given radiation exposure. As an example, the insulation necessary for a floating floor construction for a composite deck structure was investigated. A typical radiation level at the floor in an enclosure subjected to a full flashover fire is 25-30 kW/m^2, at least initially. Using the Cone Calorimeter, a floating floor system consisting of 20 mm mineral wool and a 2 mm aluminium plate was placed on top of a 0.1 x 0.1 m^2 composite sample. Thermocouples were inserted between the top laminate (polyester based FRP) and the core (PVC-foam) of the composite (see Figure 3-3). The materials used in the composite start to decompose at 250-300 ºC and the requirement for the floating floor was that it provide sufficient insulation to inhibit pyrolysis gases from the composite deck from developing during a 1 hour flashover. In Figure 4-7 material temperatures during a 1 hour exposure to a 30 kW/m^2 irradiation are shown. The construction was later used in a full scale experiment that showed that the insulation was insufficient. This will be discussed further in the description of this particular experiment.

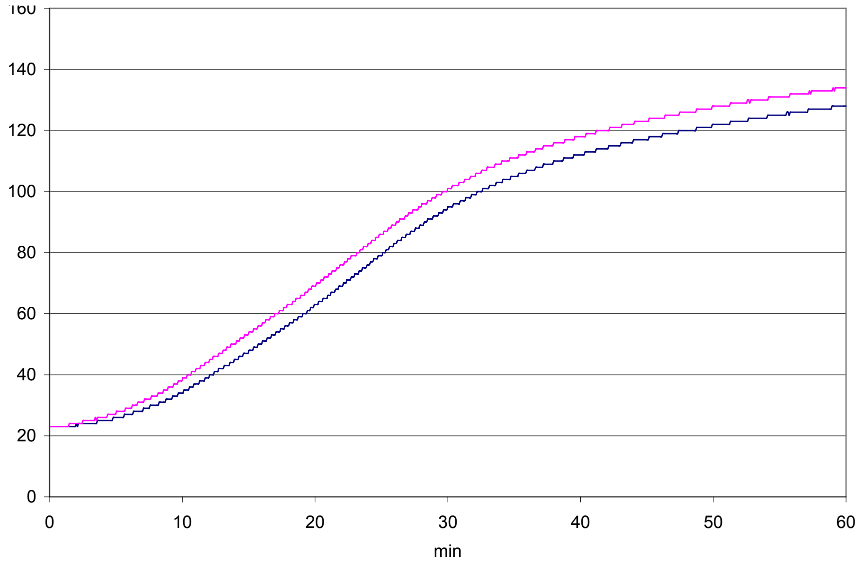

Figure 4-7 **Cone Calorimeter test using a 30 kW/m^2 radiation level. Temperature measurements were done using two thermocouples situated between the laminate and the core of a composite. A floating floor (20 mm mineral wool+2mm aluminium plate) was put on top of the composite.**

Another small-scale fire experiment is IMO A.653, “spread of flame”, where the sample is subjected to an irradiation and the criteria for passing the testis related to the length of the flame spread as a function of radiation level. This test is used, e.g., for testing of floating floors and surface lining material.

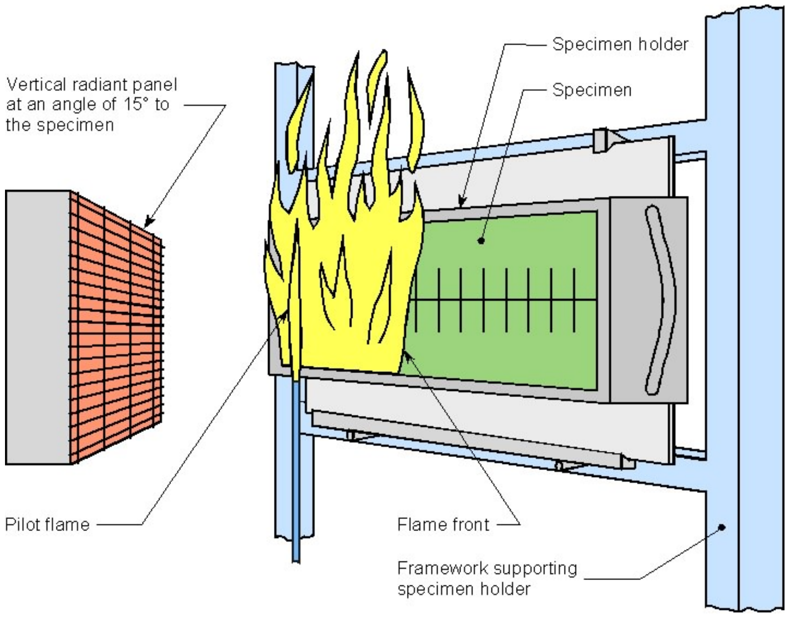

Figure 4-8 Test for flame spread according to IMO A.653

4.5.2 Fire testing of furniture

Interior materials from a RoPax passenger ferry were burnt and heat release rates (HRR) were measured. The main reason for these experiments was to provide input data for fire simulations.

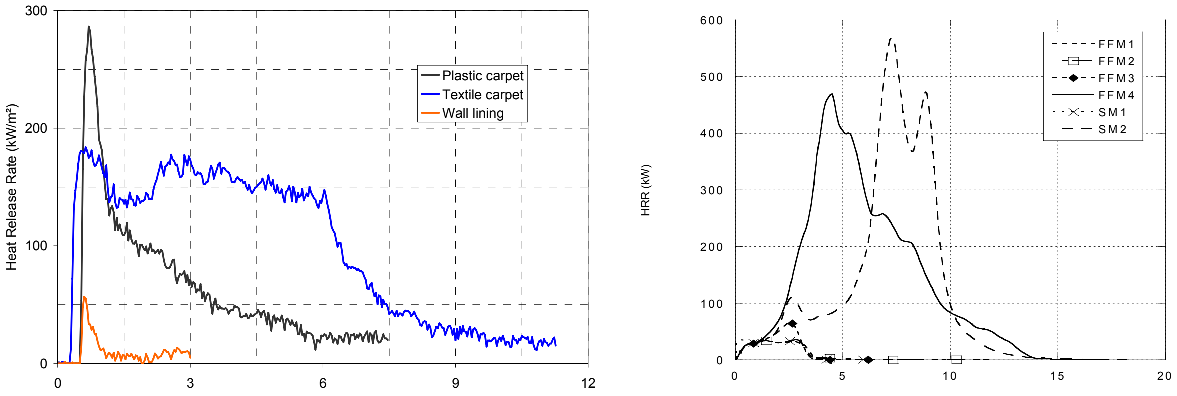

Figure 4-9 Cone calorimeter test of cabin materials (left); large scale fire tests of cabin mattresses (right)

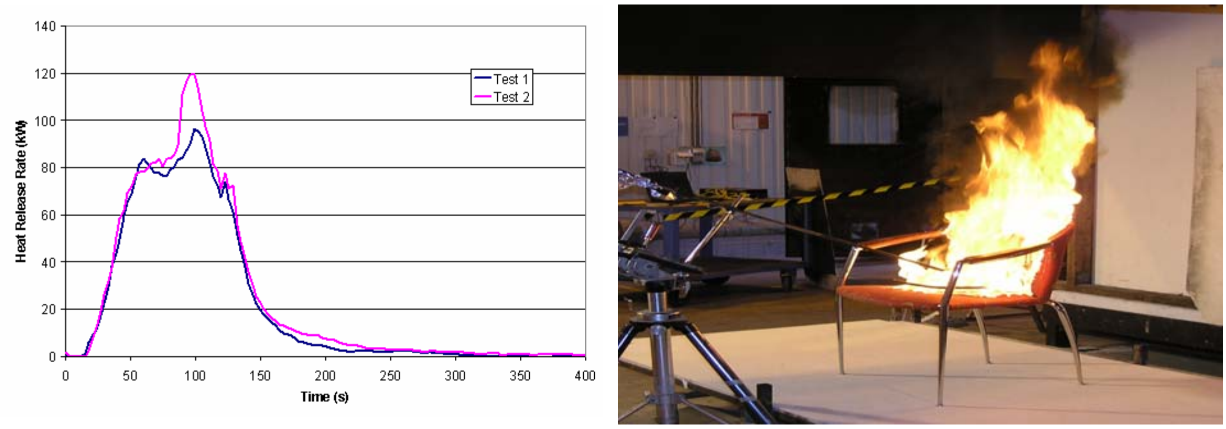

Figure 4-10 Lounge/cafeteria chairs fire tests

4.5.3 Large scale fire tests

A number of successful large scale furnace tests (see Figure 4-3) run as part of the LASS project have been important for the possibility to produce composite vessels in accordance with the HSC code. As a direct result of these tests, there are now several solutions available for FRD 30 and FRD 60 composite deck and bulkhead construction elements. Further, successful furnace tests have been made for 60 minutes fire resistance door[viii] and window[ix] constructions mounted in composite bulkheads. The successful FRD 60 tests made on penetration constructions[x] (cables, tubes...) in composite bulkhead and deck are also important.

Further, fire restricting (FRM) construction materials have been tested and certified in the Room-corner test set-up (see Figure 4-4). Actually, a fire resisting division (FRD) made of combustible material must, according to the HSC-code, be made of a fire restricting material (FRM). There are, however, other divisions than FRD's on a HSC that need to be made of either non-combustible or fire restricting materials and therefore tests were run in order to have low-weight solutions for FRM constructions.

A full list of the composite structures tested in LASS is given in Table 4-3.

Table 4-3 Tested composite constructions in LASS

Construction	Certificate owner	weight, kg/m2	thickness, mm
FRD 60 Bulkhead	Thermal Ceramics	6.95	100
FRD 60 Bulkhead	Saint-Gobain/Isover	7.5	100
FRD 30 Bulkhead	Saint-Gobain/Isover	5.4	75
FRD 60 deck	Thermal Ceramics	6.95	100
FRD 60 deck	Saint-Gobain/Isover	7.5	100
FRD 30 deck	Saint-Gobain/Isover	5.4	75
FRM (2 certificates)	Thermal Ceramics	0.96-1.5	20-25
FRM (3 certificates)	Saint-Gobain/Isover	1.4-2.0	75 mm
*FRD 60 bulkhead +penetration constr.	MCT Brattberg	-	-
*FRD 60 deck +penetration constr.	MCT Brattberg	-	-
**FRD 60 door	Hellbergs Int	-	-
**A0 window	Norac Baggerød AS	-	-
Floating floor	LASS-SAFEDOR	8	21 mm

* Thermal Ceramics FRD 60 insulation material was used in the test

** Saint-Gobain/Isover FRD 60 insulation material was used in the test

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[viii] A co-operation between LASS and the Swedish company Hellbergs Int. using an A60 door.

[ix] A co-operation between LASS and the Norwegian company Norac Baggerød AS, using an A0 glass window.

[x] A co-operation between LASS and the Swedish company MCT Brattberg AB.

4.5.4 Full scale fire tests

A unique set of real scale cabin and corridor fire tests involving composite constructions were performed at SP in December 2007 as part of the LASS project. The experiments are described in detail in an SP report[2] but will be described here to some extent due to there significance for understanding real scale fires involving composites.

The uniqueness of the experiments is partly related to the cost for running such large tests but also to the particularities of the design where a RoPax construction was imitated and FRP composites used as construction elements. In order to be able to handle the cost and complexity of the construction, the tests were run as a co-operative project between LASS and another VINNOVA financed research project "Design Fires at Sea" and in co-operation also with EU-project SAFEDOR. The main idea for the tests was to design experiments to resemble possible fires in a RoPax cabin and corridor construction.

The objectives were twofold: to study design fires, e.g., fire development and the influence of sprinkler, ventilation etc on cabin fires, and to evaluate the behaviour of a composite structure under realistic fire conditions. The fire test set-up consisted of two B-15 certified[xi] passenger cabins connected to a corridor and built inside a fire insulated plastic composite superstructure. Each of the cabins had a window opening. An open deluge (drencher) sprinkler system was installed on the outside of the superstructure in order to evaluate fire protection of the "hull".

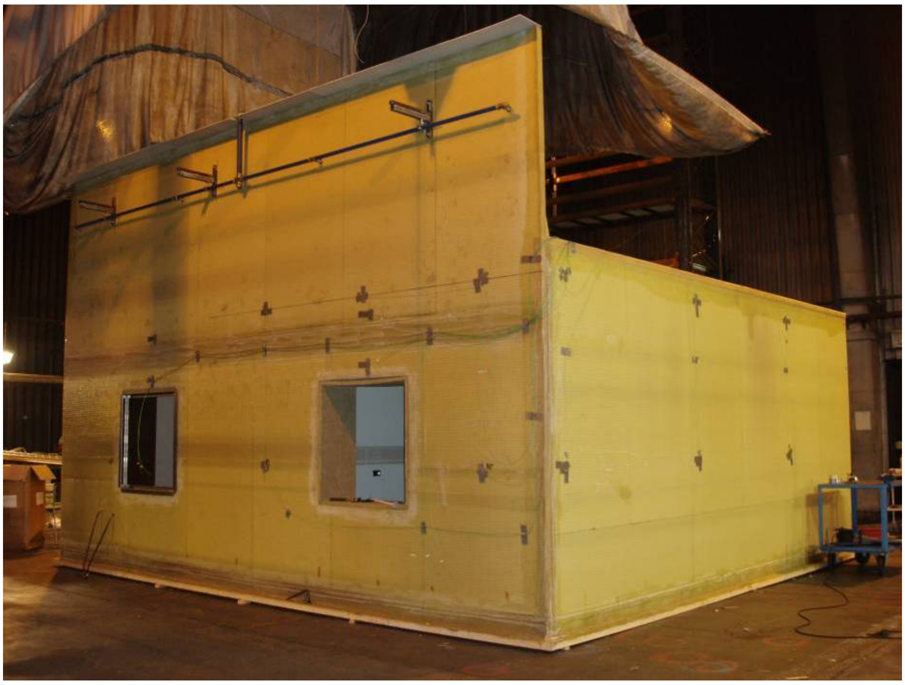

Figure 4-11 Photo of the finished composite construction. Note the outside drencher system installation, above the window openings (near the "roof").

The outer construction consisted of a composite front with two window openings and one bulkhead for the right-hand side, viewed as in figure 1.

The composite "decks" were situated above and below the two cabins and the corridor. All composite materials except the below deck were insulated using certified FRD 60

[xi] i.e. a construction having been tested according to the IMO A756 fire test to withstand a 30 minute fire with requirements for the back side temperature after 15 minutes, see Figure 4-2 and Figure 4-3

insulation. A floating floor system based on a 20 mm mineral wool was used on the bottom deck.

Figure 4-12 **Interior FRD 60 insulation of the composite, before cabin construction. Note the stiffener at the ceiling (“upper deck”).**

4.5.4.1 The structure of the cabin and corridor

The cabin and the corridor were constructed by sandwich panels with a core of mineral wool with galvanised metal sheeting. The panels had a decorative vinyl coating, with a thickness of 150 µm on both the inner and the outer surfaces. The panels and the set-up were built on-site using materials and procedures as in practice.

Figure 4-13 Photo showing the corridor and entrances to the two cabins

4.5.4.2 The interior materials

The cabin interior consisted of the following items:

- Two plus two Pullman type bunk beds. The bunk beds were fitted with mattresses and bedding material.
- A chair positioned in front of the small table
- A small table
- A hat rack
- Window curtains
- Light fixtures
- Personal belongings and luggage
- Bedding material

All interior materials used were realistic and certified according to the IMO regulations.

Figure 4-14 Cabin interior

4.5.4.3 The fire tests

Four cabin fire tests were conducted where either the sprinkler system (water mist) activated as expected thereby efficiently controlling the fire, or where the door and window openings where sealed closed and the limited amount of oxygen prohibited a large scale fire from developing. These tests are described in detail elsewhere[2]. Only the tests with particular importance for the composite construction: the flashover fire and the outside drencher tests, are presented here.

4.5.4.4 The flashover fire

In this fire test, no sprinkler was used and the cabin door was left open. This led to a very intense flashover fire that lasted >30 minutes.

The fire involved all combustible interior materials and floor covering from the cabin and the corridor. After the fire it was seen that all cabin panels were more or less deformed and that two ceiling panels had fallen to the floor. The aluminium floor plates at the floor of the cabin had melted over a large area and were completely consumed in an area between the bunk beds. The underlying fire insulation and part of the composite deck were also damaged.

The fire insulation under the upper deck and on the bulkheads was almost unaffected, except for a small spot approximately centred over the cabin, where it seemed to be eroded. It was also observed that the exposed layer of the insulation had hardened in an area that corresponded to the inner footprint of the Cabin, which indicates very high temperatures.

In the other cabin no combustible material was used except for the surface foil coating on the wall and ceiling panels. However, all surface coating on the ceiling had been consumed and the wall coating was burnt in the upper part of the cabin. The ceiling panels were slightly deformed and it is suspected that smoke from the void space spread to the cabin through the joints of the panels.

In the corridor, the wall panels were slightly deformed and the surface coating at the ceiling and walls were largely consumed by the fire. Much of the floor carpet was burnt and the aluminium floor plates were deformed but had not melted.

Figure 4-15 Flashover fire test. The flames emerge into the corridor from the burning cabin to the right.

Figure 4-16 A representative photo that gives some indication of the intense heat evolved and the very high intensity of this fire. Note the separation of wall elements in the cabin (no outer bulkhead construction on this side).

4.5.4.5 Drencher system test

In order to test the exterior drencher protection, a heptane pool fire was arranged in the window of Cabin B. In the first test, the drencher was activated at the same time that the fire started and in the second test, ignition of the outer surface was allowed before the drencher was activated. It was found that without a drencher, flame spread was quite rapid on the exterior surface but that the drencher very efficiently prohibited fire spread and also very quickly extinguished an initiated fire.

4.5.4.6 Comments

The original plan was to finalise the test programme with a very intense flashover fire using a heptane pool as fire source. The reason was that it was not believed that a standard cabin fire would provide sufficient energy to really challenge the construction materials and in particular the composite construction. However, it was found that the flashover fire described using only standard interior cabin materials and realistic luggage, was indeed enough to provide a very intense and long lasting fire. Actually, the result was such that one conclusion from the experiment must be that a more thorough investigation should be run in order to determine the suitability of the IMO regulations on the allowed combustible materials in a RoPax cabin section.

Figure 4-17 Heptane pool fire in the cabin window opening with drencher in function. The outer wall is sufficiently cooled down by the drencher and virtually no flames are seen on the outside laminate.

Figure 4-18 Fire spread on the outer wall from the pool fire without drencher activation.

Figure 4-19 The composite outer wall a few seconds (5-10 seconds) after the drencher was activated

From the composite construction viewpoint it was found that although the flashover fire was of long duration and high intensity, the maximum temperature obtained in the PVC core in the deck just above the fire cabin merely reached 140ºC. This was enough for delamination to occur but the area involved could probably quite easily have been repaired after the fire. However, an A0 steel deck construction[xii] made in accordance with the prescriptive regulations in SOLAS would most likely have been much more severely damaged and the probability of fire spread through the deck due to the temperatures involved would have been very high. Some of the ceramic wool covering the composite deck above the cabin had partially melted, indicating peak temperatures in the range of 1000-1300 ºC. Important to note from the test is that the maximum temperature measured in the composite was attained approximately 90 minutes after the fire started, which was actually some time after the fire had stopped. This was due to the fact that the heat wave reaching the thermocouple at this time. If cooling of the construction had been initiated when the fire ended, material temperatures and damages of the composite would have been lower.

The fire protection given by the floating floor in the cabin was insufficient, which led to damage in the composite deck below. The 20 mm mineral wool used was covered with an aluminium plate that had partially melted, which means that the floor had reached a minimum of 660 ºC. The result showed that it is recommended to increase the thermal insulation of the floor in a real construction[xiii].

The drencher tests clearly demonstrated that water on the outside is a very efficient remedy against fire spread on an unprotected composite surface. It is important to

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[xii] A0 means that no insulation is needed at all on the steel construction. The only requirement is a 60 minute fire resistant plate but there are no temperature requirements for the unexposed side.

[xiii] The only IMO requirement for the floating floor is that the surface material should pass the IMO A.653 test for low flame spread, see Figure 4-8.

remember, however, that the cooling effect must be initiated at an early stage to prevent heat spread to the composite core material. Therefore an efficient fire alarm and extinguishment activation system is needed.

4.6 Fire simulations

Fire simulations were used as part of the quantitative analysis (see Figure 2-1) required for the SOLAS regulation 17 approach and also for input to the Risk Analysis. Two different simulation tools were used: a two-zone fire simulating program (Branzfire[3]) and the CFD (Computational Fluid Dynamics) based fire simulation tool FDS[4]. The two-zone model is faster but also simpler tool than the CFD-code but it is a good simulation instrument when a typical two-zone approach is valid, i.e. when two distinct temperature zones, one hot upper smoke layer and one cold gas layer beneath with fresh air, are created. This is typically the case for an enclosure fire[5], such as a cabin fire (when no sprinkler is activated[xiv]).

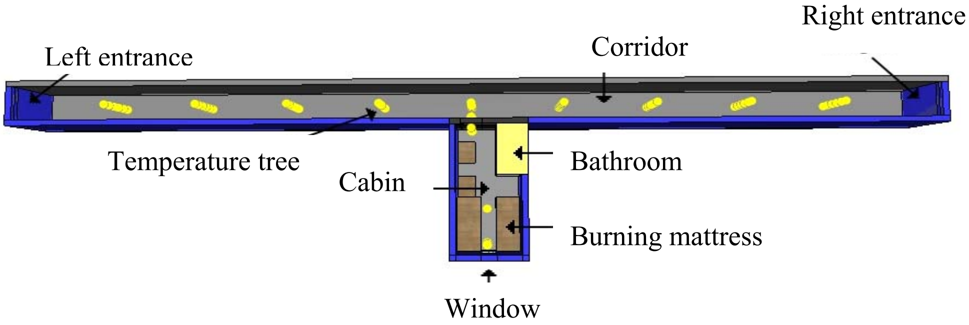

Figure 4-20 Structure for cabin fire simulation

In Figure 4-20 a geometry used for CFD simulations of a cabin fire is shown.
In the simulations, experimental data from burning mattresses (see
Figure 4-9) were used as input to the simulation. Important data obtained from such simulations include energy and temperature levels obtained in different fires. Fire simulations also provide useful information concerning smoke spread.

[xiv] A sprinkler would mix the room atmosphere quite effectively.

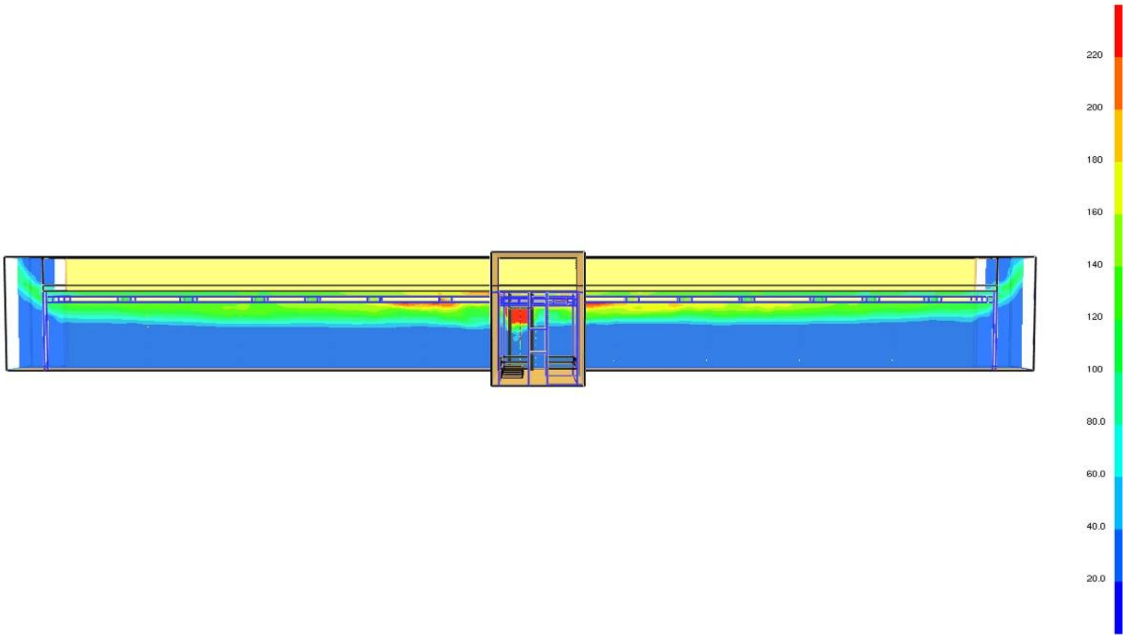

Figure 4-21 Side view of the cabin-corridor geometry showing the results of temperature simulations after 10 minutes of fire in the cabin

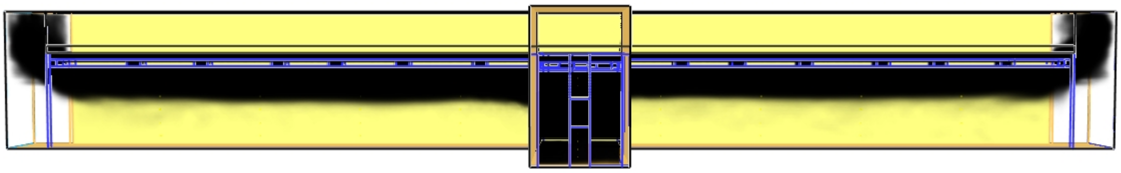

Figure 4-22 The same geometry and timing as in Figure 4-21; smoke simulation

Another type of simulation also made in the project was egress simulations and an example of the output from such a simulation for a RoPax cabin area is shown in Figure 4-23.

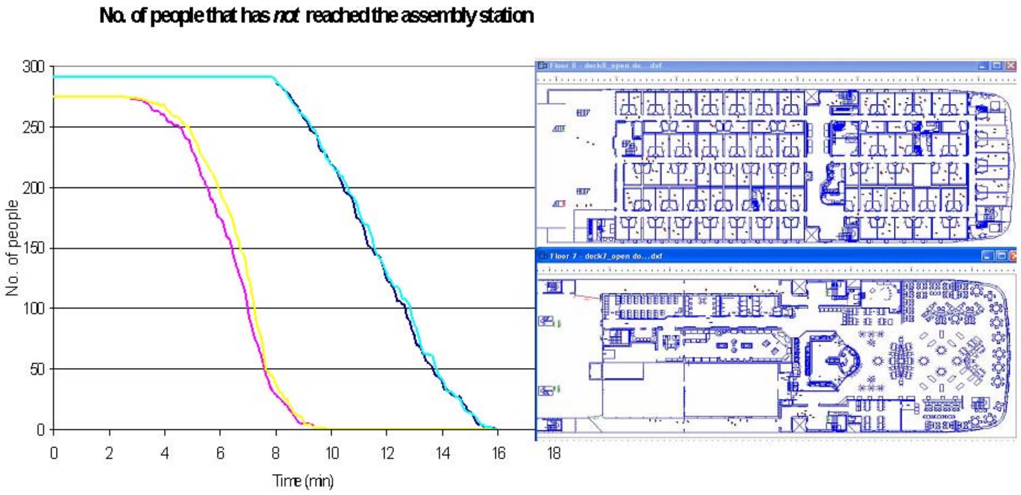

Figure 4-23 Results from an egress simulation of a cabin section

4.6.1 Simulation comparison to a large scale cabin fire test

In order to validate the simulations, a comparison was made between a simulated cabin fire and a real scale fire test (see 4.5.4). The cabin was modelled using the same enclosure geometry as for the real cabin. Material characteristics of deck and bulkheads were also modelled based on the real case.

The cabin used in the fire test is shown in Figure 4-14. Figure 4-24 shows a computer model of the test cabin. Cabin dimensions were 4.3 m x 3.0 m x 2.7 m (length x width x height). A more detailed description concerning all materials in the test cabin is given in SP Report 2008:33[2].

All materials in the figure were treated as non-burning items in the calculation model. Instead, all fuel was ‘lumped’ together and injected to the cabin in the simulation through an assumed 2 m^2 burner in the floor. The reason for this approach was that the measured HRR curve from the experiment was used as input to the simulations as we wanted to validate the laminate and gas temperature calculations. The HRR curve is shown in Figure 4-25.

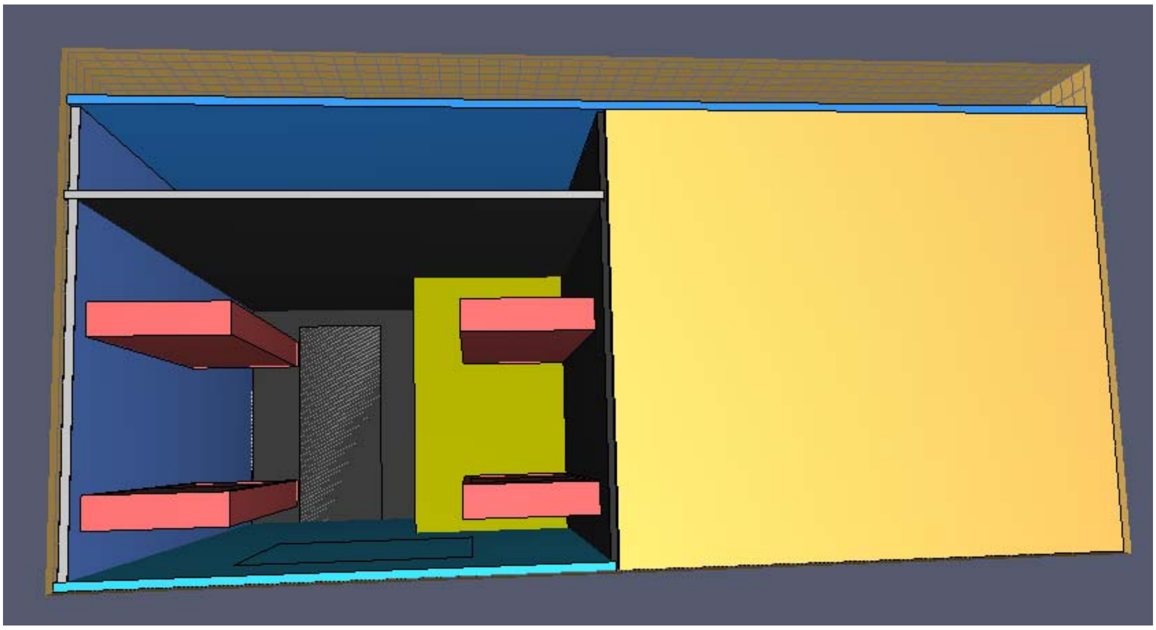

Figure 4-24 Computer model of the test cabin.

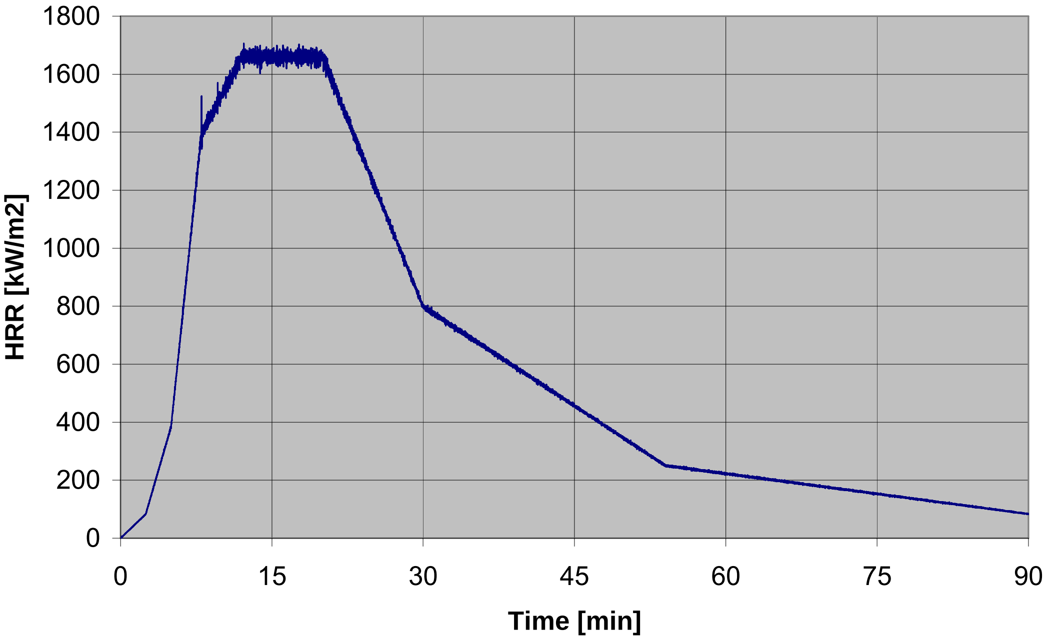

Figure 4-25. The experimentally measured HRR used as input in the simulations.

4.6.2 Results

The simulation was run for 90 minutes of fire. Gas temperatures were monitored at four locations in the gas layer in the cabin marked with 1-4 in Figure 4-26. Points 5 and 6 in the figure refer to aluminium plate temperatures on the floor. The laminate temperatures and surface temperatures of the lower face of the suspended ceiling were monitored at locations 1-3.

The gas temperatures were simulated for two different heights in each location, 50 mm below the insulation and 150 mm below the suspended ceiling (indicated by “low” in the legend). The suspended ceiling was modelled to collapse at 7 min. The calculated and measured gas temperatures 50 mm below the insulation at location 2 are shown in Figure 4-27.

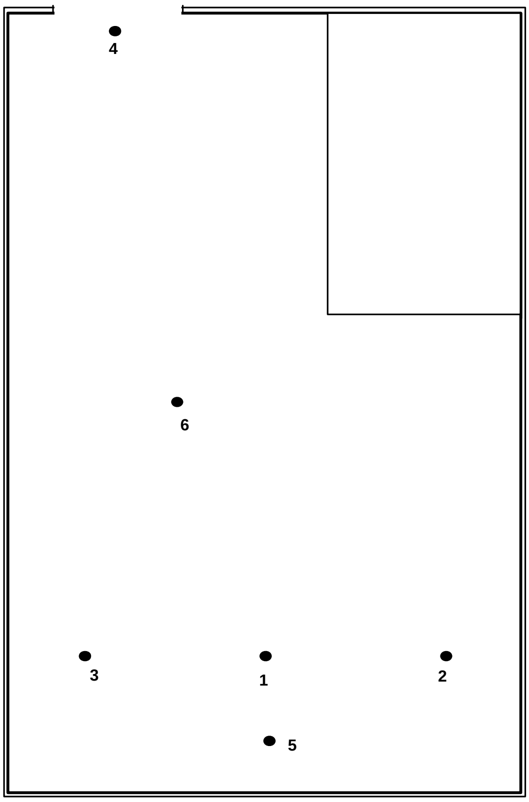

Figure 4-26. Locations of temperature monitoring in the cabin.

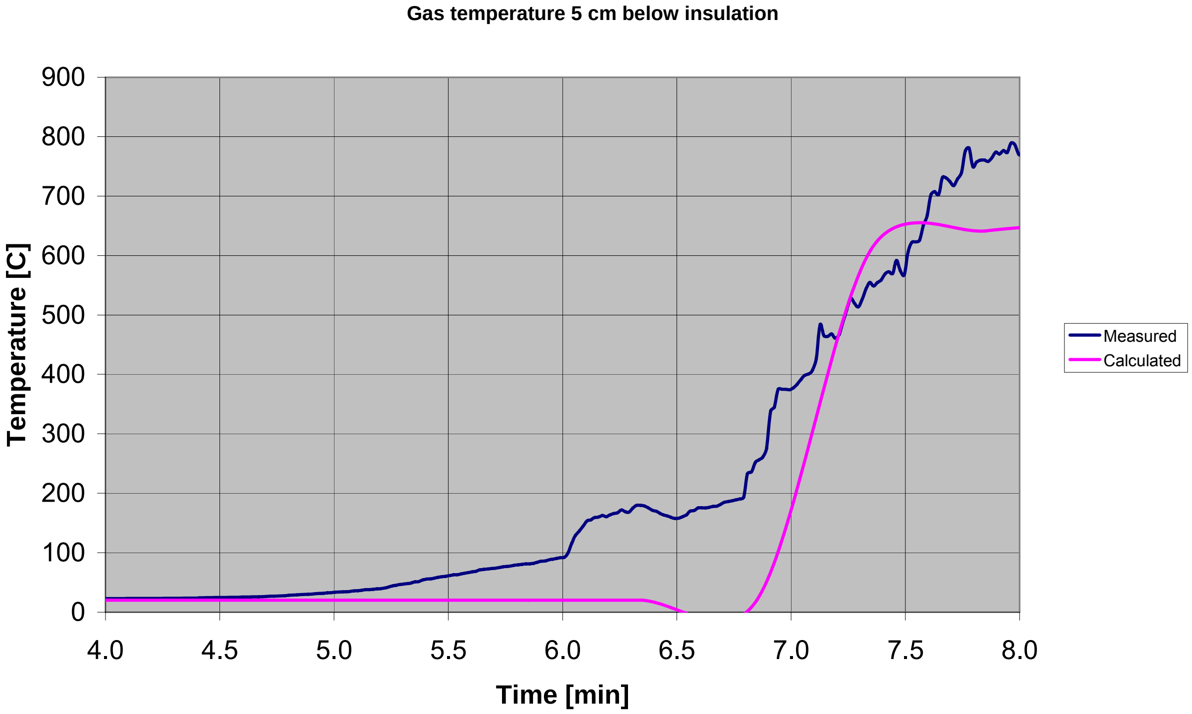

Figure 4-27. Measured and calculated gas temperatures 50 mm below the insulation.

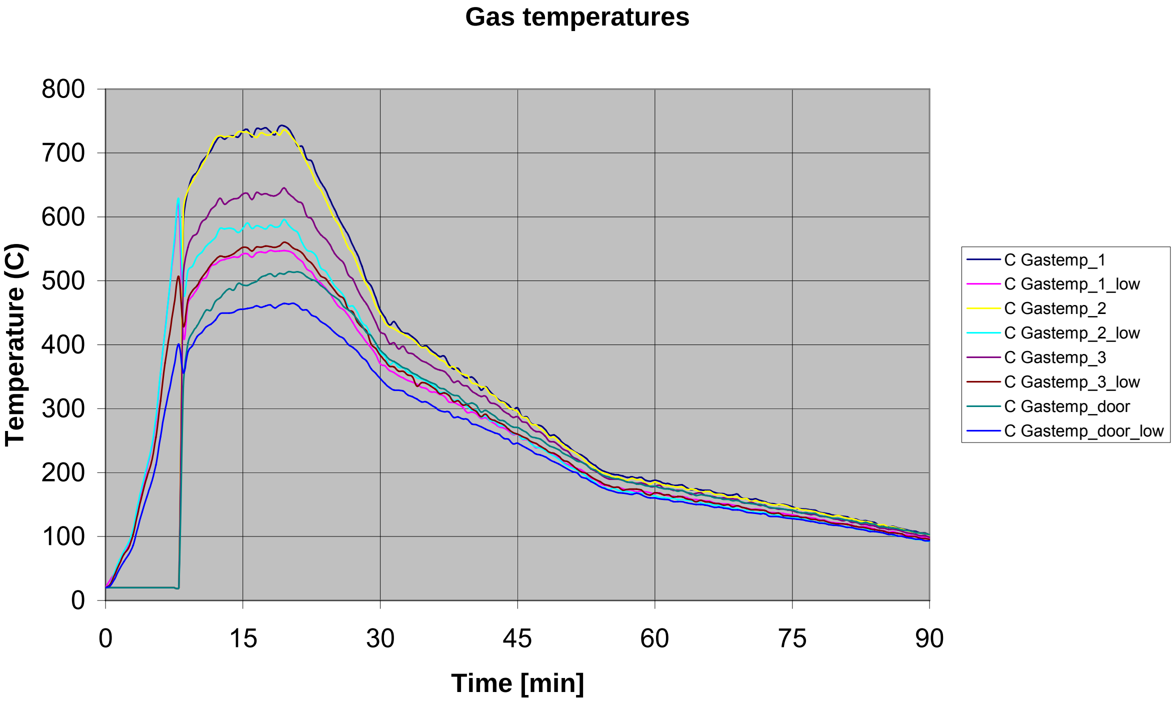

Figure 4-28. Calculated gas temperatures in the cabin. Numbers 1, 2 and 3, respectively, in the legend refers to position denoted in Figure 4-26.

Figure 4-29shows the comparison of calculated laminate temperature with measured ditto at location 2 as denoted in Figure 4-26. The reason for the short experimentally measured curve is technical problems during the experiment[xv]. As can be seen from the figure, the agreement between simulated and measured data is excellent and varies less than 1 % between 60 and 90 minutes. However, it is important to note that the measured temperatures refers to a point above the laminate, i.e. between the lightweight core and the laminate (a thermocouple was mounted in a hole pre-drilled from the backside of the composite), whereas the calculated temperature is for a point underneath the laminate, i.e. between the 100 mm insulation layer and the composite. The 1 mm thick laminate should, however, not have a very large impact on the temperature gradient after such a long time, even though it clearly influences a more dynamic situation with steep temperature gradients.

Figure 4-30 shows the calculated aluminium plate temperatures at two positions (5 and 6). The temperatures should be compared to measured data as given by Figure 4-31[2]. Note the difference in time-scale for the two figures.

[xv] Temperature measurements were lost for a while during the experiment due to a computer error

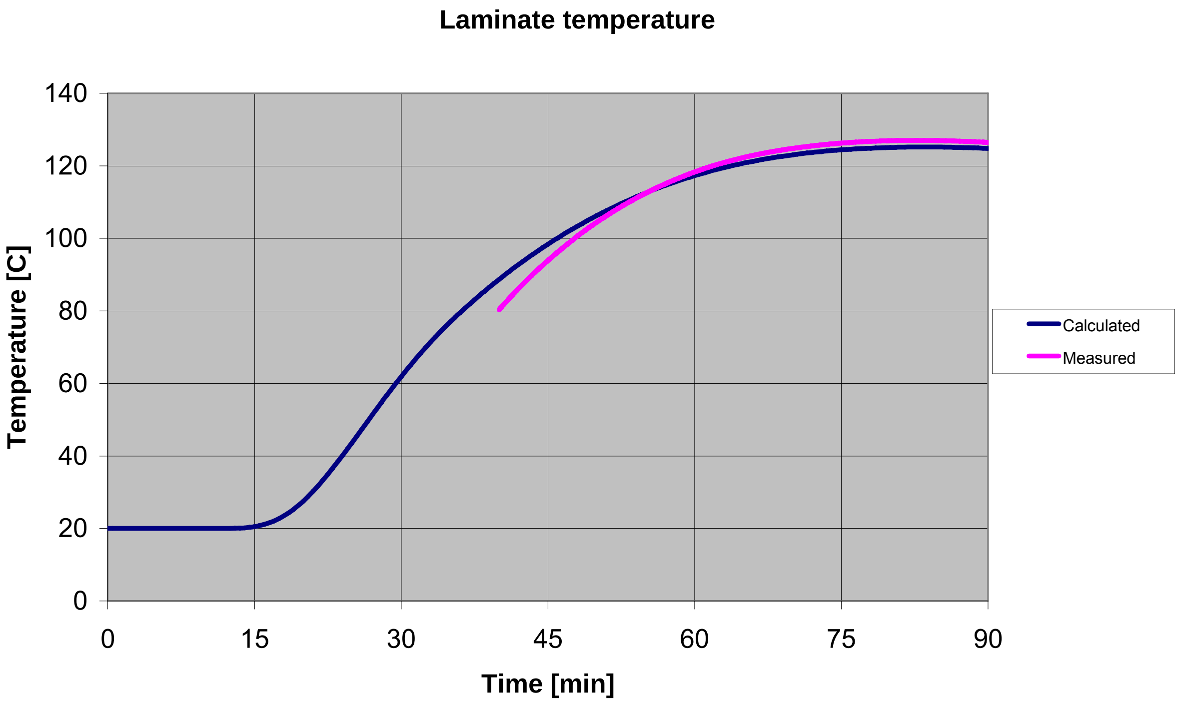

Figure 4-29. Calculated and measured laminate temperatures at location 2 (see Figure 4-26).

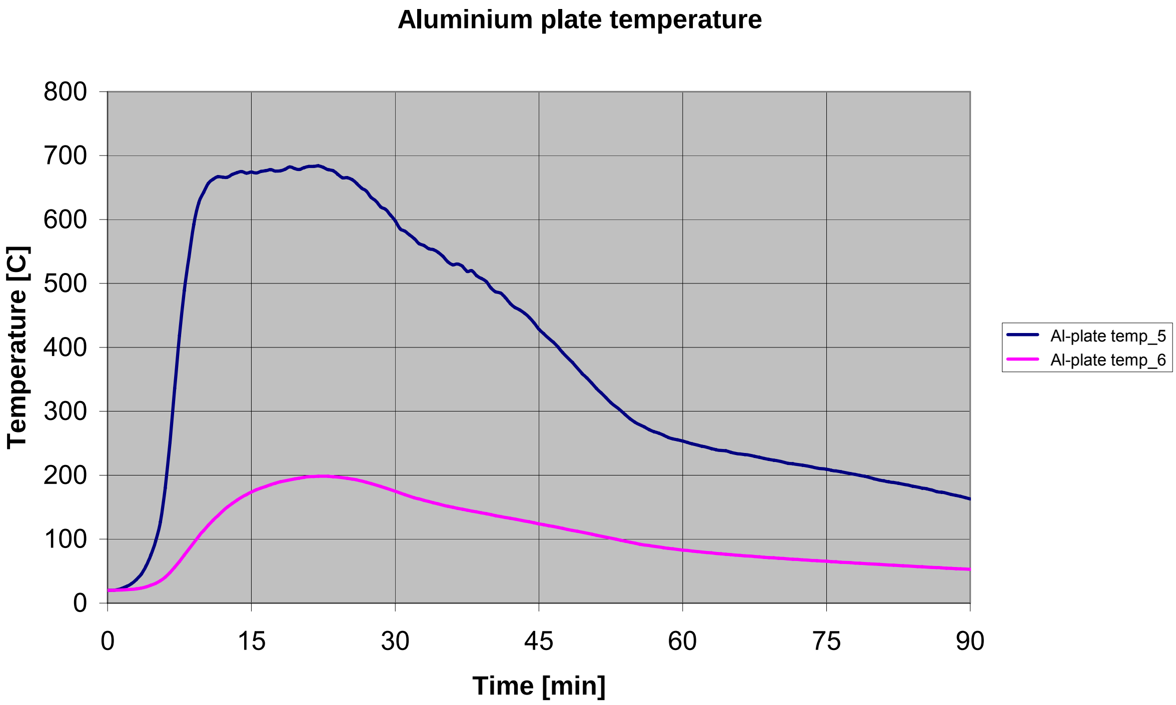

Figure 4-30. Calculated temperatures of aluminium plate at locations 5 and 6 (see Figure 4-26) as a function of time.

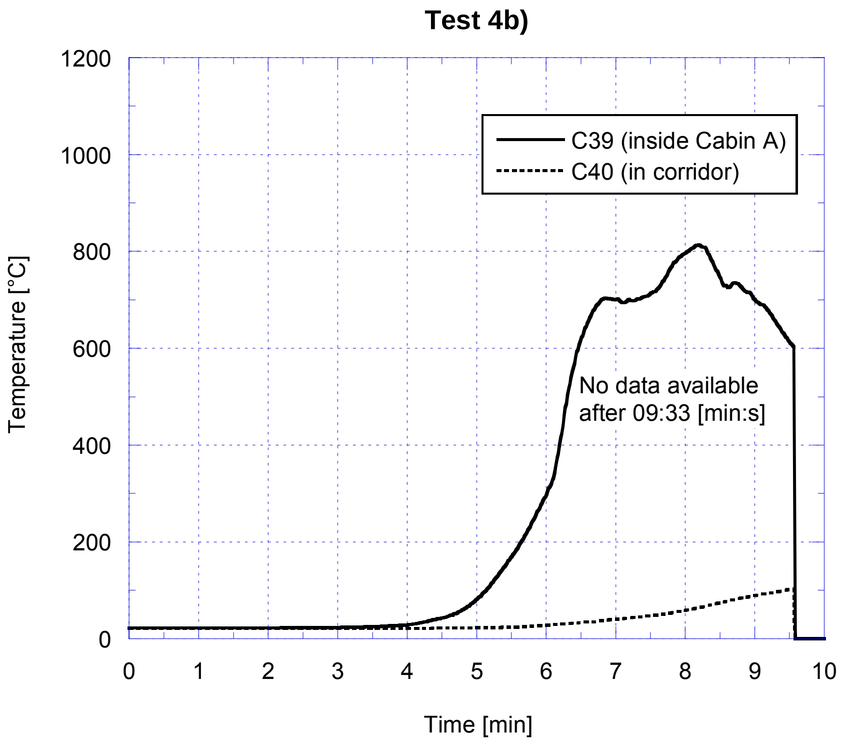

Figure 4-31 The temperatures at the Plate Thermometers at the floor in Test 4b).

4.7 Appendix-report

Included as an appendix report is a description of typical test specimens used in the project for deck and bulkhead tests for obtaining a Fire Resistance Division certificate in accordance with the IMO FTP code (MSC.45(65)). The general principle underlying the designs was to test a "worst case" construction with regards to mechanical and fire properties, i.e. thin laminates and a particularly lightweight core in the composite itself and few or no stiffener for the constructions. The idea was that the certificate obtained thereby would be usable also for any "better" construction design without further testing as the otherwise repetitive need for testing would induce an obstacle for FRP composites in ship building.

The design used at SP for fire tests is given in the appendix report: "Composite panels for deck and bulkhead fire tests".

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[1] *International code for Application of Fire Test Procedures: FTP Code*, International Maritime Organization, IMO publications, London 1998

[2] Arvidson M., Axelsson J., Hertzberg T., *Large-scale fire tests in a passenger cabin,* SP Report 2008:33

[3] Wade C.A. LeBlanc D. Ierardi J. and Barnett J.R., *A Room-Corner Fire Growth & Zone Model for Lining Materials*, ICFRE2 Conference, Maryland August 1997

[4] www.fire.nist.gov/fds

[5] Hertzberg T. Sundström B., van Hees P., Simonson M., Design fires for geometrically constrained fires, SP Report 2003:02

5 Extruded Aluminium Components for ship building

5.1 Introduction

Aluminium is in many ways a very suitable material for shipbuilding. Readily abundant, light, strong and corrosion resistant, aluminium is used for structural purposes in vessels ranging from small dingys to the largest cruise ships.

Being a young material, knowledge of aluminium as a structural material in shipbuilding is still fairly restricted compared to steel and GRP (for smaller vessels). There are some properties i.e. thermal conductivity, that must be considered when working with the material. Welding in particular is an area where aluminium differs from steel and where personnel must be skilled in handling the differences.

Aluminium is available as sheet, plate and extrusions. The extrusion process makes it easy to design custom shapes for a reasonable price which in turn can contribute to an optimized structure.

This chapter gives a short description of the possibilities of extruded aluminium components in shipbuilding applications

Figure 5-1 Cruise vessel with top decks made of aluminium extrusions

5.2 Aluminium properties

Aluminium is in general corrosion resistant due to the fast spontaneous development of a thin and tight layer of oxide. This can be enhanced by anodizing. If connected to other metals and in the presence of an electrolyte there is a risk of galvanic corrosion. For applications below the waterline, a suitable coating is usually used.

The typical physical properties for extruded aluminium (6000 alloys) are

Rp02 = 170 – 260 N/mm2
Rm = 215 – 290 N/mm2
A5 = 8 – 12 %
E = 70000 N/mm2
Thermal expansion = 23x10^-6/
Thermal conductivity = 190 W/m,C

5.2.1 Alloys

Alloys are categorized by the main alloying elements. There a two categories of alloys used in shipbuilding: 5000 series where magnesium is the main alloying element and 6000 series where silicon and magnesium together are the main elements. 5000 series alloys get increased strength from cold work where as 6000 series get it from artificial ageing (heat treatment). The static strength of heat treated 6000 series alloys will decrease approximately 40-50% in the heat affected zone after welding.

5.3 Extrusions for ship building applications

There are many companies that supply extrusions to ship builders. In many cases the customer is recommended to choose from a selection of standard sections. This is a similar situation to that when working with steel structures. But this does not provide the optimal solution.

Designing a custom extrusion enables the possibility of including other functions i.e. tracks for connecting fixtures or similar. This in turn may save time during construction and installation. Also, wall thickness and profile size can easily be adapted to meet specific requirements.

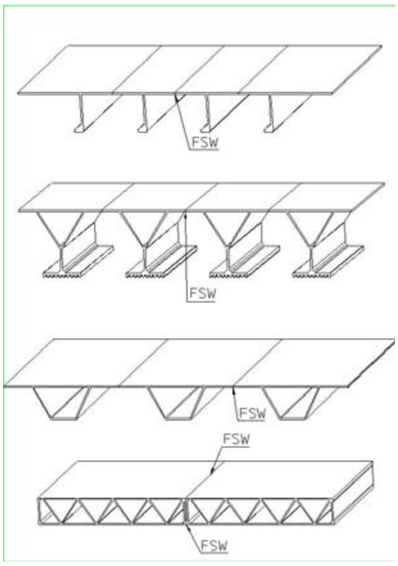

Figure 5-2 **Standard (top) and custom sections joined into panels for ship applications. The bottom section is welded on both top and bottom sides**

5.4 Joining methods

Aluminium is readily joined by welding, mechanical fasteners, adhesive bonding or a combination or the above said methods. MIG (metal inert gas) is the most common welding method used in shipbuilding. Several suppliers offer equipment for this.

One method that is steadily growing in use is Friction Stir Welding (FSW), a method invented by The Welding Institute in Cambridge, England. In this process the metal is joined in a solid state as opposed to a molten state as in MIG. The benefits are significantly less distortion and higher strength in the heat affected zone, compared to MIG. The FSW process is done in an industrial environment with controlled process parameters which leads to lower quality costs.

Another advantage with FSW is that the welded panel already weld approved, no further inspection of the welds is required. This saves time and money when assembling the panels to the ship.

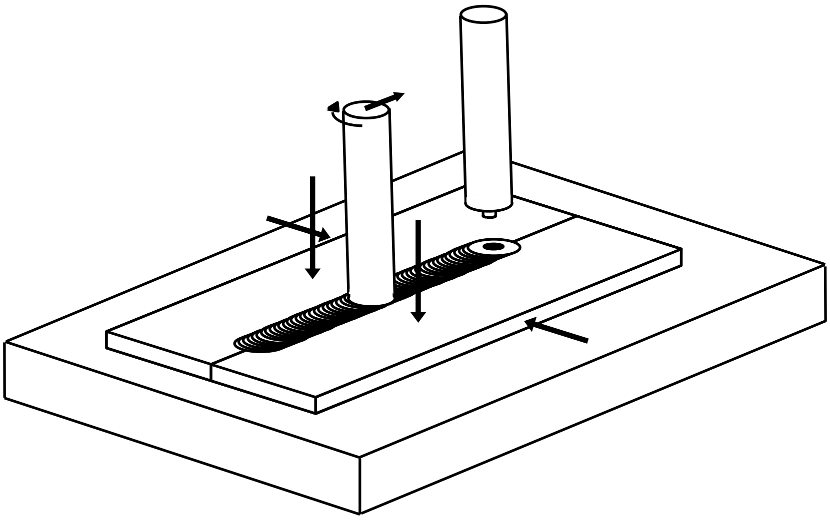

Figure 5-3 **Principle process of Friction Stir Welding. The joining tool is under rotation, forced down upon and moved along the joining line between the work pieces.**

5.5 Prefabricated components

Extrusions are supplied, depending on the supplier, in a wide variety of pre fabricated states ranging from mill finished to fabricated, surface treated and assembled components. For shipbuilding applications, the LASS-partner Sapa supplies mostly mill finished, pre cut, and or FSW joined panels. Panels are available up to 14 m in length and 3 m in width and based on solid or hollow cross sections.

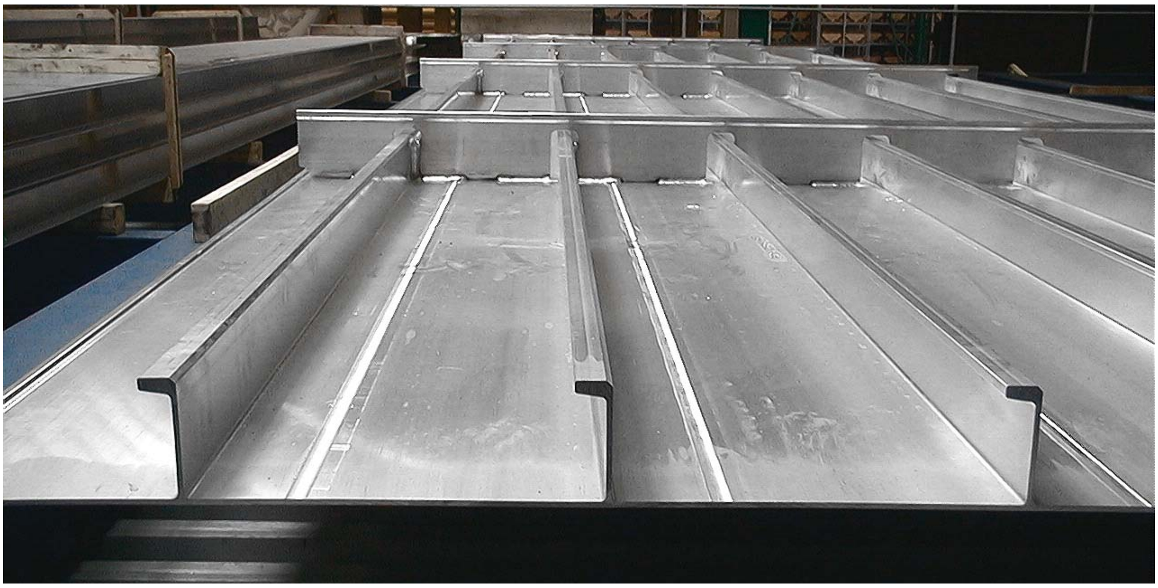

Figure 5-4 Prefabricated FSW panel with transverse stiffeners

5.6 Appendix-reports

Investigations made as part of the LASS project concerning aluminium are described in the following appendix-reports:

- Extrusion of Aluminium-Vanadium alloys
- Laser-Ultrasonics for examination of AL-surface
- Shear testing of two aluminium alloys
- Surface treatments counteracting galvanic corrosion.

6 Composites cost-questionaire analysis

6.1 Introduction

LASS, has between the years 2005 and 2008 been focussing on the use of lightweight aluminium and FRP based composites for ship building. There are a number of reasons for using such materials rather than traditional steel but there are also some obstacles and negative aspects to overcome. The type of obstacles can be divided into

1. Technical
2. Tradition
3. Cost

For the third obstacle, cost, other economical issues than merely production costs needs to be included in the analysis. LCC (Life Cycle Cost) analysis has therefore been utilised in the LASS project and this tool has clearly demonstrated economical benefits of using lightweight construction materials for ship building. More about this will be mentioned in a later chapter.

There are, however, also reasons to look at the initial cost for production and this chapter will provide some such information on composites and composite vessels based on LASS project investigations but also on a questionary sent to Nordic ship yards and composite manufacturers.

6.2 Questionary objectives

The questions were defined in order to get a general overview of the production cost for composites and single skin FRP panels and also indications of the production cost for a composite ship hull. Included in the questions were only man-hour costs plus overhead, during manufacture. Excluded were material costs, development costs etc. Also mould making costs for the hull construction questions was excluded. The reason for the rather simple approach was to try to keep the questions and the answers as simple as possible to allow an easy comparison between participants and also to facilitate for them to take part in the investigation.

Another objective of the investigation was to see what factors the companies thought could be important for the development of composite production in the future and what they considered to be obstacles to the development.

6.2.1 Participating industries

Sixteen Nordic industries were identified that either produced composites or composite ships. Of the contacted group, nine answered to the questions (56 %), seven of them were ship yards and two were manufacturers of composite materials.

There is a large variation within the responding group with regards to company size and type of production. It might be easier for a smaller company to keep overhead costs down than for a large one. On the other hand, it is probably easier for a large company to negotiate low material prices. However, the answers at least provide a frame for understanding of the man-hour costs involved in composite production.

In the table below is given the names and web-addresses of the companies that took part in the investigation.

Table 6-1 Industries that provided data to the analysis

Company	Ship yard	Country	contact information	Maximum length of composit hull (LOA)
Fibrocom Oy, Mikkeli,	No	Finland	www.fibrocom.fi	-
FY-Composite Oy, Nokia	Yes	Finland	www.fy-composite.com	No information
Joptek Oy	No	Finland	www.joptek.fi	-
Kockums	Yes	Sweden	www.kockums.se	140 m
Swede Ship Composite	Yes	Sweden	www.swedeship.se	75 m
Fosie Plast	No	Sweden	www.fosieplast.se	-
Danish Yachts	Yes	Denmark	www.danishyacht.com	50 m
Br Aa	Yes	Norway	www.braa.no	40 m
Mundal	Yes	Norway	www.mundal.no	No information

6.3 Questionary

The whole idea of a voluntary industrial participation in the investigation required the amount of work for answering to be fairly small. This is also a criticism that might be directed against the investigation as some questions might be considered too unspecified. Another such critical point is the fact that there is a large variation in type and/or size of the industry. Obviously, it would have been interesting also to see the variation in other costs such as material and equipment cost but the amount of work necessary for the participants would then have been much larger.

The questionary was divided into two parts; the first part with five questions was meant for ship yards only and the second part with four questions was intended for all participants. Questions specifically aiming at cost estimates were divided into different materials so that the nine questions become fourteen. Further was cost estimates asked for two different amounts of produced units (e.g. 10 and 20 ship hulls in question no 1), which probably was not such a good idea as several of the responding industries only gave one answer without specifying whether the high or the low number of produced entities were used as a base for the estimates. In the questionary results presented below, only the lower number of units is therefore presented as it is assumed that this number is most relevant for the majority of the industries and therefore most likely used as base for the calculation.

6.3.1 Questions for ship yards only

Below is shown part one of the questionary, i.e. the ship yard only questions.

1. What is your typical production cost in €/m^2 and €/kg for ship hulls made from the materials below, if you only consider man hour costs? Please give estimates for serial production of 10 and 20 ship hulls.

    a. Steel.
    b. Aluminium.
    c. Glass/polyester/sandwich.
    d. Carbon/vinylester/sandwich.

2. What are in your opinion the most important reasons for differences in production costs in your answers to question no 1? Please state briefly

3. What is in your opinion the largest obstacle for increased use of FRP composite materials in ship building? Please motivate briefly

   a. Legislation
   b. Technical obstacles
   c. Fire safety
   d. Other

4. Do you notice an increased interest from costumers regarding life cycle costs such as cost for operation (fuel, maintenance) and costs for end of life treatment (reuse, recycling, energy recovery etc.)?

5. What is the largest possible (LOA) composite ship you could manufacture?

6.3.2 Questions for all participants

Four questions were intended for all participants:

6. What is your typical production cost in €/m^2 for flat <u>sandwich</u> panels made from the below materials, if you only consider man hour costs? Consider 2000 m^2 and 10 000 m^2 panel production of FRP composites, when a 50 mm 80 kg/m3 PVC-foam core is used? Panel size is 2.5 x 8 m and fibre weaves used are 3+3 quadriaxial non crimp fabrics with a surface density of 850 g/m^2.

   a. Glass/polyester/sandwich.
   b. Carbon/ vinylester/sandwich.

7. What is your typical production cost in €/m^2 for flat <u>laminate</u> panels made from the below materials, if you only consider man hour costs? Consider 2000 m^2 and 10 000 m^2 panel production of FRP composites. Panel size is 2.5 x 8 m and fibre weaves used are six quadriaxial non crimp fabrics with a surface density of 850 g/m^2.

   a. Glass/polyester
   b. Carbon/vinylester

8. What novelties during the last 5 years have, according to your opinion, been most efficient in lowering composite production cost, on a scale from 1 (lowest) to 4 (highest)? Please motivate briefly your choice.

   a. material cost
   b. equipment development
   c. method of manufacturing
   d. other

9. In what areas do you expect developments that will have important cost impact for composite production in the forthcoming 5 years, on a scale 1-4? Please motivate briefly your choice.

    a. material cost
    b. equipment development
    c. method of manufacturing
    d. Other

6.4 Results

Not all participants did answer to all questions. This might be due to that a question was considered irrelevant, e.g. not all ship yards use all materials specified in question no 1 or that the respondent wanted to keep some economical information in questions 6 and 7 secret.

In Table 6-2 is shown the answer frequency for all questions and a short explanation for the question. Please see full questionary (6.3) for all question details.

Table 6-2 Number of answers from the participants

Question no	Regarding	Number of answers
1a	Hull construction cost	1
1b		2
1c		3
1d		4
2	Cost variation explanation	4
3	FRP obstacles	6
4	LCCA and LCA	6
5	Maximum LOA	4
6a	Sandwich panel cost	7
6b		5
7a	Laminate panel cost	7
7b		5
8	Previous production development	8
9	Expected development	7

6.4.1 Man-hour costs

For the estimates (questions 1, 6, 7) of man-hour costs (including overhead) necessary for the production of hull, sandwich or laminates, the span of minimum and maximum costs together with the associated mean and median values are given below.

Table 3 Result of cost inquiries in questions 1, 6 and 7

Question no	Regarding	Min-max cost	Mean value	Median value
1a	Hull construction cost	-	-	-
1b		21-28 €/kg	24.5 €/kg	24.5 €/kg
1c		11-19 €/kg	16.1 €/kg	17.0 €/kg
1d		16-34 €/kg	18.7 €/kg	16.8 €/kg
6a	Sandwich panel cost	16-300 €/m^2	135 €/m^2	120 €/m^2
6b		15-200 €/m^2	79 €/m^2	42 €/m^2
7a	Laminate panel cost	11-200 €/m^2	72 €/m^2	55 €/m^2
7b		14-200 €/m^2	78 €/m^2	33 €/m^2

Question 1a was disregarded from as only one industry had provided an answer. The cost for a steel hull production should, however, typically be somewhere around 30% of the given aluminium production cost.

It is noticeable that the span, in particular for the sandwich and laminate production cost is very wide. This might have to do with the fact that the industries involved differ very much in size and therefore might have quite different overhead costs. Also the actual man-hour cost for the employee differs between the countries[1].

Table 6-3 Cost per working hour in the Nordic industry in 2006[1]

COUNTRY	COST PER HOUR OF WORK, INCLUDING TAXES
Norway	32.6 €
Denmark	28.1 €
Sweden	25.2 €
Finland	23.7 €

6.4.2 Other questions

Question number 3

In this question, the opinions on the main obstacle for using FRP composites in shipbuilding were asked for. Four areas were suggested: Legislation, technical obstacles, fire safety and "other". The list below is a ranking of all answers where almost all agreed on the fire safety issue and most of the answers also included the need for knowledge.

1. Fire safety and how to prove it
2. Lack of knowledge as well as an existing general scepticism towards FRP materials in the group of potential buyers
3. Lack of academically or other people educated in FRP-design
4. Cost for simple FRP-parts might be higher than for aluminium

Question number 4

Regarding the customer interest for life cycle analysis (LCA) and life cycle cost analysis (LCC), everybody answered that they saw an increasing demand for both LCC and LCA. Some citations are given below:

- ”End of life ship treatment is asked for by all larger ship owners”
- ”Maintenance is more important than end-of-life for the LCA argument”
- ”LCC argument is very important”
- ”Composite in fishing ships helps protecting the catch and thereby provides a higher price for the fish” (!)
- ”Better thermal insulation and less maintenance is an important argument for using composites”

Question number 5

Regarding maximum length of a composite ship that the yard can produce, see Table 6-1

Question number 8

Regarding the last 5 years novelties for lowering composite production costs, the following was responded (8 out of nine industry responded to the question but several answers obtained from some)

- 7 says new manufacturing methods is the prime reason for a lowered production costs; 2 explicitly says vacuum infusion is the new technique used
- 2 says that development of equipment has been important

- 1 says material cost was the most important factor

Question number 9
Regarding the expected next 5 years novelties having an impact on production costs, the following was responded (7 answers in total)

- All says material cost is the most important parameter but that the price might change both ways
- Second in rank is equipment development
- Third in rank is method of manufacturing
- Production logistics is also mentioned as an important parameter

Comparing questions 8 and 9 it seems that the industry do not foresee a development “quantum leap” of production methods similar to the introduction of vacuum infusion. In fact, they consider the parameter most important on which they will have the least chance of influencing, material cost. This might be an indication that they are not preparing for large investment in technique or machinery to lower production cost but instead prepared to produce based on existing tools. Or it might be an expectation on future large variations in material costs.

6.5 Conclusion

One must obviously be very careful when making conclusions out of only 9 respondents. However, the industries involved represent an important part of the Nordic composite shipbuilding and composite manufacturing industries.

The production costs obtained differs a lot but at the same time provides a finger print of the cost levels to expect. Interesting information obtained was what parameters the industry expects to be important for the future development (mainly material cost) and also what they think are major obstacles (mainly fire safety).

The request for cost and environmental information (i.e. for LCA and LCC) from the clients to the participating industries is a very positive sign for the composite industry as these factors are strong points for composite ship building.

It would obviously have been very nice to make a more detailed and full investigation where all cost aspects of composite ship manufacturing would have been covered. However, the work done was made within a rather limited time frame and the main interest was to get an idea of easily comparable costs, but also to get other important information from the industries with regards to future and trends. In this sense the investigation was successful.

Acknowledgements
The investigation was made possible thanks to all participant industries that kindly put time and effort into providing answers.

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[1] M. Larsson, Internationella löner för industriarbetare, Löner och löneutveckling år 2000–2006 för industriarbetare i 34 länder, Landsorganisationen LO.

7 Case study WP3a; a high-speed craft with composite hull

Kurt Olofsson
SICOMP Swerea

7.1 Introduction

Composite materials have been the preferred hull material choice for small boats, during the recent 40 years. An indicated trend is that the usage will spread to smaller ships and structures in larger ships. Advances in materials- and manufacturing technology during the recent 10-15 years strengthens this trend. Of primary importance is here the general introduction of the vacuum infusion process in the ship building industry. This enables important improvements regarding material quality, system weight, man-hour reductions, production cost, etc.

7.2 Existing high-speed craft

The Swedish LÄSS project (light weight construction applications at sea, www.lass.nu) has studied the influence of light-weight design, using both composite and aluminium materials, on several concept ships. One such concept ship is a 24 m aluminium high speed craft with a fully loaded speed of 27.5 knots, see Figure 7-1. It was designed to be built in a series of some 20 ships. Only two were in fact built due to military budget cuts. The relatively small size together with the high speed makes it a suitable object for light-weight design. The existing modern military transport ship (Transport Ship 2000), made from aluminium, has been derived into several civil versions to enable comparisons regarding production cost and Life Cycle Cost (LCC).

Figure 7-1 Military Transport Ship 2000

7.3 Project goal

The project goal was to convert the aluminium ship to civil DNV-standard as reference ship, then design a corresponding composite ship with 30 % lower structural weight for the insulated hull, similar ship performance and 25 % lower production cost and LCCA for 20 years service.

7.4 Procedure

The development was concentrated on the empty hull including insulation. Systematic design of several ship versions towards the same specification and ship standard was performed to quantify the function and value of lightweight construction for high-speed ships of this size. The existing military aluminium ship developed and owned by the Swedish Defence Material Administration, have been modified for civil passenger usage. New specification, general arrangement and insulation plans for the different ship versions were established.

7.5 Ship specification

A new ship specification was established[1]. Some main requirements were:

- 36 passengers and 3 crews
- 10 ton load displacement
- 3 or 2 water jet propulsions
- Developed for production of 20 ships

Utilisation cycle: 20 years service. 3000 yearly running hours. 26 knots normal loaded operational speed with 80 % running time. 20 knots loaded operational speed with 10 % running time. 10 knots loaded operational speed with 10 % running time.

7.6 Ship versions

The new general arrangement drawing is in Figure 7-2. The separate 4 m^3 fuel tank in Version 0 have 600 kg in structural weight. The composite ships have hull integrated fuel tanks which approximately saves these 600 kg. The same type of water jet machinery is used in all versions to enable comparisons without influences from differing machinery performance. One machinery unit consists of a Scania DSI 14 68M diesel engine with a maximum power of 460 kW, which drives a water jet propulsion unit. These machineries are a dominant part of the ship with a unit weight for engine plus water jet propulsion, of 3080 kg and a unit price of 250 kEuro. Version 0, 1, 3 have three water jet propulsions. Version 3A has two water jet propulsions and 33 % smaller fuel tanks. The smaller fuel tank translates into a reduction of the loaded displacement by 1100 kg, due to reduced fuel weight. More fire insulation is used in the composite ship versions compared to the aluminium ship due to DNV HSLC-code regulations. The composite ships are manufactured using vacuum infusion in separate tools.

The following ship versions were studied[2]:

Version 0: aluminium.
Version 1: Sandwich with glass/vinylester.
Version 3: Sandwich with carbon/vinylester.
Version 3A: Version 3 with two water jet propulsions and 33 % smaller fuel tank.

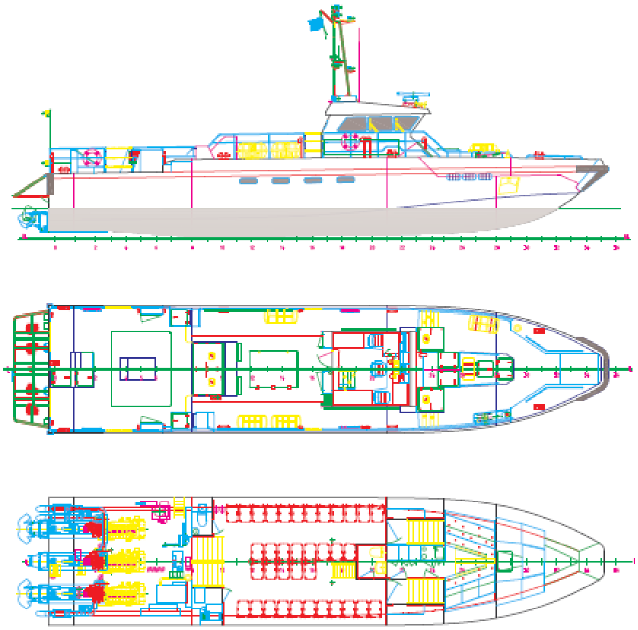

Figure 7-2 General Arrangement of civil passenger ship with 3 water jet propulsions.

7.7 Insulation

New insulation plans (fire-, thermal- and noise insulation) for the different ship versions were established. Specific thermal- and moisture insulation are not included in the composite versions, since they were considered not to be needed due to the inherent properties of sandwich composite materials. Approved fire insulation materials according to DNV HSLC-code regulations, were used. Fire insulation was increased above regulations to ease certification and reduce the needed specific noise insulation for the ship versions. This means that A60 fire insulation was used in the engine compartment instead of the required A30. Fire restricting material was also used in all internal compartments including below the waterline, in the composite ship versions. The military Transport ship 2000, have a lower total insulation weight at 2590 kg, which is mainly due to its lower fire insulation standard. Table 7-1 and Figure 7-3 shows the obtained insulation weights listed by each insulations primary function. The insulation package is identical for all composite ship versions, which eases development and analysis.

Table 7-1 Hull insulation materials

INSULATION	MATERIAL	VERSION 0 [KG]	VERSION 1 [KG]	VERSION 3 [KG]	VERSION 3A [KG]
Other	Cover, support	755	653	653	653
Noise	Damping compound, damping elements, mineral wool	1766	901	901	901
Fire	Firemaster 607, Fireliner FPG Mk2	462	1374	1374	1374
Thermal, Moisture	Glass wool	291	-	-	-
Total	-	3251	2928	2928	2928

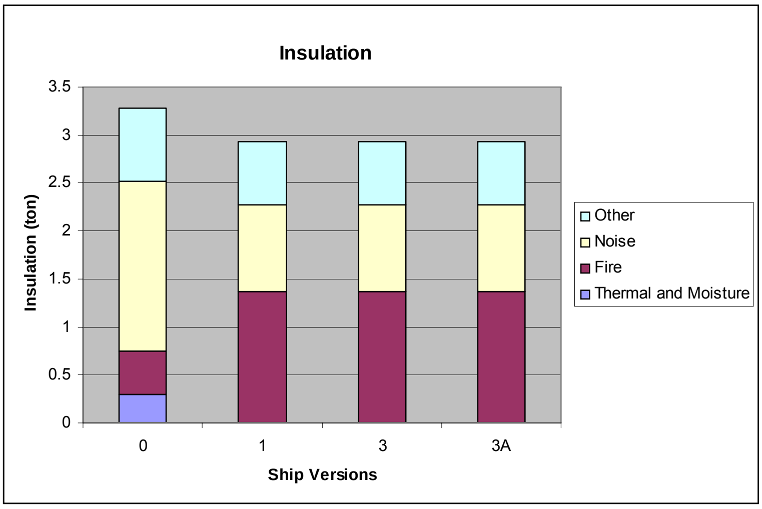

Figure 7-3 Hull insulation materials

7.8 Dimensioning

All the ship hulls were dimensioned according to the DNV HSLC-code[3]. Version 3A uses the same dimensioning as the one obtained for Version 3. A further slight reduction in hull weight can hence be gained for Version 3A by taking away supporting structures for one engine, which is hence neglected here. Chosen composite hull materials were DNV certified glass fibre, carbon fibre and vinylester/Divinycell. A similar structural layout was used as for the reference ship. Sandwich laminates were used as much as possible in the design. Simplified production was introduced in the design to reduce the production cost including use of a minimised number of fibre weaves, weave thicknesses and PVC-densities. The empty insulated hull is defined in the same way as in the specification for the original military ship. This means that the engines and most additional equipment are not included in the empty insulated hull.

The hull structural weight is given in Table 7-2. The empty insulated hull displacement is presented in Table 7-2 and Figure 7-4, with fuel tank and some minor equipment added. Weight reduction for the empty hull with insulation package is 28-43 % for the studied ship versions compared to the reference ship, Version 0.

Table 7-2 Hull structural weight

Material	Type	Version 0	Version 1	Version 3	Version 3A
aluminium	SIS 4140, 4212	10.6 ton	-	-	-
Fiber	E-glass	-	3.1 ton	-	-
Fiber	T700 carbon	-	-	1.8 ton	1.8 ton
Resin	Vinylester	-	2.6 ton	2.0 ton	2.0 ton
Core	PVC Divinycell H60, H80, H100, H130	-	1.7 ton	1.3 ton	1.3 ton
Total	-	10.6 ton	7.4 ton	5.1 ton	5.1 ton

Table 7-3 Hull displacement

Ship Data	Version 0	Version 1	Version 3	Version 3A
[1]Hull displacement excl. insulation	11.7 ton	7.9 ton	5.6 ton	5.6 ton
Insulation weight	3.3 ton	2.9 ton	2.9 ton	2.9 ton
Hull displacement incl. insulation	15.0 ton	10.8 ton	8.5 ton	8.5 ton

[1] Including fuel tank (Version 0) and minor hull mounted equipment.

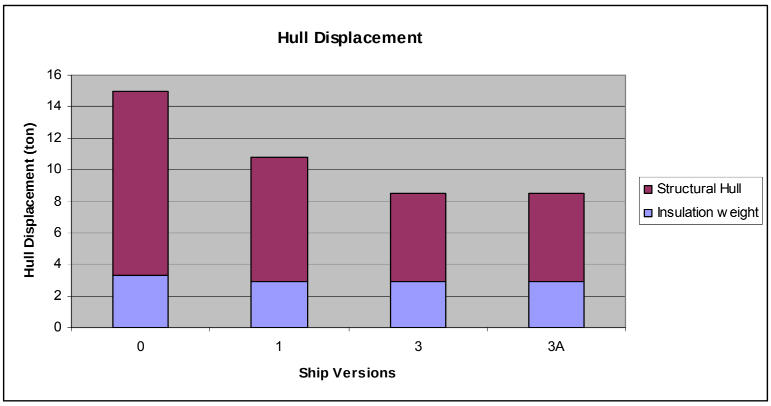

Figure 7-4 Insulated hull displacement

Measured data during delivery trials on the two manufactured military ships have been used together with calculations to predict ship performance. These data includes speed and fuel consumption in fully loaded and unloaded conditions. The original military ship increased its top speed from 27.5 knots to 33 knots when the displacement was altered from 48 to 38 tons (by switching from full to zero load). These values are well in line with the obtained top speed values in Table 7-4 for Version 0, 1, 3. The drag reduction and top speed for Version 3A when one water jet is removed have been estimated in collaboration with Rolls-Royce. All ship versions can fulfil the utilisation cycle. Version 3A is, however, the only version that shows a significant reduction in fuel consumption by the use of a light insulated hull together with one engine less.

Table 7-4 Ship data

Ship Data	Version 0	Version 1	Version 3	Version 3A
Total loaded displacement [ton]	47.6	43.4	41.1	36.9
Top speed [knots]	28	29.5	31	27.5
Maximum installed power [kW]	1380	1380	1380	920
Power fully loaded at 26 knots [kW]	1100	1030	990	845
Fuel consumption fully loaded at 26 knots [liter/hour]	264	257	247	212
Fuel consumption fully loaded at 20 knots [liter/hour]	165	148	137	114
Fuel consumption fully loaded at 10 knots [liter/hour]	38	33	30	28

7.9 Cost

The production costs have been calculated without tax, with 4 % interest rate and 5 % inherent profit. Production of a 20 ship series, at a shipyard in Sweden, is studied in the cost calculations[4]. The material types used in the hull with insulation, cost between 2-43 Euro/kg. Initial costs for development (marketing, ship specification, quotation, contract, design, dimensioning, construction, drawings, quality system, etc) and manufacturing equipment (tools, cutting, welding, measurements, 50 % assumed remaining manufacturing equipment value, etc.) as well as finalisation costs (certification, delivery approval, etc.) have been estimated. The material waste during empty insulated hull manufacture is assumed to be 3-6 %, depending on the used materials and manufacturing methods. Some hull material is delivered pre-cut to shape to the shipyard, i.e. aluminium sheets for Version 0 and fibre weaves and core material for the composite ship versions.

All composite versions show improvements towards the reference ship (Version 0) for the empty insulated hull, see Table 7-5 and Figure 7-5. Production cost is predicted to be lowered by 30-39 % for the insulated hull. The material share for the insulated hull is much lower for the aluminium ship which indicates that the manufacturing process, vacuum infusion, for the composite ships is more rational. The man-hour cost for mounting of the insulation package is substantial. The hull manufacture waste is generally smaller for the composite ships than for Version 0.

All composite versions show improvements towards the reference ship (Version 0) for the total ship production cost and LCC, see Table 7-6, Figure 7-6 and Figure 7-7. The LCC-analysis is approximate with some minor cost influences neglected. The production cost for the complete ship is lowered by 11-26 % Especially Version 3A benefits from the reduction in the number of expensive engines from 3 to 2. Maintenance and remaining ship values are estimated from experience. Composite hulls have generally less problems with fatigue and corrosion, which are the main reasons for the assumed differences. Composite hulls are here assumed to have the same value in Euro after 20 years of service as when they were new. The LCC is lowered by 5-21 % for the composite versions. The LCC is completely dominated by the fuel cost for this application, which explains why Version 3A is the best one. Composite hulls are hence indicated to be a good choice for this type of ship with light-weight benefits translated into lowered production costs and LCC. Carbon fibre hulls are indicated as the optimum selection.

Table 7-5 Production cost for empty insulated hull

Cost Type	Version 0	Version 1	Version 3	Version 3A
Total manhour cost [kEuro]	427	211	209	209
Hull mounted equipment [kEuro]	29	17	17	17
Material (brutto) [kEuro]	57	85	131	131
[1]Material share [%]	11	28	37	37
Hull manufacture material waste [kEuro, ton]	3, 0.8	2.5, 0.3	4, 0.2	4, 0.2
Total [kEuro]	512	313	357	357

[1]Excluding hull mounted equipment.

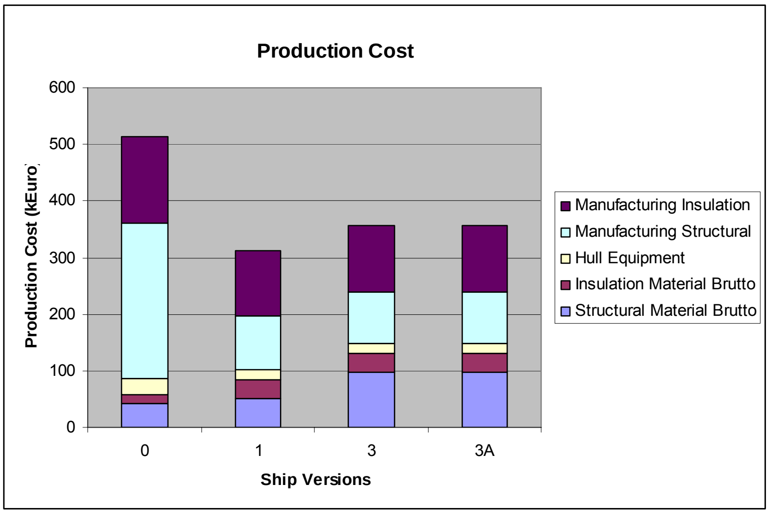

Figure 7-5 Production cost for empty insulated hull

Table 7-6 Ship cost data for studied versions.

Ship Data	Version 0	Version 1	Version 3	Version 3A
Total ship production cost [MEuro]	1.70	1.46	1.51	1.26
Maintenance [kEuro/year]	15	11	11	11
Remaining ship value after 20 years service [% of original purchase price in current value]	70	100	100	100
LCC-cost during 20 years operation [%]	100	95	92	79

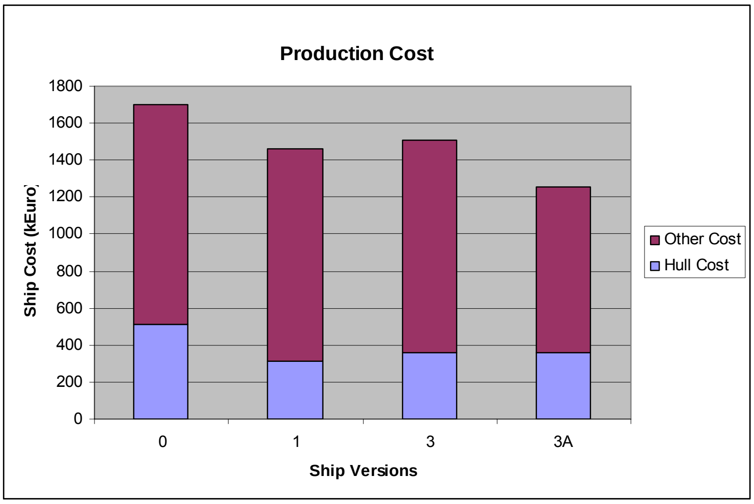

Figure 7-6 **Total ship production cost**

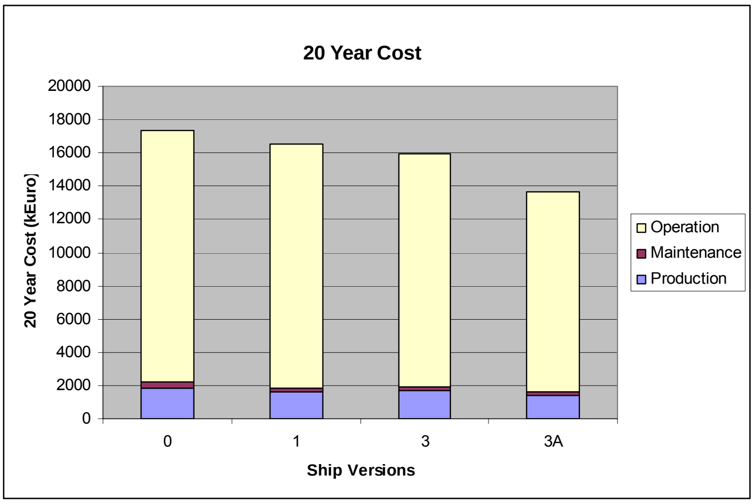

Figure 7-7 **LCC for ship versions**

7.10 Coast guard craft

The Swedish defence material administration has performed related studies[5] (included as an appendix in Swedish) on possible future use of similar ship designs for the Swedish coast guard, derived from Transport ship 2000 along the lines of Version 3A; see Figure 7-8. This ship is a 24 m composite material high speed craft, 48 tons loaded displacement with a fully loaded speed of 30 knots using water jet propulsion. A target for the study was a ship that was robustness reinforced above the demands in the DNV HSLC-code due to the tough service conditions for coast guard craft. A separate specification has therefore been added for reinforcement towards increased service robustness. Proven reinforcement principles from the previous carbon/Divinycell/vinylester military “Stridsbåt 90E” have been applied using the DNV HSLC-code. Implemented extra reinforcements, includes the keel (to support anchoring on beaches, sea bed contacts at speed and dry docking) and hull (to support docking to port and ships at sea and movement through ice). The coast guard craft is hence separately reinforced with 1320 kg, which represents an approximate 26 % increased structural hull weight. This can be regarded as an upper limit case for robustness reinforcement.

Figure 7-8 Projected new coast guard craft with composite material hull

Linear scaling indicate that the empty insulated hull cost for the passenger ship (Version 3A) increases with 14 %, if it is reinforced in a similar way with 26 % increased structural hull weight as the coast guard craft. See 3A Reinforced in Figure 9. Comparisons with the other ship versions indicate that this cost increase could still be acceptable if a really robust ship was needed and the ship performance was not significantly affected.

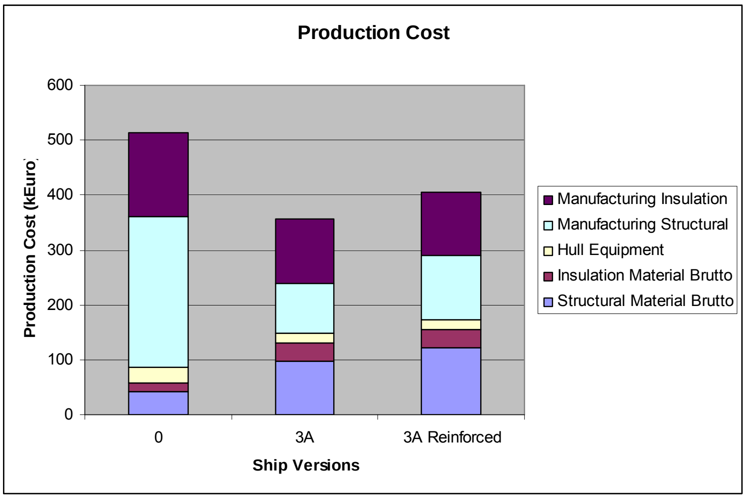

Figure 7-9 Production cost for empty insulated hull

7.11 Conclusions

Composite high-speed craft have been studied in several versions. The influence of lighter insulated hulls on the ship performance, have been analysed. Composite hulls show a competitive purchase price and low LCC, for this application.

Version 3A described in this report is the most promising compared to the reference ship (Version 0) with predicted 52 % lower structural weight for the hull, 43 % lower weight for the insulated hull, 30 % lower empty insulated hull production cost, 26 % lower ship production cost, 21 % lower LCC for 20 years service and similar ship performance for the intended usage.

7.12 Appendix-reports

Appendix-reports made in relation to WP3a is:

- Degree project – Composite failure predictions
- Degree project – Manufacturing methods for composites (Sw)
- Prestudy of new surveillance ship (Sw)
- Degree project – Robust constructions (Sw)

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[1] Olofsson K., Hjortberg M., "Specification for High-Speed Craft with Composite Hull", LÄSS-project Report, 2006

[2] Olofsson K., "Conversion of Military Ship to Civil Ship with Composite Hull", *LÄSS-project Report*, 2007

[3] Arnestad G., "Structural Dimensioning of High-Speed Craft", *LÄSS-project Report*, 2007

[4] Olofsson K., Edlund A., "Manufacturing Parameter Influences on Production Cost", *Proceedings of ICAC 98*, Hurghada, Egypt, 1998

[5] Sörensson M., Dahlström N., Sjöling S., Lönnö A., "Prestudy of new Surveillance Ship for the Swedish Coast Guard", *Swedish Defence Material Administration Report*, 2007

8 Case study WP3b; a sandwich construction on a superstructure of a high speed ferry

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This chapter discusses the possibility of using light weight FRP composite material for the construction of a super structure for an 88 m long Catamaran. Different concepts have been studied using material and spacing of pillars as parameters. Structural analysis for each concept is performed. The most lightweight concept is further evaluated using Finite Element Analysis method. Thus both Analytical and numerical methods have been used to confirm the feasibility of having a composite super structure for the vessel.

The report is a short version of a Licentiate Thesis presented as part of the LASS project[1].

8.1 Introduction

Innovative materials and technology like composites and sandwich construction are actively being used in the transport industry and in recent times there is a greater awareness of the possibility to implement light weight materials also in larger sea going vessels. FRP's have been extensively utilised e.g. in manufacturing small boats for a number of years and its success in an area where wood was the conventional material for construction can be attributed to[2]:

Competitive investment costs, especially where a number of hulls are to be fabricated out of the same mould.
Low maintenance hassles and a very low maintenance cost.
Ease of making complex shapes

This report describes a preliminary study to look into the design of a composite superstructure for Stena Carisma, an 88 m high speed aluminium ferry capable of carrying 900 passengers and 210 cars.

Smith[2] and others[3,4] have investigated the sandwich superstructures for steel and aluminium ships. For larger ships, the major problems found were initial cost and lack of stiffness for the light weight materials. Smith concluded that if the superstructure must contribute to global or hull girder strength, then it should be made of steel. If not, then composites can be used. However, rapid advances in technology make it possible to fabricate also larger ships completely of composite materials.

Figure 8-1 **75.2 m Mirabella V and 73 m Visby Corvette - Longest Glass and Carbon Fibre vessels**

8.2 Problem Description

When different materials are used, the issue of joining them together also presents challenges. Traditionally, such a joint would contain mechanical fastenings such as bolts and metallic clasps and would involve point loads or holes to be drilled in the sandwich structure. These holes pose a problem for the composite structure[5] as point loads are considered to be debilitating. Hence it is important to study the behaviour of the joint.

8.3 Methodology

A structural analysis of the composite superstructure using an analytical and numerical approach was made. Four concepts were generated on the basis of material used and spacing of pillars on the public deck. A study of a section of the superstructure was performed and the results extrapolated to the total structure. Scantlings etc were computed according to the DNV HSLC code for the section.

The HSLC requirements for composite panels were put together in a calculation module where an optimum value was sought at the same time as the weight of the structure was kept to a minimum. This process of optimization was then included in a greater subroutine where panels and the spacing of transverse and longitudinal frames were optimized.

To ensure that the values obtained from the optimisation were good and also to ensure that the global loads of the vessel did not have an adverse effect on the structure, a Finite Element study was also performed. Global loads were applied, according to the procedure as defined by the ‘Classification Notes No. 30.8’. The existing Stena Carisma superstructure is designed not to contribute to global strength but in the FE study it was also investigated if the superstructure can contribute to global strength by reducing stresses along the hull. The FE calculations were performed with guidelines from the DNV regulations, however due to limited data available, not all load cases could be studied. Only those cases were primarily studied which were supposed to affect the super structure the most.

8.3.1 Limitations and Boundaries

A major limitation of this study is that no experiments have been performed to consolidate the results obtained from the analytical and numerical calculations.

The process of optimization involves the use of a simplex algorithm. Other methods of optimisation were not tried due to time constraint. All structural FE calculations were performed as linear analysis; a non-linear approach could give appreciable results. Further were pillars assumed to be uniformly distributed, which is not the case in the existing vessel.

8.3.2 Analytical Study

An analytical model was used to understand the behaviour of the sandwich superstructure by which four different concepts were generated:

1. Glass Fibre with five rows of pillars
2. Glass Fibre with three rows of pillars
3. Carbon Fibre with five rows of pillars
4. Carbon Fibre with three rows of pillars

A section of the superstructure, 18 m long, was analysed with the different concepts. All the concepts were compared to a similar aluminium section to get an estimate of the weight savings that could be achieved. It was found that some of the concepts were heavier than the aluminium structure due to the extra requirement for fire insulation which increased the total weight of the structure[xvi]. The concepts heavier than aluminium were discarded for numerical study using the FE model of the complete ship.

8.4 The Ship

HSS 900 or Stena Carisma is an 88m long aluminium catamaran travelling between Göteborg in Sweden to Fredrikshavn in Denmark. As the name indicates, it is a high speed sea service (HSS) type of vessel. It is mainly used for transferring passengers and cars. The particulars of the ship are as given in Table 8-1.

Table 8-1 Particulars of HSS 900

L	Length overall	88 m
B	Breadth	30 m
T	Draught	3,7 m
V	Speed	38 knots
	Displacement	1600 m^3
	Building Material	Aluminium
	Gross Tonnage	408 tonnes
	Port of Registry	Göteborg
	Flag	Swedish
	Engines	2 x ABB-Stal GT 35
	KW	34000 KW

The vessel is classified under DNV HSLC (high speed light craft and Naval Surface craft); as *1A1 HSLC R1 car ferry*. It was built in 1997 at the Westmarin West Bygg shipyard in Norway.

[xvi] It should be noted that the original aluminium vessel was already highly weight optimised

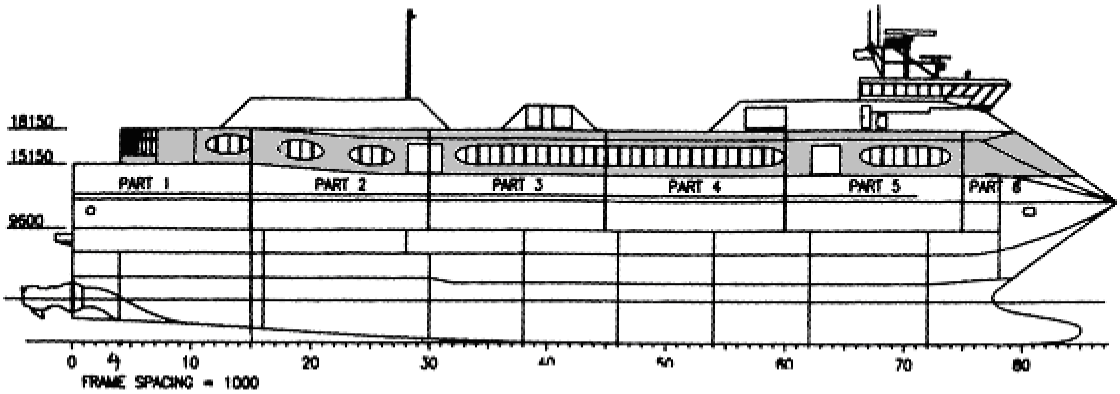


Figure 8-2 The shaded portion is the superstructure

The shaded portion depicted in Figure 8-2 is studied for construction with light weight materials. Frames # 48 to Frame # 66 are looked into in this analytical study. Particulars of the section are as mentioned in Table 8-2.

Table 8-2 Particulars of the Section

Length from Frame 48-66	18 m
Breadth of the section	30 m
Height of the section	3.8 m
Weight of the section	10 tonnes

8.4.1 Pillar Spacing

The existing structure has five rows of non-uniformly distributed pillars.

Four composite concepts were investigated in this study: two 5-pillar designs and two 3-pillar designs, using uniformly distributed pillars at 4.6 m and 9.2 m respectively. The 3-pillar design is shown in Figure 8-3.

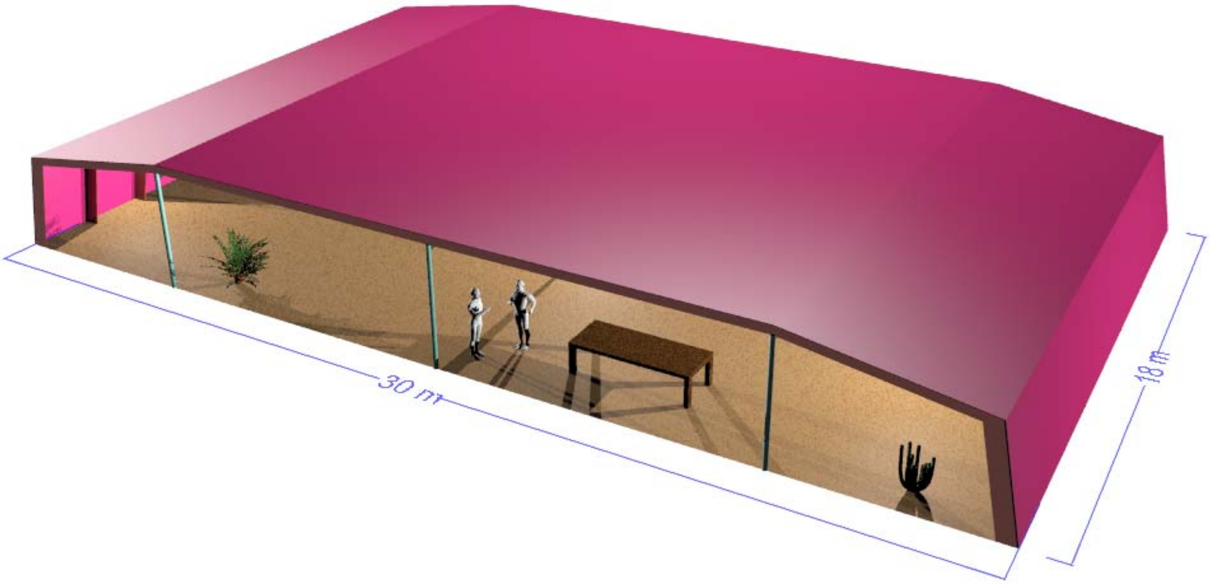


Figure 8-3 An image of the structure with three pillars

8.4.2 Materials and Material Models

Glass or carbon fibre together with vinylic Ester resin was used as laminate material. A Divinycell H-grade PVC foam was used as the core. As the structural requirements on the structure are not very high, the H-60 core serves the purpose well. Carbon fibres used are multi axial and high strength with high elongation to failure. The properties of the materials are as given in Table 8-3.

Table 8-3 Material Properties

Fibres			
Property	Unit	E – Glass	Carbon Fibre
Young's modulus	GPa	72	230 / 40
Density of fibre	kg/m^3	2600	1760
Poisson's Ratio	-	0.2	0.25
Resin			
Property	Unit	Vinyl Ester	
Density	Kg/m^3	1100	
Young's Modulus	GPa	3.1	
Poisson's Ratio	-	0.35	
Core			
Property	Unit	H 60	
Nominal Density	kg/m^3	60	
Shear Strength	MPa	0.8	
Shear Modulus	MPa	22	

From these basic materials, different material models were built. Models were defined for the panel laminates and for the webs and flanges of frames and girders. In total, nine different material models were formulated; the isotropic core material and eight different laminates made of glass or carbon fibres together plus vinylic ester resin, with the fibres arranged in different directions. In any single concept however, only five material models were used, comprising of either the carbon fibre vinylic ester combination or the glass fibre vinylic ester mixture. Thus at no stage were both carbon and glass fibre used in the same concept.

Based on pillar spacing and the type of material used, weight estimates were made for four different designs. In this report, Concept 1 is explained in detail and results for the other three are presented in a general way. The concepts can be summed up as following:

Concept 1 - E glass fibre with 5 rows of pillars
Concept 2 - E glass fibre with 3 rows of pillars
Concept 3 - Carbon fibre with 5 rows of pillars
Concept 4 - Carbon fibre with 3 rows of pillars

8.4.3 Loads

The Aluminium structure has been designed for a load of 3 kN/m^2 and 6.5 kN/m^2. For its composite counterpart, the loading was finalised after communication DNV. Loads on the structure determined from the DNV formulas are smaller than the minimum defined loads. Hence the minimum defined loads have been used for the calculations.

The structure was divided into two major sections in terms of loading, the upper panels which are under a loading of 3 kN/m^2 and the side of the roof, subjected to 6.5 kN/m^2 as shown in Figure 8-4. There exists a difference between the loadings of the two panels as the side of the superstructure is exposed to higher sea pressure than the upper panels. The upper flat panel, also serves as a weather deck, however passengers are not allowed to go there. Primarily, only maintenance personnel are permitted in that area. In this document, the upper panels are referred to as flat and inclined roof and the side panel is referred to as side roof or side panels.

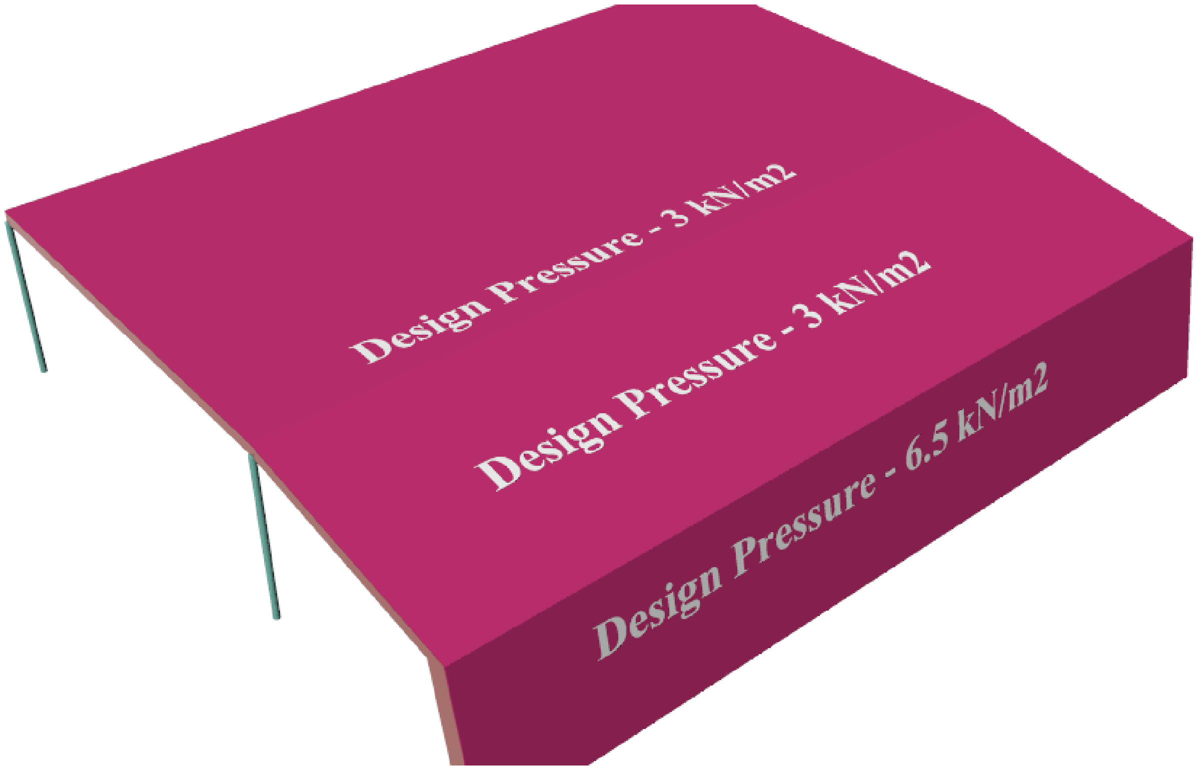


Figure 8-4 Loading of the Structure

8.5 Concept 1 – E Glass Fibre with Five Rows of Pillars

8.5.1 Sandwich Design

The preliminary structural design is based on DNV-rules, the main sections and chapters that had to be used are as mentioned below.

Part 3, Chapter 4, Section 5 (July 2004)
Part 3, Chapter 4, Section 7 (July 2004)
Part 3, Chapter 4, Section 8 (July 2004)

The parts for which the calculations are done are as labelled in Figure 8-6. The public deck will remain unchanged; it is only the structure above the public deck that will be studied for construction with the new materials.

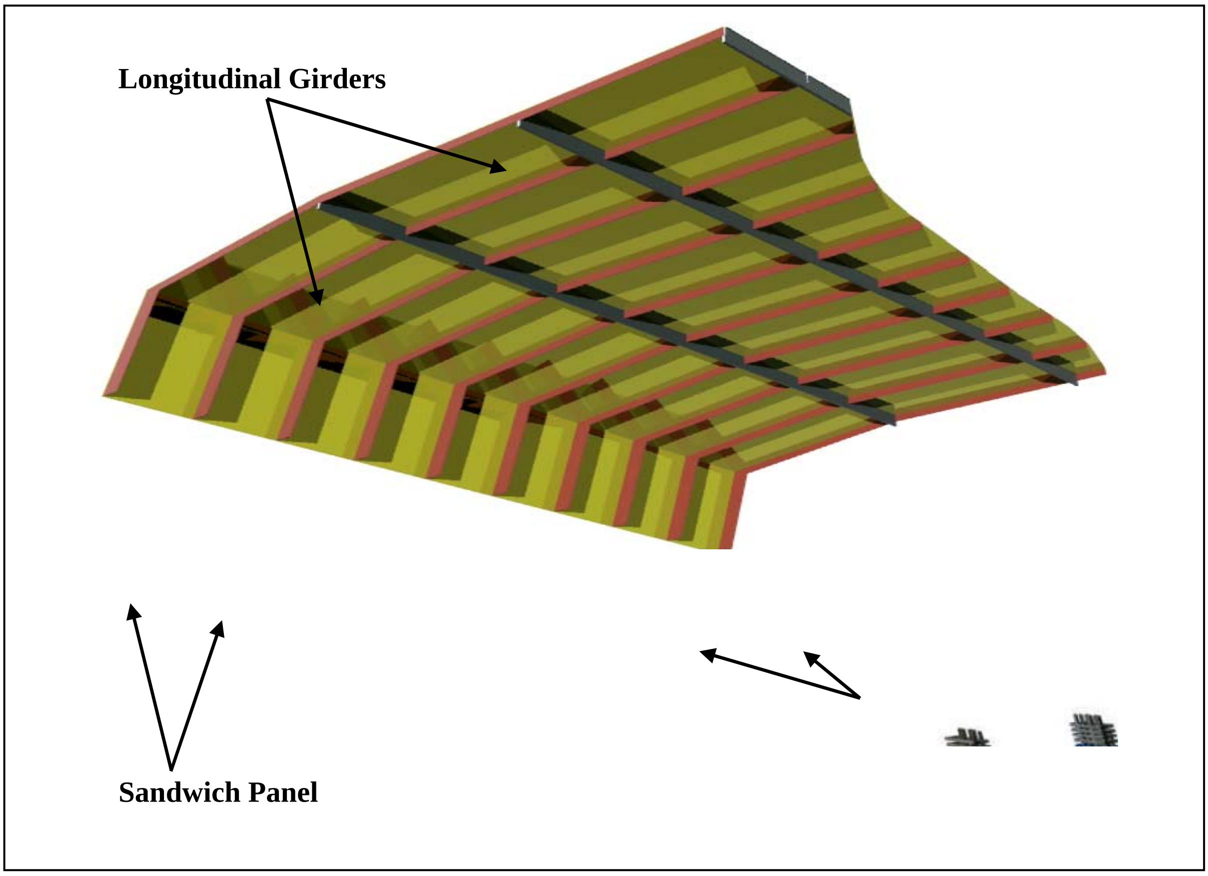


Figure 8-6 An underside view of the Structure

8.5.2 Spacings of Frames and Stiffeners

In the present configuration, there are longitudinal stiffeners that are extruded from the aluminium plate (Figure 8-7) and are spaced at a distance of 140 mm. The transverse frames are at a distance of 2 m, not shown here, and are supported by longitudinal girders which are in turn at a spacing of 4.6 m. For the sandwich construction, the longitudinal stiffeners are done away with as the sandwich offers considerable stiffness. An investigation into the web frame spacing [1 and 2], has shown that it is sufficient to maintain the present standards at 2 m for transverses. The girders which are primarily supported by the pillars have been removed in concept 2 and 4, where there are only three rows of pillars. The spacing of the longitudinal girders is thus 4.6 m for the 5 pillar scenario and 9.2 m for the 3 pillar concepts.

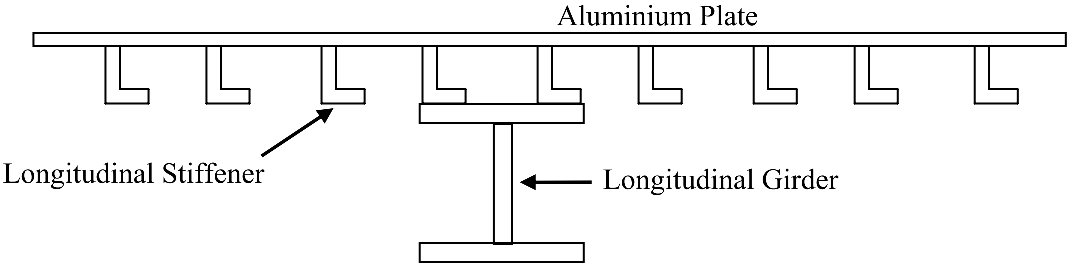


Figure 8-7 **Present Arrangement of the deck plate, stiffeners and Girder**

8.5.3 Minimum Requirements and Laminate Design

The skin laminates are to contain at least 25% by volume of the fibre. After some literature survey, a 50% fibre volume fraction has been chosen to work with. The HSLC code also specifies the minimum amount of reinforcement in terms of weight (g/m^2) that has to be present in the laminates and this is given by

$W \geq W_0 .(1 + k.(L-20))$

The various coefficients used here are as mentioned in the nomenclature. This gives a minimum requirement of 2260 g/m^2 for glass and 1580 g/m^2 for a carbon fibre laminate. The core of the sandwich should have shear strength of 0.5 MPa and compression strength of 0.6 MPa. The lay-up of the fibres is made to ensure uniform properties in the major x and y directions.

8.5.4 Sandwich Panel

A typical sandwich panel comprises of two laminates and a core. The laminates are the same thickness, as shown in Figure 8-8. The requirements on such a panel as laid out by the DNV regulations are as mentioned below.

Normal Stress on the laminates
Shear Stress in the Sandwich Core
Local Buckling or wrinkling of the skin
Allowed deflection of the whole panel

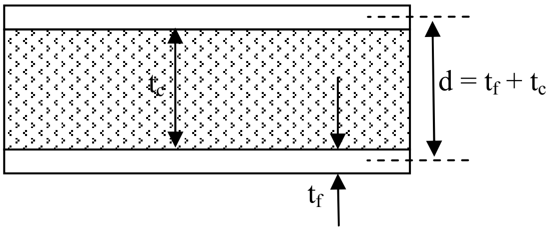


Figure 8-8 **A typical sandwich section**

There are mainly two kinds of panels that are required for this structure. The top section of the roof is designed for 3 kN/m^2, while the sides for 6.5 kN/m^2 (see Figure 8-4). The increased loading on the sides is compensated for by a thicker core. An optimization module was written in Matlab to help in calculation of the scantlings of the core and the laminate. It was found that the higher loading of 6.5 kN/m^2 on the sides should be compensated by increasing the core thickness instead of that of the laminate. The effect on weight increase is the least this way.

8.5.5 Frames & Girders

The requirements on the frames are specified as section modulus (Normal stress), web area (Shear stress) and effective bond area. In general all frames are made with a core inside covered by a laminate. A typical frame is as shown in Figure 8-9. Boundary conditions for the frames and girders are assumed to be partially fixed. DNV rules provide the three options of fixed, simply supported and partially fixed. Both fixed and simply supported are considered to be conservative and open minded approach. Using partially fixed BC, produces result between the other two. The longitudinal girders are supported at the pillars and the transverse frames at the longitudinals.

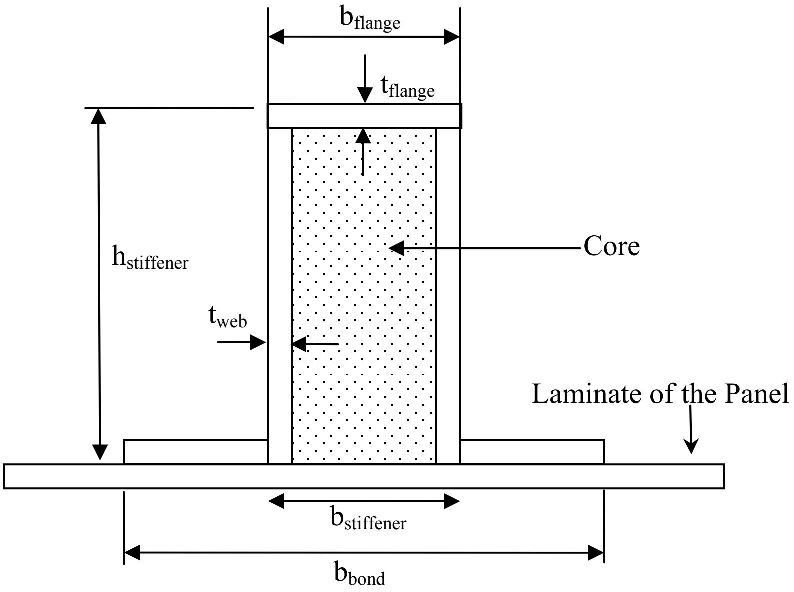


Figure 8-9 A typical sandwich section

The lay-ups of fibres in the web, flange and the laminate of the panel (effective flange) are different. Varied material models are used for different parts of the frames and girders; hence the frames are treated as composite beams. Stress calculations are performed for each of the individual members of the frame.

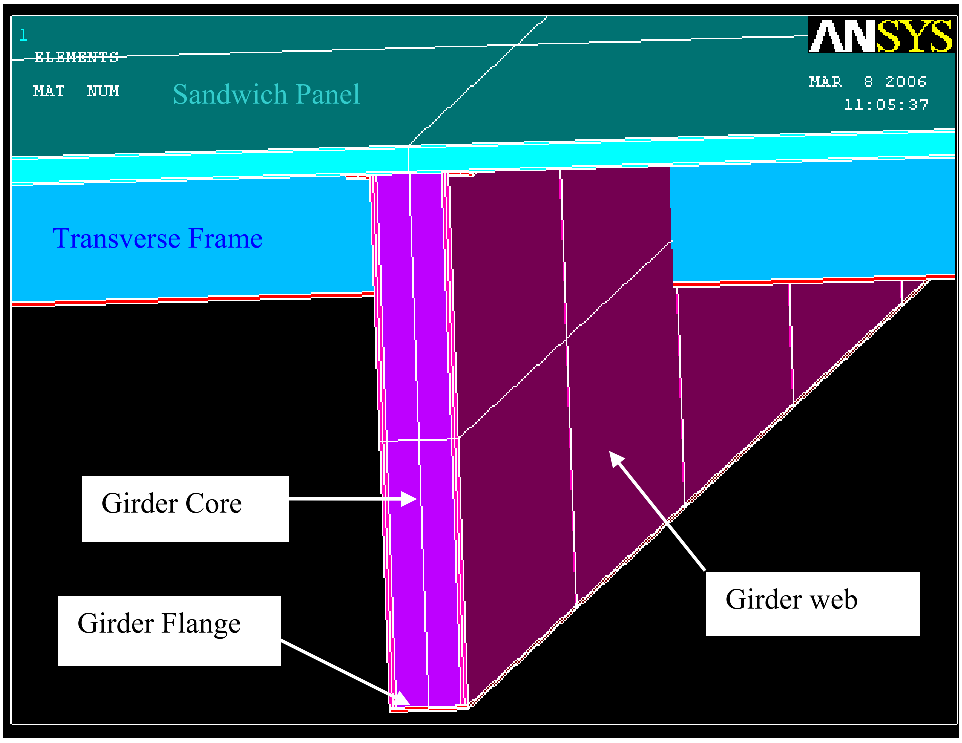


Figure 8-10 **Different colour codes show different material models used for making up the frame and girders**

8.5.6 Natural Frequency Calculations

To perform the natural frequency calculations, the 18 m long structure was modelled in FEM software, ANSYS. An attempt was made to make a solid model in FEM, however the computational time required for the same was very high. Thus the model was remade using shell elements, which reduced the computational time and made it easier to perform the calculation using the computational power available. The elements used are specific to ANSYS, SHELL91 to model the sandwich panels and BEAM189 for the frames and the girders. The total number of elements in the model is 1098 and the number of nodes is 2503. A meshed preview of the model is shown in Figure 8-11.

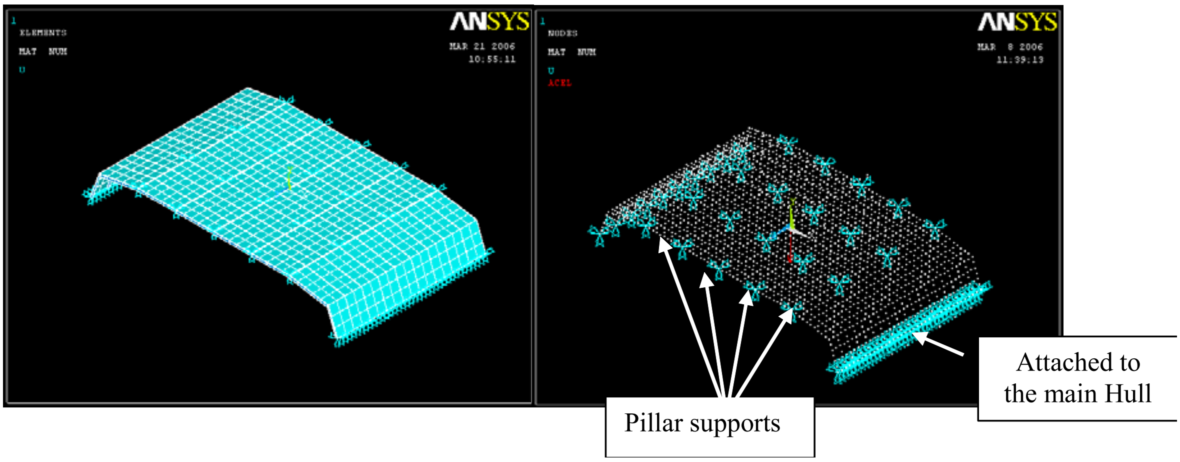


Figure 8-11 **A meshed preview of the 18m structure & the boundary conditions for the FEM analysis**

The structure is assumed to be simply supported at the points where it meets the hull and at the points where it is supported by the pillars as shown in Figure 8-11. As this is a natural frequency calculation, loads have not been defined in this model. It is assumed that the presence of other superstructure sections fore and aft of this structure would not affect the natural frequency calculations. This model was also used to get an estimate of the deflections with the prescribed DNV loadings of 3 kN/m^2 on the flat sections and 6.5 kN/m^2 on the side panels (static analysis).

8.6 Structural Results for Concept 1

Out of the four concepts, results are discussed here for only the first, i.e. glass fibre with five rows of pillars.

8.6.1 Panels

For the upper flat panels, which are exposed to a pressure of 3kN/m^2, calculations reveal that the core thickness of 25 mm and a laminate thickness of 1.76 mm would fulfil the requirements. Similarly, the side panels are 40 mm thick in core and 1.76 mm in laminate thickness, the obvious choice of thicknesses is as shown in the following figures (all dimensions are in mm).

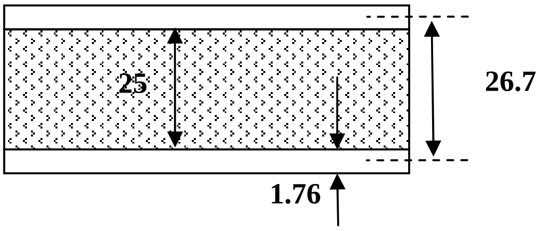


Figure 8-12 Design of the flat roof panel

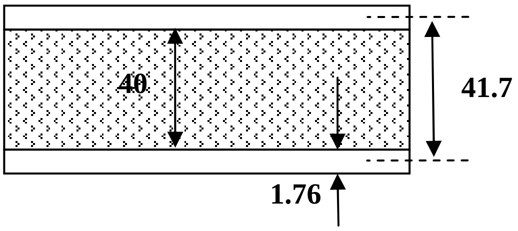
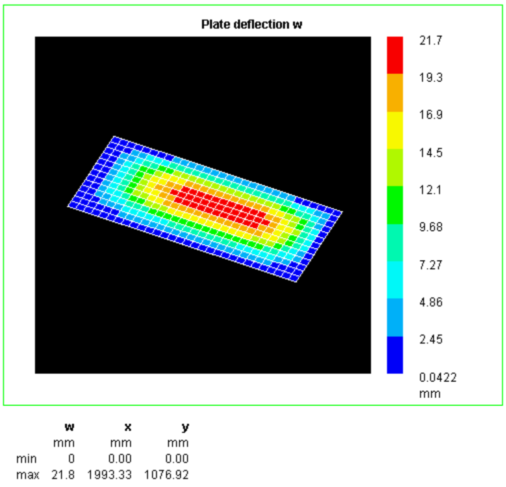


Figure 8-13 Design of the side roof panel

8.6.2 Deflection of the Panel

The minimum requirements on the deflection of an individual panel state that the ratio of deflection to breadth (w/b) should not exceed 0.02. For a panel of this size, this implies a maximum allowed deflection of 40 mm, which is very high. It is assumed here that the maximum allowed deflection should not exceed the thickness of the panel or 28.5 mm. This is in accordance with the ‘First order shear deformation theory’ for composite plates.

A finite element simulation of only the plate with this construction was done. In order to emulate the partially fixed BC of DNV, one of the longer ends of the plate is assumed simply supported and the other fixed, similarly for the shorter edge. The deflection obtained is 21.8 mm, which lies in the allowed limits. The affect of the assumed boundary condition can be seen in the figure below, the right edge of the longer side is deflecting more than the left edge. However, this analysis is only for one panel. The combined affect of all the panels clubbed together will cause sagging of the central panel expectedly more than what this FEM study of a single panel indicates. To look more into the depth of that, a preliminary FE analysis is mentioned later in the report.



	w	x	y
	mm	mm	mm
min	0	0.00	0.00
max	21.8	1993.33	1076.92

Figure 8-14 A finite element deflection of the panel

8.6.3 Frames and Girders

The requirements on frames and girders are defined in the terms of section modulus by the classification society. According to DNV, if the webs and flanges of the beam members are made of different kinds of lay-ups of fibre material, then the requirements are defined in terms of effective section modulus. As the frames and girders are of significant height and breadth it has been found to be a weight saving feature to have different lay-ups in the webs and flanges. Thus the effective section modulus has been computed for each beam.

There are four kinds of cross sections used for frames and girders. The basic structure of all of them is the same as discussed earlier in 8.5.5. The various sections are shown in the following figures, all dimensions are in mm.

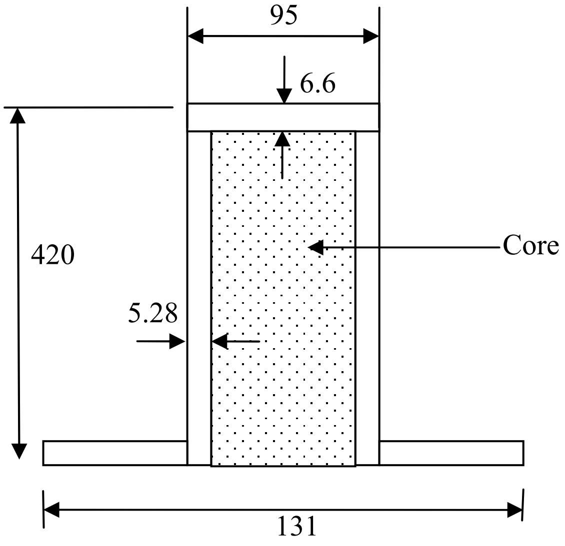


Figure 8-15 Design of Longitudinal Girder

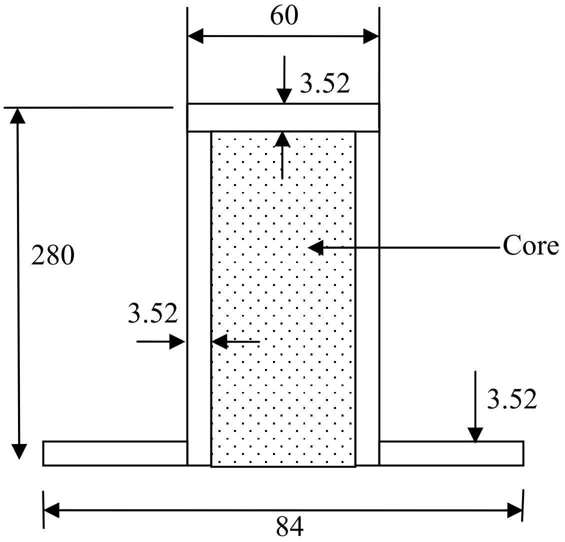


Figure 8-16 Design of the flat roof transverse frame

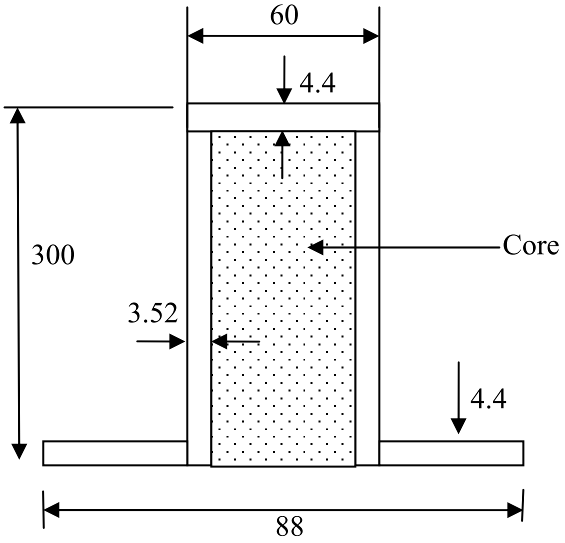


Figure 8-17 Design of the inclined roof transverse frame

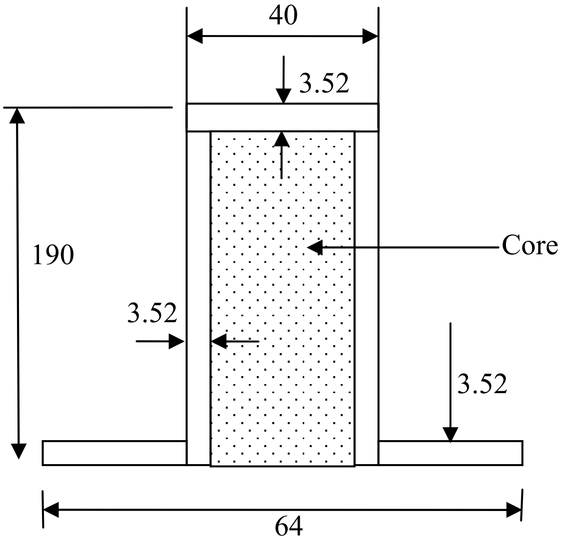


Figure 8-18 Design of the side roof transverse frame

8.6.4 Deflections in the Structure

To ensure that the deflections of the structure are within prescribed limits, a static analysis of the structure was carried out. It was seen in 8.6.2, that the deflection of an individual panel is about 21.8 mm. A global model of the structure was analysed to confirm the combined affect of the loads acting on the structure. In the case of the individual panel, the deflections are relative only to the edges of the panel. In a global model, the deflections are taken relative to the boundary conditions, thus deflections are superimposed from the deflections of the surrounding structure.

Results from this analysis showed that the maximum deflection is 24.8 mm, this is more than the earlier suggested 21.8 mm but still less than the thickness of the plate. Hence first order shear deformation theory still holds and this is an acceptable level of deflection, both from DNV's viewpoint and also from a more theoretical approach.

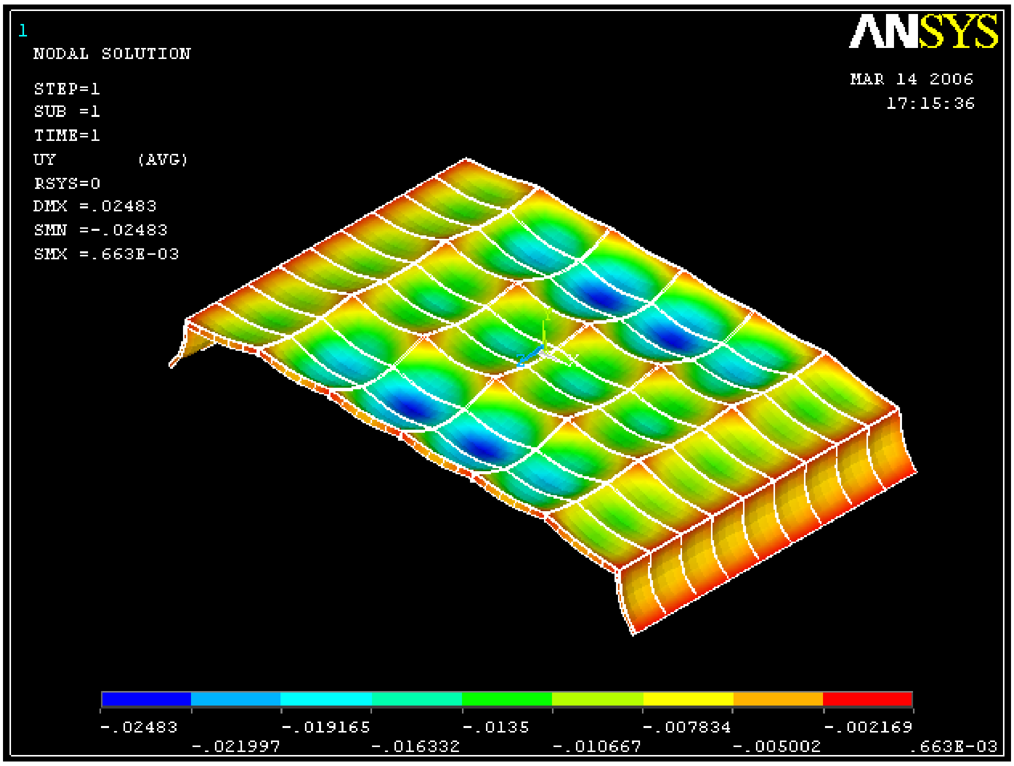


Figure 8-19 Deflections in the structure

8.6.5 Natural Frequency

The requirement on natural frequency is based on the level of frequency which perturbs humans. The natural frequency of the human brain is about 7 Hz, hence preferably the frequency of the structure should be more than at least 9 Hz. The modal analysis of the structure resulted in the first mode as 16.4 Hz, which seems to be in the safe zone. Other modes are given in Figure 8-4.

Table 8-4 The first five natural frequencies of the structure

Mode	Frequency
1	16.4 Hz
2	17.7 Hz
3	18.4 Hz
4	19.3 Hz
5	20.8 Hz

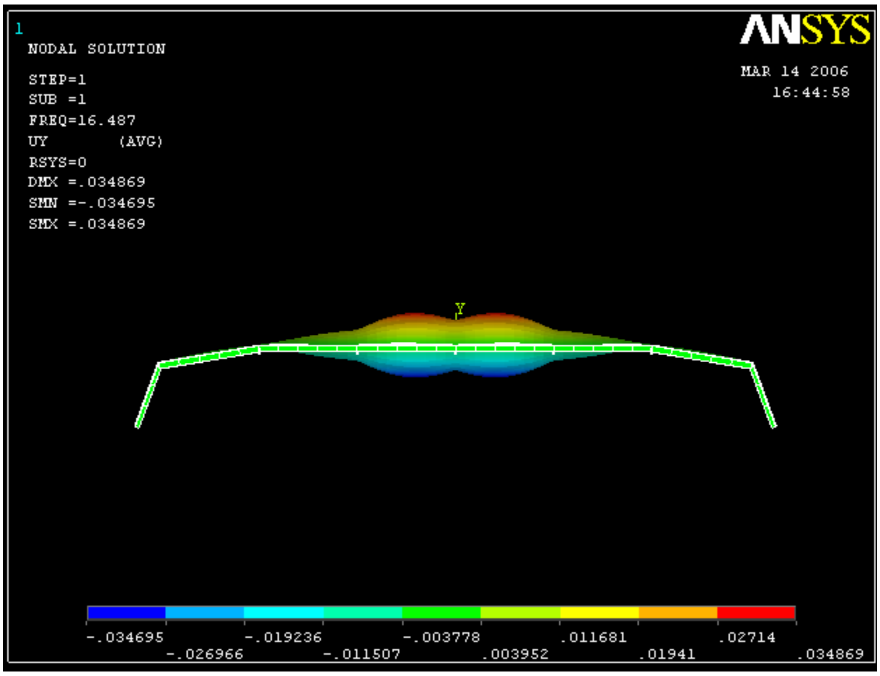


Figure 8-20 The first natural frequency of the composite superstructure

8.6.6 Fire Safety – Requirements and Solutions

The objective of having a composite superstructure would be defied if the issue of fire hazard is not addressed. It has to be ensured that the risk of a fire causing major damage is minimized. The regulations laid down by the High speed code are adhered to in order to obtain appropriate certification from the classification society.

Flowchart in Figure 8-21 shows the systematic approach taken to study the fire requirements of the structure. An initial investigation informed that the requirements for this craft are defined by the –
DNV HSLC rules
2000 HSC code
However it says in the DNV HSLC code (Pt.1. Ch.2. Sec.1.A 205),

"The rules for classification of HSLC comply with HSC code (chapter 18 is excluded) for craft with service restrictions R1 and R2. For craft with more restricted service notations, equivalent requirements are established by this chapter."

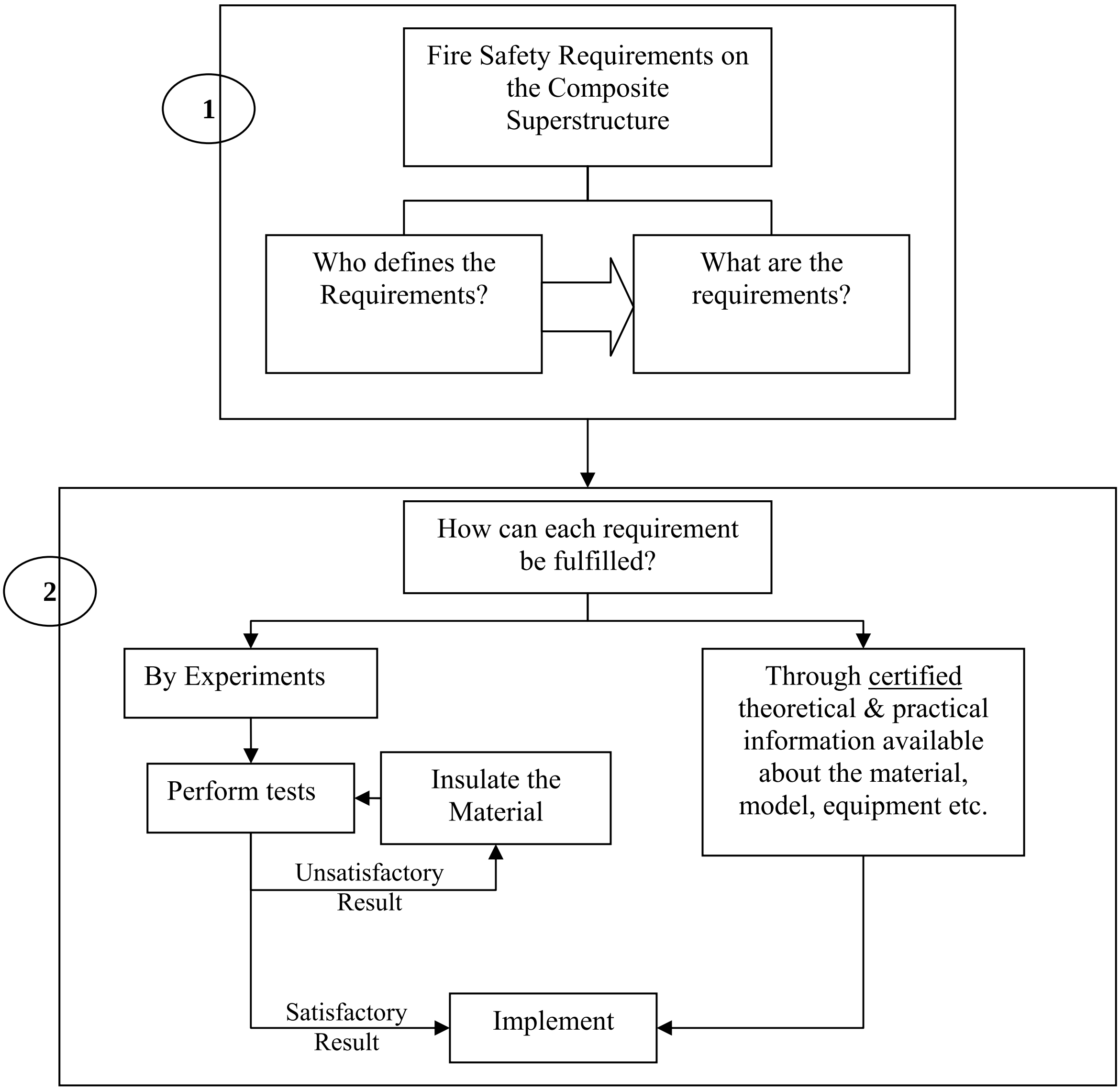


Figure 8-21 Flowchart for understanding the fire requirements of the Superstructure

As Stena Carisma is a R1 classed vessel, hence the HSC code has been referred to at all stages, for the fire safety regulations. Thus the work is to be conducted in the direction where we get approval and certification from IMO for complying with HSC code.

From 1.8, pg 14 of the 2000 HSC code,

1.8.1
"A certificate called High-Speed Craft Safety Certificate is issued after completion of an initial or renewal survey to a craft which complies with the requirements of the code. The certificate shall be issued or endorsed either by the administration or by any person or organization recognized by it. In every case, that Administration assumes full responsibility for the certificate."

As DNV is an organization that is approved by IMO to issue the safety certificate, they can also provide us with similar certification.

8.6.7 Classification of Spaces

The first step to understand that fire safety requirements on the structure is to understand the distribution of the spaces and classify them. With reference to HSC code, 7.3.1, pg 58, major spaces identified on the public deck under the composite superstructure are:

Areas of Major Fire Hazard, requiring A-class divisions:
Galley on the public deck
The store room on the public deck which contains flammable liquids
The sales shop as its area is 200m^2, containing flammable liquids

Areas of moderate fire hazard requiring B-class divisions: None

Areas of Minor Fire hazard requiring C-class divisions:
Public places, which would be a majority of the public deck
The food serving kiosks
The information Kiosks at the back end

Control Station (D-class divisions; not Shown in Figure)

Any evacuation stations & escape routes (E-class divisions; not Shown in Figure)

Open Spaces (F-class divisions) – At the back of the ship and on top of the weather deck.

Figure 8-22 shows the classification of various spaces on the public deck. A majority of the spaces are classed as areas of minor fire hazard. The requirement for such areas is that they should be made of a non-combustible or Fire Restricting Material (FRM).

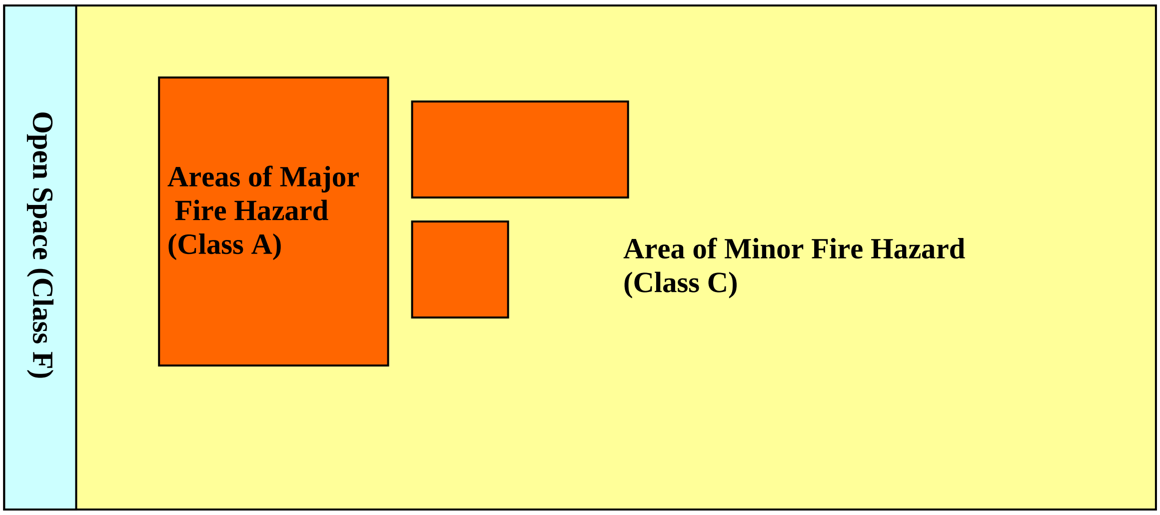


Figure 8-22 Classification of the Space on the Public Deck

For the different spaces defined above, the HSC code defines certain requirements on the structural fire protection times for separating bulkheads, decks etc. Considering that there are five different kinds of spaces on and around the public deck, there would be different kinds of boundaries between these spaces. There are various times that these boundaries must withstand in order to obtain a classification society approval.

8.6.8 Weight Distribution for Concept I

After the preliminary design, a weight estimate of the various components of the structure for the 18 frames for Concept I was done and summarised in Table 8-5.

Table 8-5 Ratio of Laminate and core weight for different structural components

	Component	Laminate Weight (Kg)	Core Weight (Kg)	Total Weight (Kg)
1	Flat Roof panels	3476	777	4253
2	Side Panels	772	276	1048
3	Flat roof Frames	707	145	852
4	Inclined roof Frames	434	88	522
5	Side Frames	169	21	190
6	Girders	897	188	1085

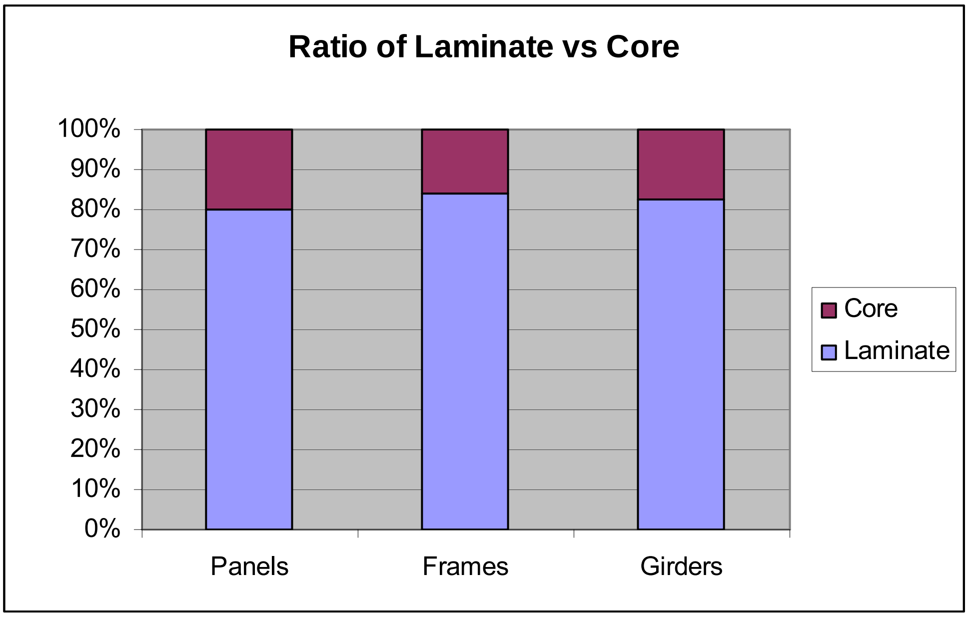


Figure 8-23 Percentage of Laminate and Core weight in the Structure

The weight of the adhesives and bonds is taken to be 16% the weight of the structure as mentioned in[6], which is based on the experience of Kockums shipyard. Total weights are as summarised in Table 8-6.

Table 8-6 Weight summary of the structure

Structural part	Weight (Kg)
Web frames	1564
Girders	1085
Panels	5300
Subtotal	7949
Adhesives and Bonds	1272
Total	9221

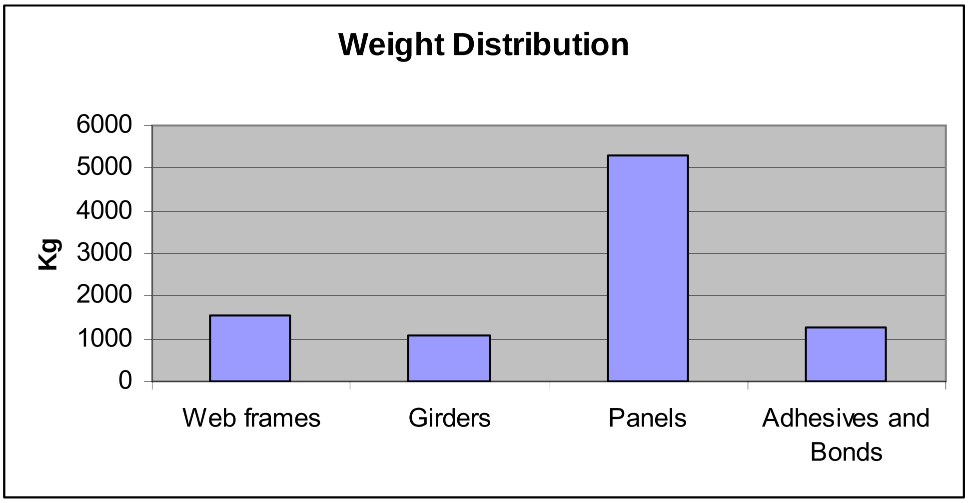


Figure 8-24 Distribution of the weight in the structure

The weight of the aluminium structure is about 10000 kilograms, which implies a saving of about 779 kilos on the glass fibre structure. This is about 7.8% of the total structure.

8.7 Comparisons of Different Concepts – Deflections, Natural Frequency and Weight

The maximum deflections have been checked to ensure that the personnel feel comfortable while walking on the panels and that the basic assumptions of the First order Shear Deformation theory are not violated. The maximum deflections and natural frequencies are as shown in Table 8-7.

Table 8-7 Maximum Deflections and natural Frequencies of the four concepts

	Maximum Deflection	Natural Frequency
Concept 1	24.8 mm	16.4 Hz
Concept 2	33 mm	12.1 Hz
Concept 3	18.5 mm	21.5 Hz
Concept 4	22.9 mm	18.4 Hz

Structural weight of various concepts is presented in Table 8-8. In concept 2 and concept 4, the numbers of pillars are lesser. This reduction of pillars increases the scantlings of the frames and girders causing an increase in the weight of the structure, but this increase is coupled by the removal of the two rows of longitudinal girders and pillars from the public deck, which reduces the total weight of the structure. The weight of one pillar is 18.5 Kg and there are eight pillars in all that are removed, thus total weight of removed pillars is 150 Kgs. In Table 8-8, the reduction of the weight of the pillars is mentioned in row 2.

Table 8-8 Weights of the different concepts

	Original Aluminium Version	**Concept 1**	**Concept 2**	**Concept 3**	**Concept 4**
Structural Weight (Kg)	10000	9222	10809	6440	7639
Reduction (Kg)	-	-	150	-	150
Total Weight (Kg)	10000	9222	10659	6440	7489
Percentage Saving	0 %	7.8 %	- 6.6 %	35.6 %	25.11 %

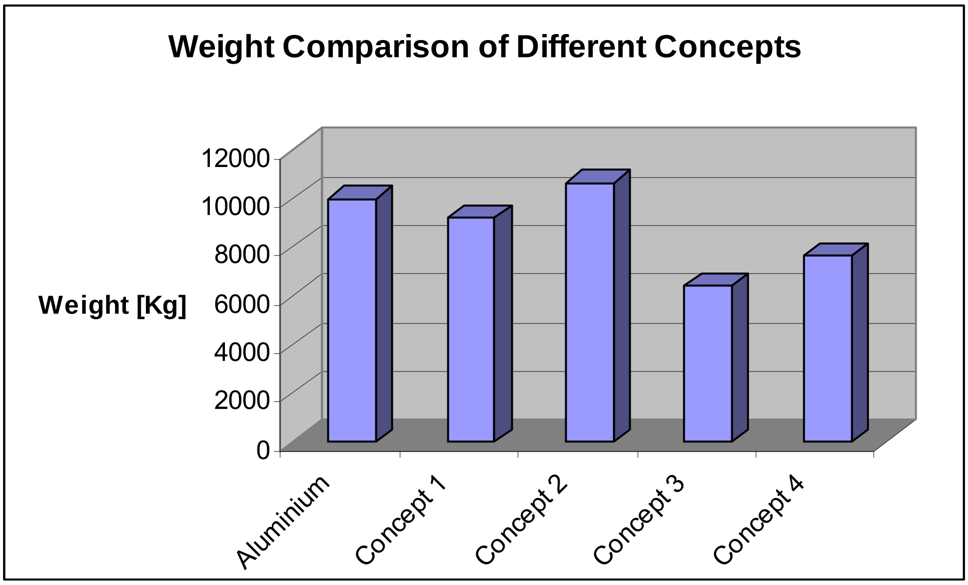


Figure 8-25 Structural Weight Comparison of the Different concepts

However, as mentioned earlier, the structure when made out of composites would be requiring fire insulation and this ad on to the weight of the total structure. The total area of the structure that would have to be covered with' fire restricting material' is 634 m^2 (18 m section). With an insulation thickness of 17mm and density of 96 kg/m^3, the weight of the insulation is 1034 kg, which is almost 10 % weight of Concept 1.

Table 8-9 Weight Comparisons with Insulation

	Original Aluminium Version	Concept 1	Concept 2	Concept 3	Concept 4
Structural Weight (Kg)	10000	9222	10809	6440	7639
Insulation weight (Kg)	-	1034	1034	1034	1034
Total weight (Kg)	10000	10256	11843	7736	8673
Percentage Saving	0 %	- 2.5 %	- 18.4 %	22.6 %	13.2 %

If it were possible to class the composite as ‘fire restricting material’, a 10 % weight saving could be achieved.[xvii]

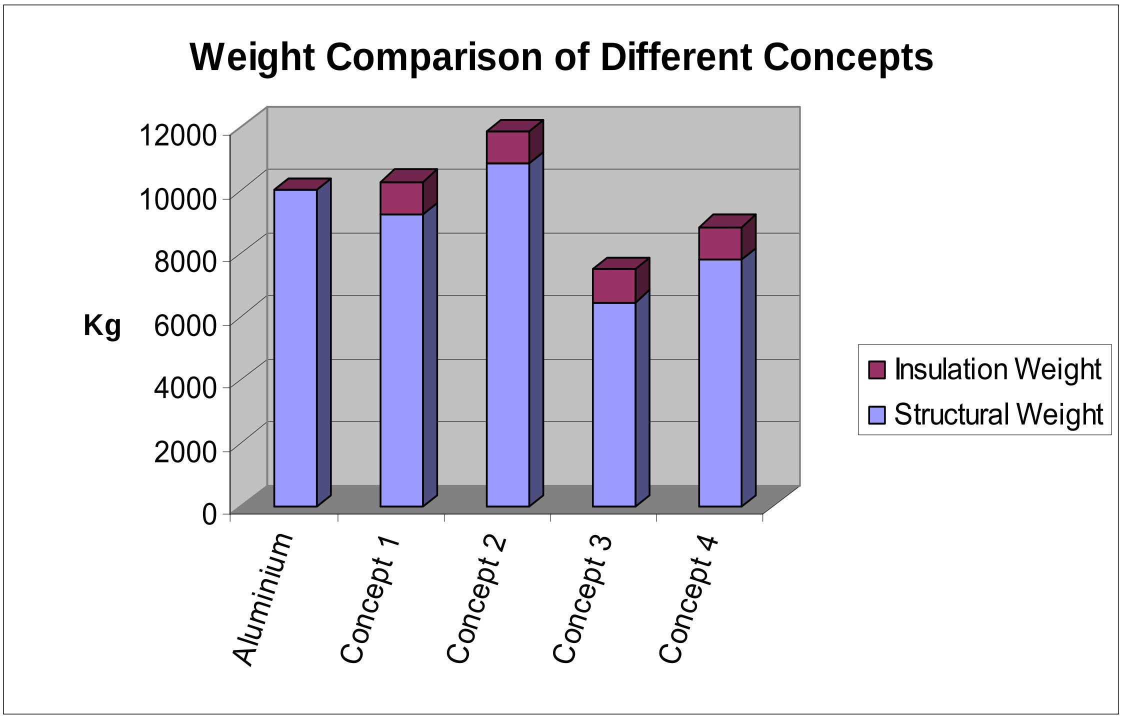


Figure 8-26 Weight Comparisons with Insulation

[xvii] The composite, having very good insulating material in itself, do not require comfort insulation in the same way as the aluminium and it was estimated from STENA that the weight of the fire insulation, 1034 kg mentioned, was approximately the same as the existing comfort insulation, i.e. the amount of insulation would be the same for both construction materials (editor comment).

8.8 Global Strength Analysis using FE Approach

The FEA model study is done to get a better understanding of the behaviour of the composite superstructure. The study is done using finite element software ANSYS MULTIPHYSICS, version 10.0.

It was found from the study of the four different concepts that the three pillar concepts were not beneficial from the viewpoint of weight saving. And the three pillar glass fibre structure also did not help in weight reduction. Hence only the five pillar carbon fibre structure has been considered for the FEA study.

The model of the ship is made from three primary materials – aluminium, carbon fibre/ vinylic ester laminate and a PVC core. For ease of modelling the midship section of the ship is extended to a length of 88 m. The bow and stern are not modelled as shown in Figure 8-27. Instead an aluminium plating of 3 mm is used to cap the two ends of the ship.

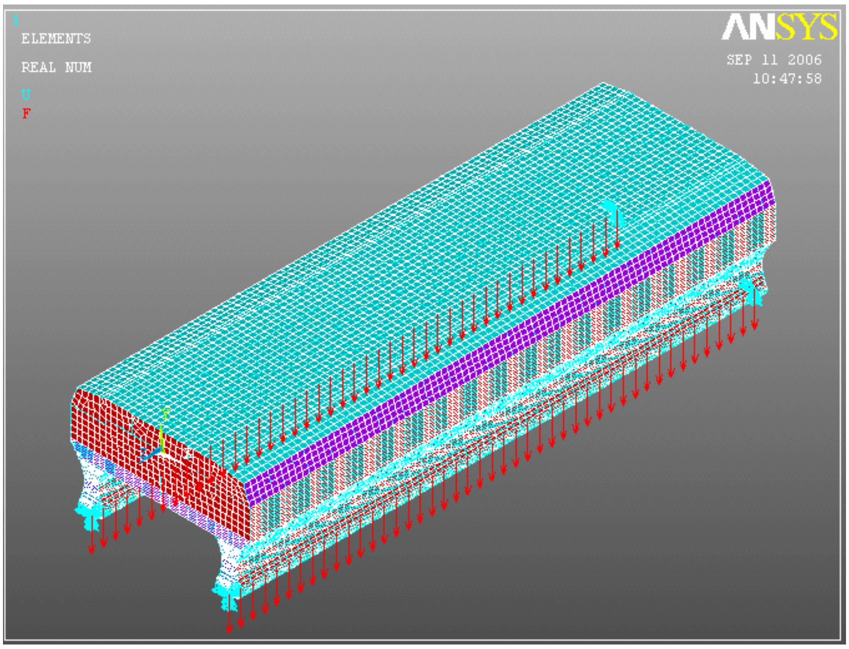


Figure 8-27 Modelling of the Sagging Bending Moment

The various colours in Figure 8-27 indicate aluminium plates of various thicknesses along the length of the ship. Bulkheads in the two hulls of the catamaran are spaced at a uniform distance of 8 m from each other. Floors are modelled at 4m each. Openings such as windows are not included in the analysis.

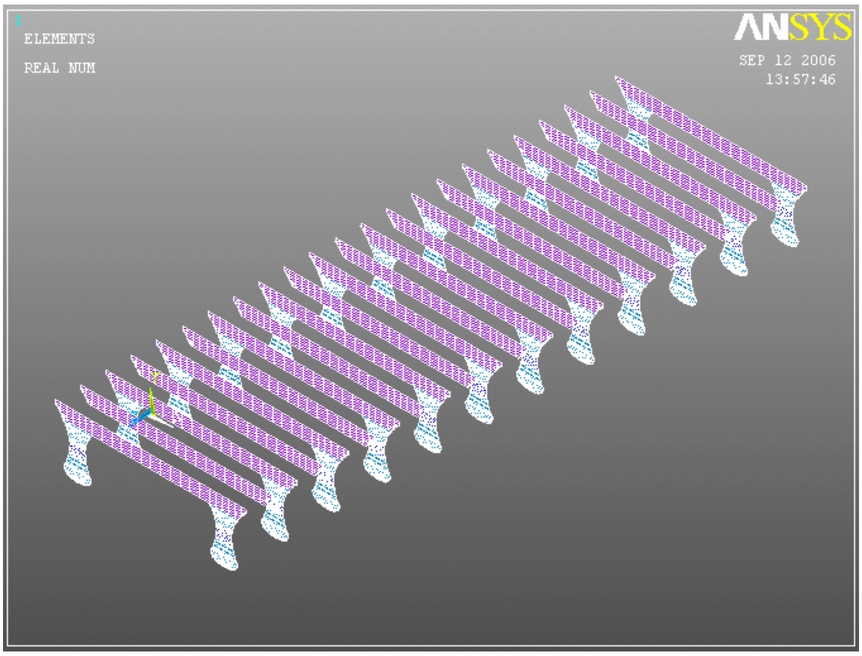


Figure 8-28 Aluminium Bulkheads and Floors in the Hulls of the Catamaran

Primary loading conditions that have been studied to understand the behaviour of the catamaran from the viewpoint of finite element loading are that of sagging bending moment and torsional and pitch connecting moment. For the twin hull, the twin hull load of torsion and pitch is very important to understand and deal with. Also the twisting caused by the torsion would have a direct effect on the superstructure.

8.8.1 Loading Case 1 - Sagging Moment

The sagging moment is generally much greater than the hogging moment for ships of this kind. For Stena Carisma, the sagging moment is almost twice that of the hogging moment. The FE study is based on the sagging moment. The loads are modelled as uniformly distributed loads along the length of the ship, there by creating a simulation of a uniformly loaded beam. Bending moment at the centre of the ship is computed to be almost the same as required by the classification society.

$M_{TotSag} = M_{sw} + 0.14 \cdot C_w \cdot L^2 \cdot B \cdot (C_B + 0.7)$

Where
M_{sw} – Still Water Bending Moment
C_w – Wave Coefficient
L – Length of the Vessel
B – Breadth of the Vesssel
C_B – Block Coefficient of the Vessel

For Sagging $M_{sw} = 0$
$C_w = 0.08 \cdot L = 0.08 \cdot 88 = 7.04$
$L = 88$
$B = 30$
$C_B = \Delta / (1.025 \cdot L \cdot B_{WL} \cdot T) = 0.55$

M_{TotSag} = 286218240 N-m

The maximum value of the shear force along the length of the ship as defined by DNV rules is given by the following formula.

$Q_B = M_B / (0.25 \cdot L)$

The maximum shear force is thus **13009920 N.**

To get a similar value of BM & shear Force along the length of the ship, the loads are applied as shown in Figure 8-27. These loads are applied on the keels of the two hulls of the vessel. Each load is equal to **296000 N**. Loads are applied at every web frame spaced at a distance of 2 m each. The vessel is simply supported at the bottom fore ends of the ship. At the aft end, the bottom two corners of the vessel are restrained from moving in X and Y directions and allowed to move in the longitudinal direction of the vessel.

The maximum deflection obtained from this loading is **199 mm** at the centre of the ship.

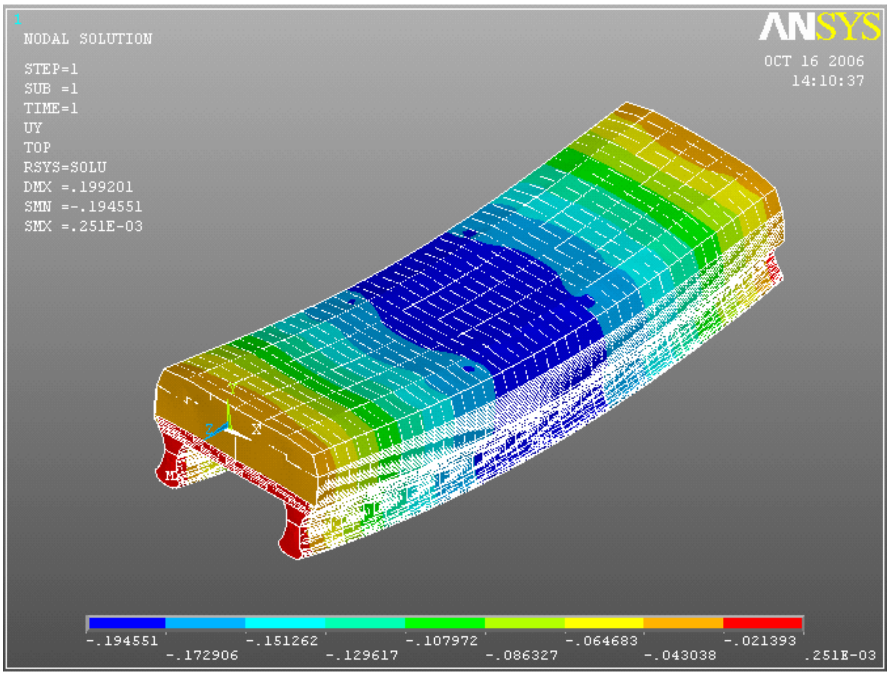


Figure 8-29 Deflection for load Case 1

The shear force distribution is as shown in the following graph. Maximum shear force at the ends is **13010000 N**, which agrees with the shear force distribution recommended by the DNV rules.

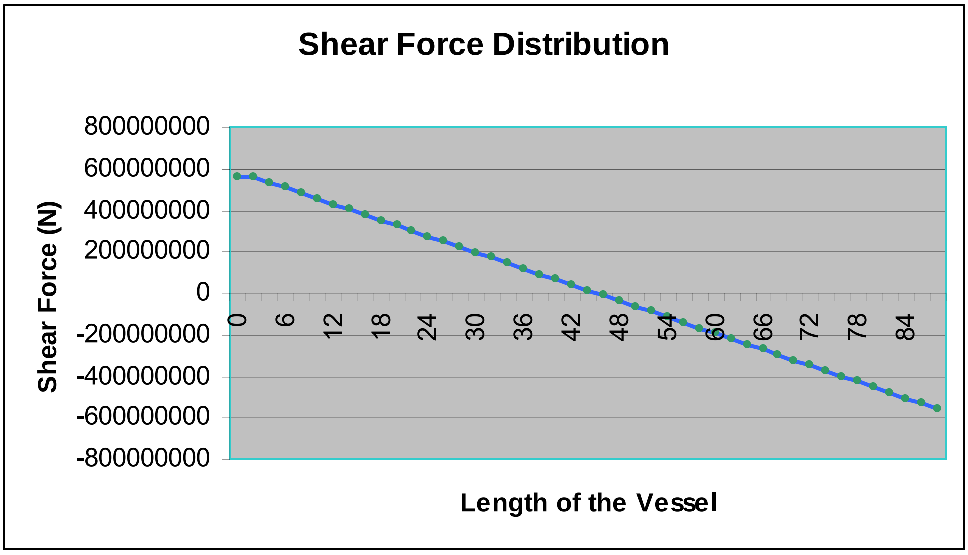


Figure 8-30 Shear Force Distributiong along the vessel

The bending moment distribution is as exhibited in the following graph. A maximum BM of **286218240 N-m** is achieved at the centre of the vessel. As per DNV, the shear force to be attained is **13009920 N.** Hence it is in agreement with DNV regulations.

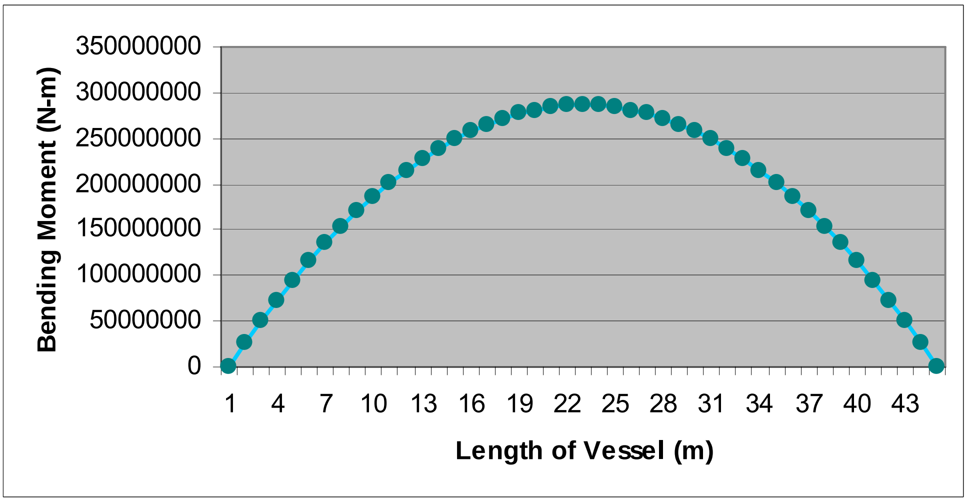


Figure 8-31 Bending Moment along the vessel

8.8.1.1 Stress Distribution in the Crossections

The maximum stress on the catamaran is experienced at the centre bottom of the hull; at **111 MPa** (note yield stress of aluminium used **120 MPa**). The maximum stress on the superstructure is **40 MPa** in the blue region as shown in the figure below.

The neutral axis of the cross section is closer to the bottom of the vessel; however the stress is lower at the top. This is mainly due to the superstructure being made of carbon fibre sandwich construction. As can be seen in the figure on the right, the stresses are higher on the side of the superstructure than on the top. This is so because; the top is made from a thinner core than the side. This causes a lesser modulus of elasticity of the side walls than the top as the contribution from the core is more significant. The modulus of elasticity of the core is less than that of the carbon fibre laminate.

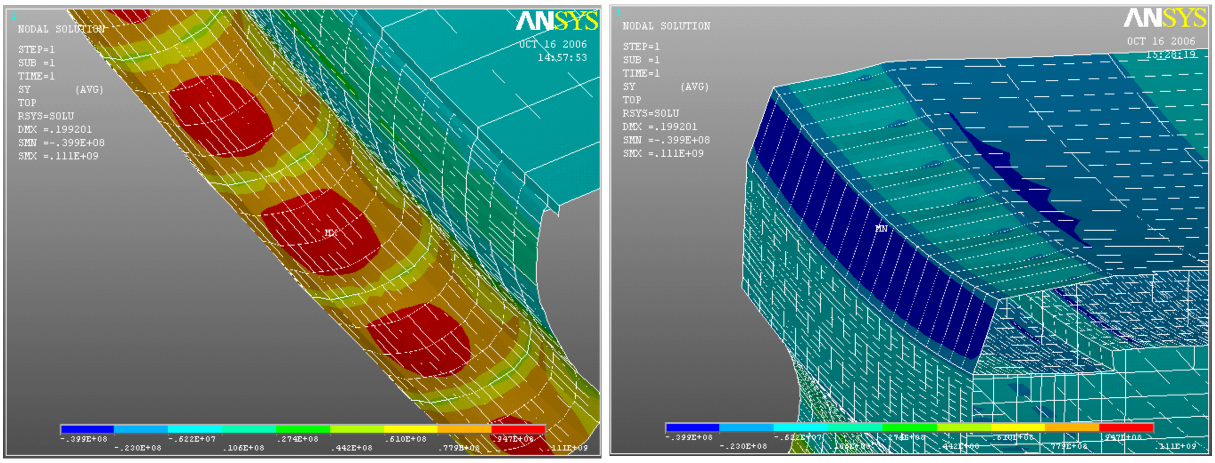


Figure 8-32 Maximum stresses in the Hull and the Superstructure

8.8.1.2 Aluminium hull without the Superstructure

In the present aluminium ship, the superstructure is split into parts and does not contribute to the global strength of the vessel. If the superstructure is made to contribute to the global strength then it could lead to lower stresses along the hull. To get an estimate of the stresses without the superstructure contributing to the global strength an FE analysis has been conducted of the hull structure without the sandwich superstructure. This analysis would give a better idea if the superstructure would contribute to reducing stresses or not.

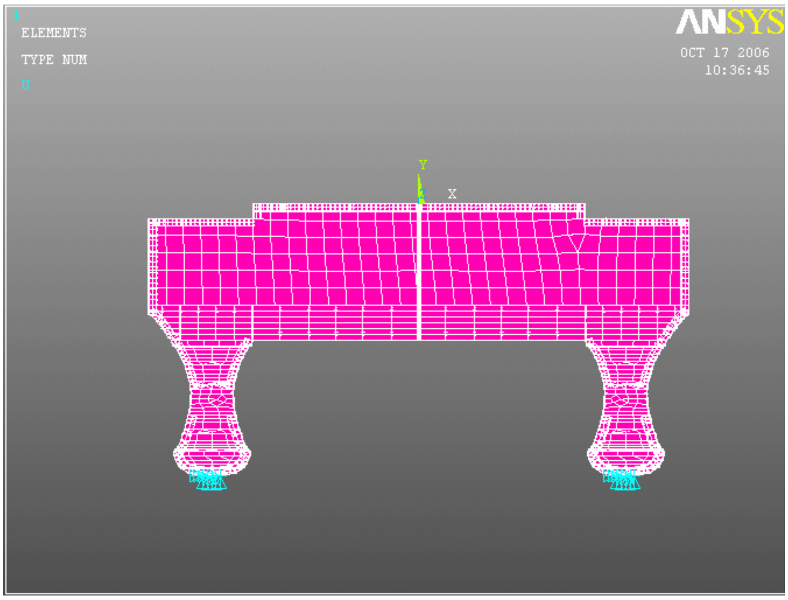


Figure 8-33 Model for FE Analysis of the hull without the superstructure

The maximum stress on the hull without the superstructure contributing to global strength is **120 MPa,** which is almost equal to the yield stress of the aluminium used. Thus if the superstructure is made to strengthen the hull, then the maximum stress reduces by almost **9 MPa.**

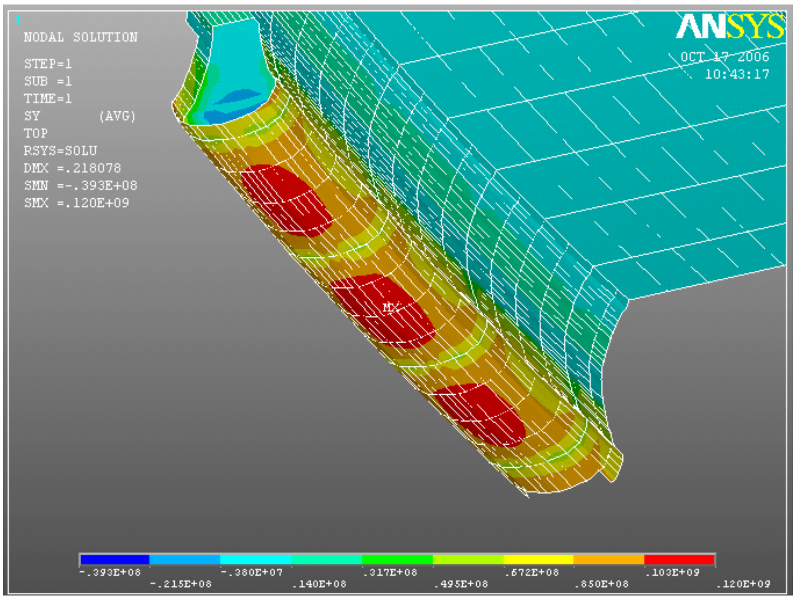


Figure 8-34 Maximum stress in the hull without the superstructure

8.8.2 Loading case 2 - Torsional moment / Pitch Connecting Moment

To induce a torsional and pitch connecting moment in the hull of the catamaran, loads are applied in opposite directions in each half of the hull of the vessel, as shown in Figure 8-31.The load upward and the downward loads acting on the frontal half of the vessel induce a moment about the longitudinal centre line of the vessel. A similar load at the aft end of the vessel induces a moment in the opposite direction at the aft end. These two moments together produce a twisting of the whole vessel. The combination of these loads also produces a pitch connecting moment along the transversal centre line of the ship.

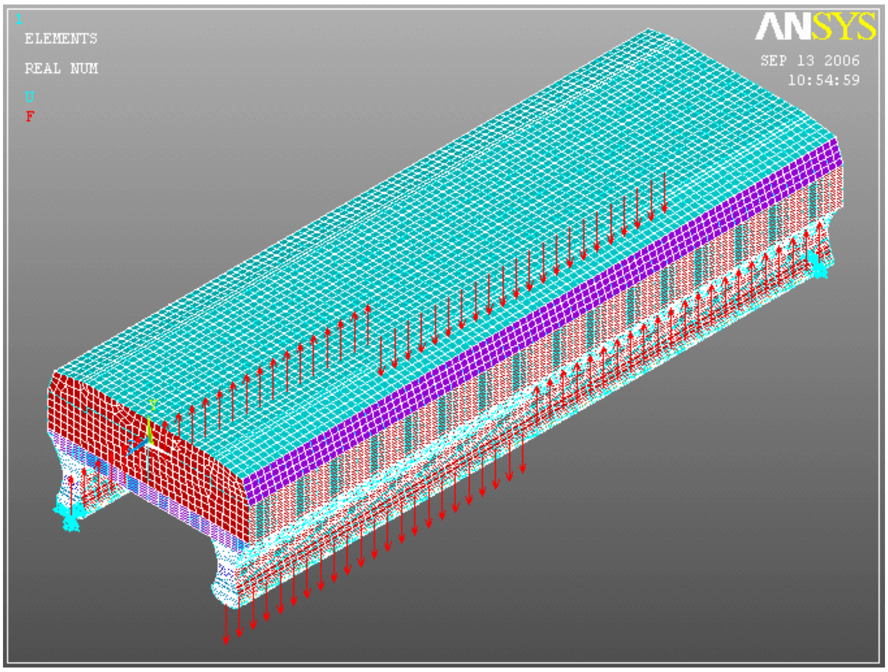


Figure 8-35 Deflections due to Torsional and Pitch Connecting Moment

As per the DNV regulations, the pitch and torsional moments are computed using the following formulas.

$Mt = \Delta \cdot a_{cg} \cdot b / 4$

Where
a_{cg} – Design Vertical Acceleration
b – Distance between centre lines of the two hulls

$Mt = 1600 \cdot 4.23 \cdot 25.5 / 4 =$ **43146000 N-m**

$Mp = \Delta \cdot a_{cg} \cdot L / 8$

$Mp = 1600 \cdot 4.23 \cdot 88 / 8 =$ **74448000 N-m**

To induce a moment equivalent to these values in the structure, a load of **49000 N** has been applied at each web frame along the keel of the vessel, either in upward or downward direction as shown in Figure 8-31. These loads cause a twist along the longitudinal centre line of the ship. The twist is best shown in the following figure.

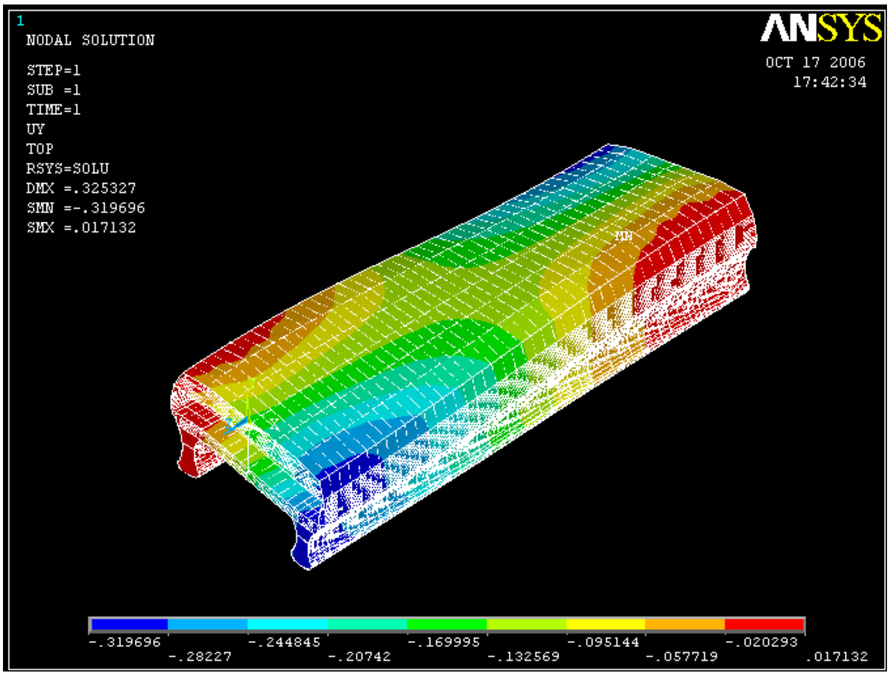


Figure 8-36 Deflections due to Torsional and Pitch Connecting Moment-

The maximum deformation in the structure because of the twisting moments is **325 mm.** The deformations are the same at the fore and the aft of the vessel. Symmetry in deformations can be seen by inspecting the colour distribution in Figure 8-36.

The maximum stress in the ship because of this loading case is **108 MPa** at the lower side of the aluminium hull.

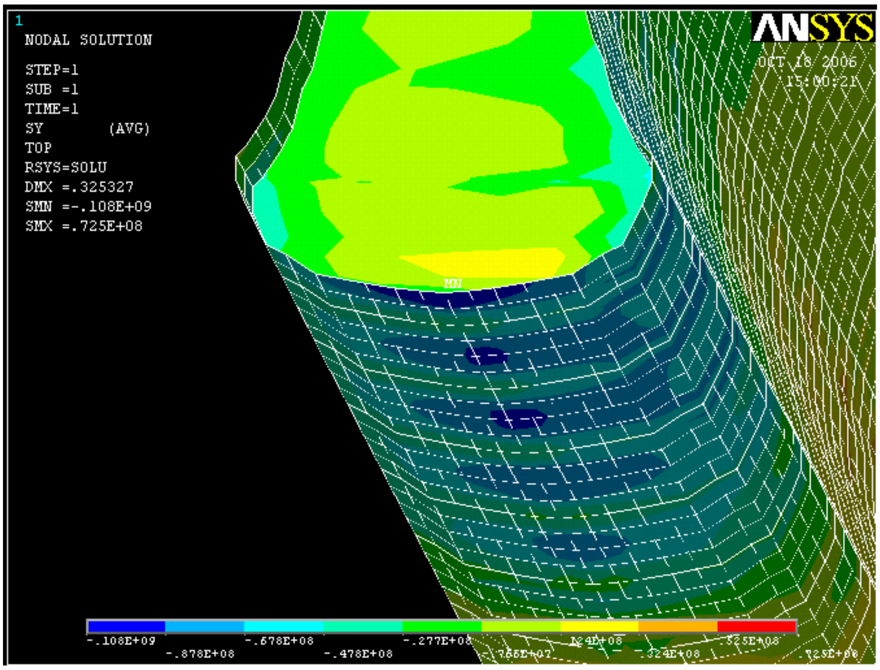


Figure 8-37 Maximum Stress due to Torsion

The stresses in the super structure are within acceptable limits ranging from **31 Mpa** in compression to **33 MPa** in tension.

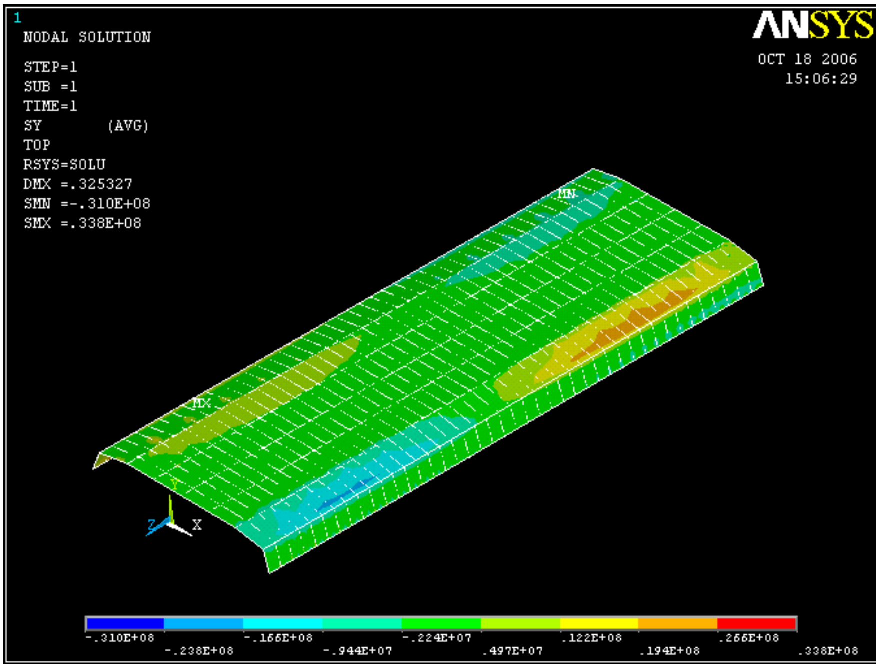


Figure 8-38 Stresses in the Superstructure

8.8.3 Torsional Analysis without the Superstructure

Similar to the study conducted for the 1st load case, this scenario has also been studied for understanding the behaviour of the hull without the superstructure. Same load values are applied at the same points to see the torsional response of the hull. The maximum deformation in this case increases to **365 mm**, about 11% more than that of the ship with the superstructure.

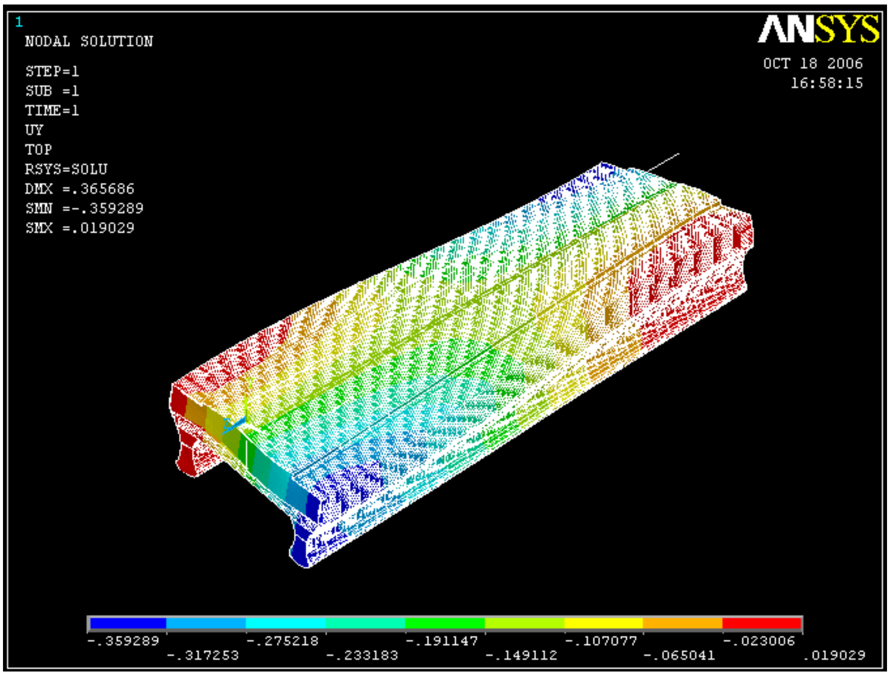


Figure 8-39 Deflections, without the Superstructure

The maximum stress in the superstructure is **117 MPa,** about **9 MPa** more than that of the ship with the superstructure.

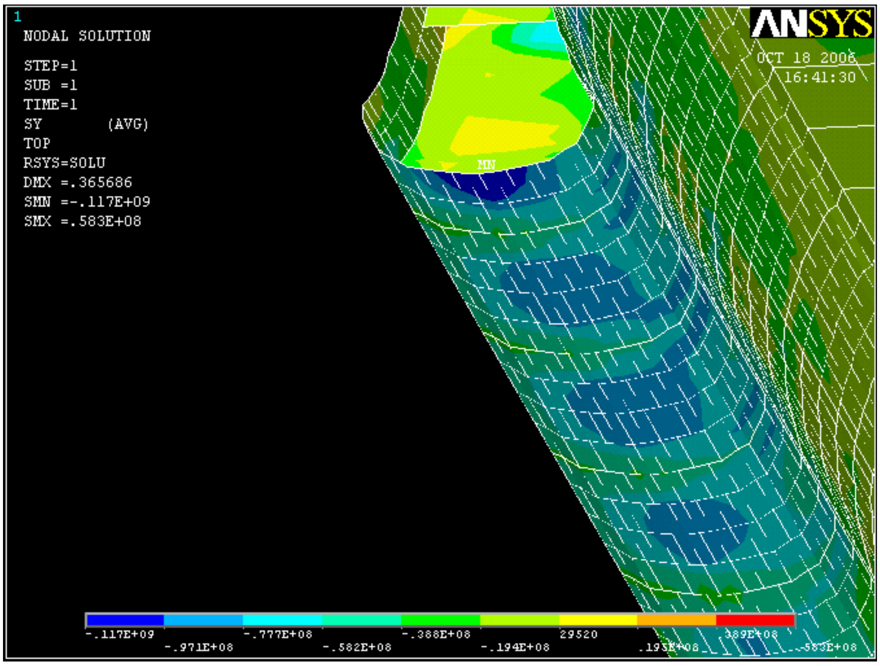


Figure 8-40 Stresses, without the Superstructure

8.9 Conclusions of the FE study

The results obtained from the FE study have been tabulated in the following table. All deflections and stresses are with in acceptable values.

Table 8-10 Maximum Stresses and Deflections in the Vessel

Load Case	Deflection	Stresses
Sagging Bending Moment with Carbon Fibre Super Structure	199 mm	111 MPa
Sagging Bending Moment without Super Structure	216 mm	120 MPa
Torsion / Pitch Moment with Carbon Fibre Super Structure	325 mm	108 MPa
Torsion / Pitch Moment without Super Structure	365 mm	117 MPa

As a conclusion of the FE study, it seems safe to build a superstructure of carbon fibre sandwich construction. This study makes some approximations by not modelling the bow and the stern of the vessel as they are. In the sagging analysis, the load distribution is also an estimate of the realistic situation, where the proper hydrodynamic loads should be modelled. The stresses are at acceptable levels through out the hull and so are the deflections.

To build the superstructure as a part of the whole vessel is advantageous from the viewpoint of stress reduction. The superstructure contributes to the global strength of the hull if modelled out of a single mould and attached to the vessel as its integral part. A safety margin, albeit a small one is obtained by including the strength of the superstructure in the global strength.

8.10 Results and Discussions

The feasibility of having a composite super structure has been studied. During the process of design, a number of issues were addressed like structural optimisation, Finite Element Analysis, Fire Safety etc. DNV lays provides regulations for composite vessels in their High Speed Light craft code (HSLC). In this study therefore, these regulations are used as guidelines for design and structural calculations.

As the main idea behind the project was to reduce the light weight of the structure, a procedure of fulfilling the various requirements of the class and at the same time keep the weight to a minimum has been developed. Optimisation using the simplex algorithm was used to find the most optimum point for controlling the weight. The variables that directly affect the weight are:

- Face thickness
- Core thickness
- Frame spacing

The face and core thicknesses were optimised using a simplex algorithm, using as constraints the regulations provided by DNV. For every frame spacing the weight of the panel was optimised. A range of frame spacings were tried from 0.1 to 4 m. It was found that between 1 and 2 m the weight was approximately the same. Hence a frame spacing of 2 m has been used for the design.

It was found that the global loads do not adversely affect the superstructure and that the superstructure can make a significant contribution to the global strength if made an integral part of the whole ship..

Using glass fibre based FRP's was shown to be less weight-efficient than carbon fibre FRP's. Thus for this study, carbon fibre is the recommended material to use. Glass fibre based composites was found to provide 6% weight reduction of the superstructure compared to the original aluminium design where as using carbon fibre, a weight saving of 35 % was found possible.

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9 Case study WP3c; a RoRo vessel with an aluminium deck house

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SSPA

Here is presented a summary of SSPA report 40043670-1: “Increased shipping efficiency, Consequences from change of material, steel to aluminium, in the superstructure of a 200m car carrier vessel”.

9.1 Introduction

SSPA, Wallenius Marine, SAPA and Light Craft Design Group are all part of the LASS sub project WP3c where the consequences and benefits of replacing steel with aluminium is investigated. Wallenius Line’s PCTC ship *M/S Undine*, designed for transporting cars and trucks, will act as concept ship for WP3c. *M/S Undine* is a Panamax vessel with an original length of 199 meters, a deadweight of 22 616 tons and a capacity for 5 890 cars.

The area where the change of material is considered is isolated to the ship’s deckhouse. Different versions of the deckhouse onboard the concept ship are compared with regards to stability, performances of the ship and economical aspects. To provide a common base for these comparisons the displacement and vertical centre of gravity of the ship in loaded condition should remain the same.

To examine the benefits associated with a lighter construction a section of the existing deckhouse in steel was defined to be compared with different versions of the corresponding section manufactured in aluminium. The section is positioned approximately mid ships, representing the general geometry of the deckhouse (garage and accommodation) above the Upper deck. See figure below for a schematic view of the garage and accommodation part of the deckhouse.

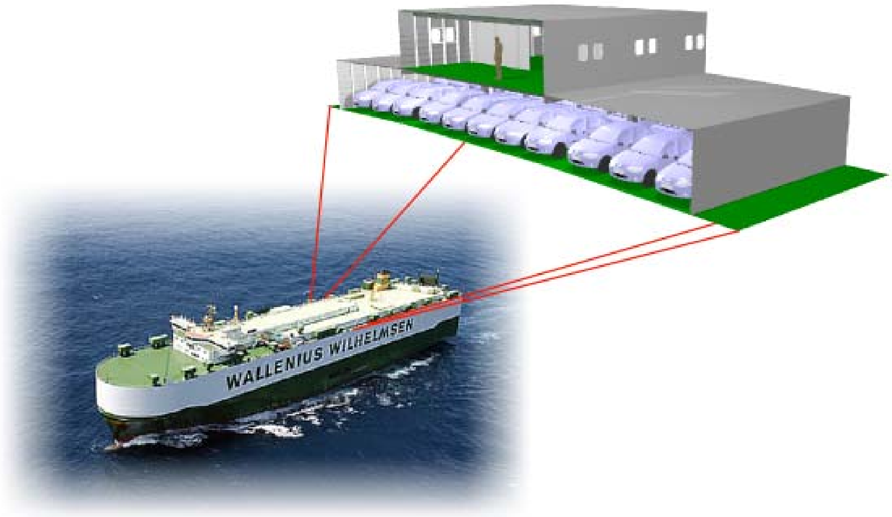

Figure 9-1 Schematic view of the garage and accommodation part of the deckhouse

The deckhouse is proposed to be a straight forward aluminium design, similar to the ones common onboard High Speed Light Craft vessels. The aluminium design will, as the concept ship, be designed according to Lloyd's rules and regulations for classification of ships.

During the project several versions of the concept section were studied:

Steel –1	Original version, shows the ship in its present state.
Steel –2	Shows a more refined steel version according to class rules. Same rules are used as for the aluminium structure.
Alu –1	Represents the first version of the aluminium structure.
Alu –2	Refined version of the aluminium structure.
Alu –3	Refined version with hollow profiles and fewer beams.

Benefits from a lighter deckhouse can be measured in less ballast, less fuel consumption, higher speed, less pollution or lowered vertical centre of gravity.
However the philosophy in WP3c regarding the structural weight saving of the concept ship can be summarized as follows:

- Saved weight will correspond to the weight of increased load (increased number of vehicles).
- The vertical centre of gravity for the modified deckhouse and added cargo shall, if possible, not be moved upwards for the modified version.

This will give no, or very slight, changes in ship stability, weight of ballast and fuel consumption.

9.2 Requirements

The design Alu –1 is aimed to be used as guidance and reference object to coming, more optimised structures. The following limitations have been used during the work:

- The design shall follow the class rule book.
- The proposed structure shall be built out of aluminium.
- Only the structure and insulation is considered regarding weight and cost calculations.
- Saved structural weight will correspond to added load from increased number of vehicles.
- The vertical centre of gravity for the modified deckhouse and added cargo shall, if possible, not be moved upwards for the modified version.
- The deckhouse is not considered to contribute to the global hull beam.
- In the Garage two lines of pillars are considered.
- Natural frequencies of plates or panels shall not be less than 10 Hz.

While designing Alu –2 and Alu –3 the same requirements are used with exception for the first, regarding rules. The structure for Alu –2 and Alu –3 is designed using FEA and the guidelines from Lloyd's dealing with direct calculations.

The structure is designed with consideration to the following major fields:

- Stress levels
- Structural deflection
- The structure’s natural frequencies
- Buckling
- Structural (and fire insulation) weight
- Economical aspects

9.3 Concept Section

The concept section of the deckhouse is positioned approximately amidships and consists of a section from the levels of the deckhouse. The Garage section is positioned on the Upper Deck and the Accommodation section is positioned on the deck above named Garage Deck. In the study the two sections were assumed to be situated right on top of each other, see figure below for a schematic view of the represented region. This isolated section of the ships deckhouse was analysed and is considered to represent the whole deckhouse.

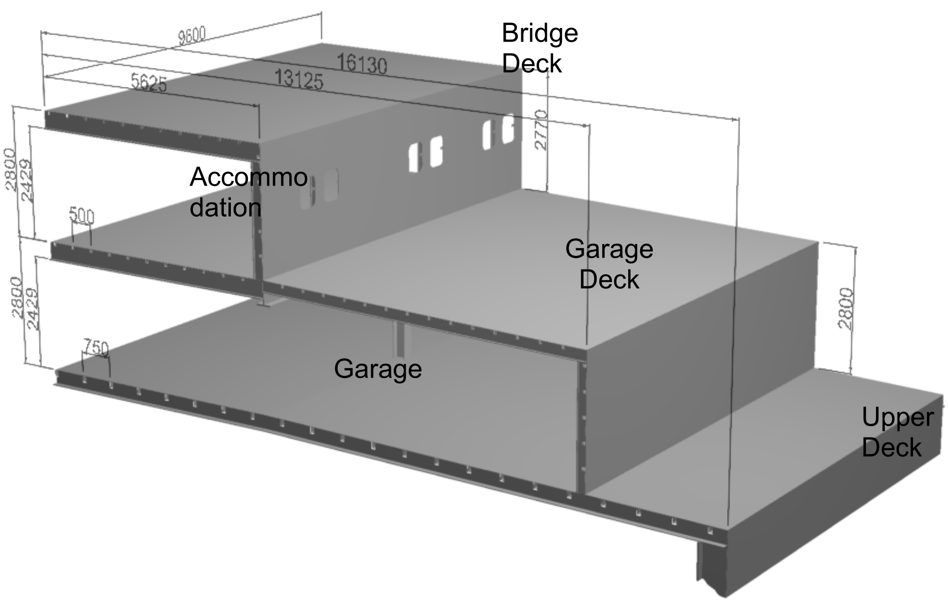

Figure 9-2 View of the concept section with overall dimensions in mm.

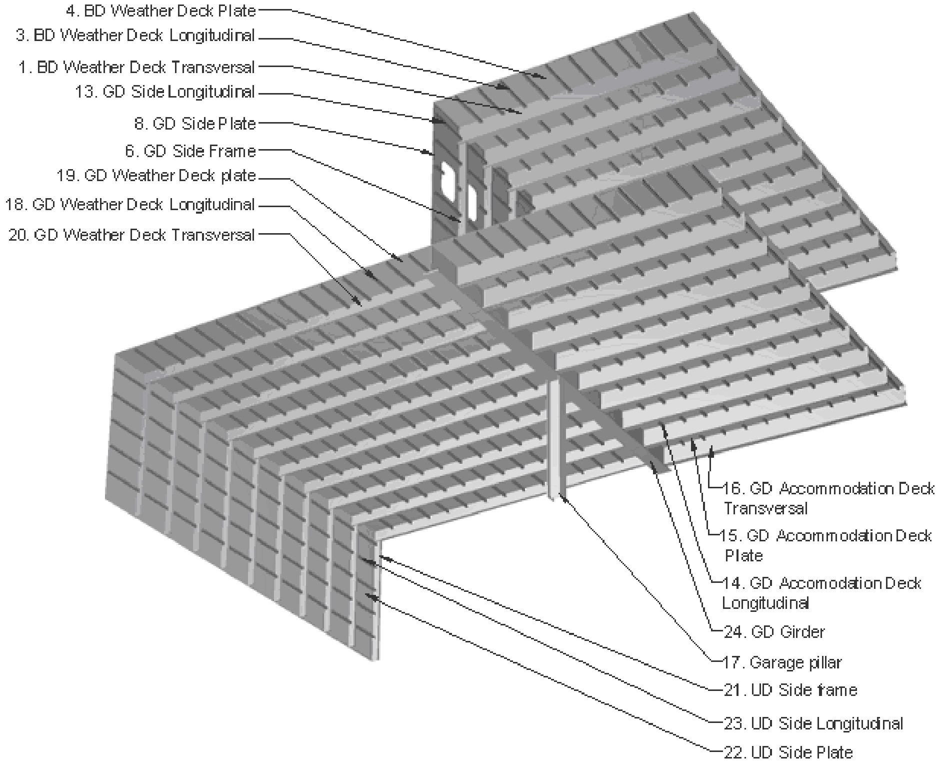

Figure 9-3 The different components of the concept section in aluminium

Information and results derived through the study of the section will be used to verify the design and also to estimate weight reduction for the whole deckhouse when built in aluminium. It was assumed that all areas that exist in the original deckhouse will also be found in the alternative layout. The Upper Deck will remain virtually unchanged and still be a steel design.

9.3.1 Specifications for the Concept Section

Length of section	9.6 m
Beam of section	26.25 m
Height of section	5.74 m
Weight of steel structure	40.31 ton (Steel -1. As built)
Free height for vehicles	2200 mm, criteria for deflection of beams

9.4 Extended Garage

To visualise the benefits of a lighter deckhouse, an alternative general arrangement was made for the *Upper Deck* and *Garage Deck*. This arrangement assumes that the deck area for accommodation onboard the new version should remain the same as onboard the original ship. The garage is proposed to be extended 58.4m forward in line with existing Upper deck arrangement, which give an additional area of 1533m^2. The Upper Deck accommodation area, which is originally positioned in front of the Garage, will be moved up to the Garage deck. The concept section geometry will remain. This brings with it that the Garage Deck accommodation area need to be extended 63 meters aft.

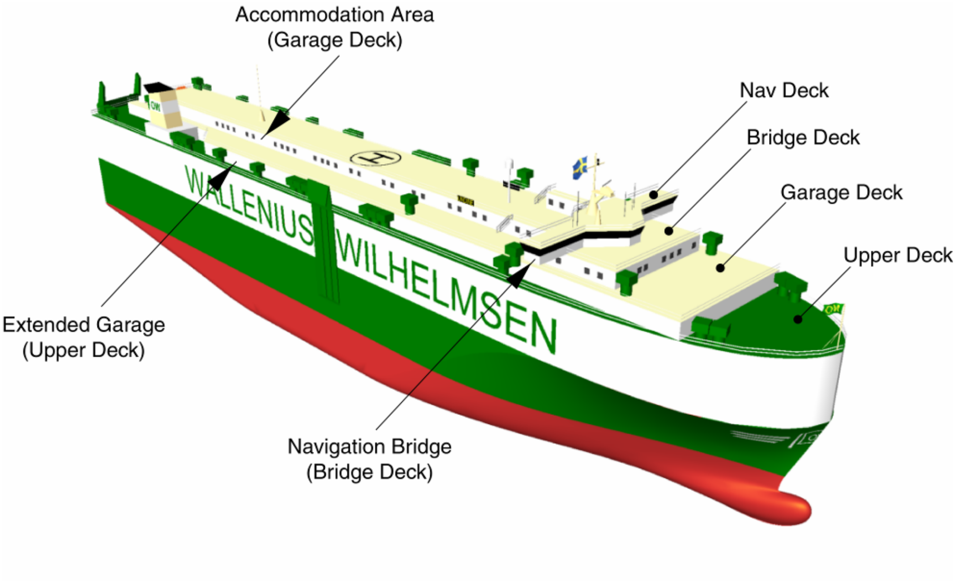

Figure 9-4 M/S Undine with extended garage

9.5 Lloyd's Rules and Regulations

M/S Undine is classed according to Lloyd's rules and regulations for classification of general cargo ships and thus any new version must also be approved by Lloyd's. In short the design of the deckhouse can be done in one of two ways to receive approval from classification societies.

1. *Rule Book*. Hand calculations following the general semi-empirical rules specified by the classification rule book. This approach would probably result in a lower initial design cost but higher weight of the vessel. Scantlings derived in this manner should also be verified by using ordinary solid mechanics formulae.

2. *Agreed Loading/Direct Calculation*. If the loads prescribed by the rules are not directly applicable to the current design there is a possibility to decide on an alternative load, i.e. *Agreed Loading,* together with Lloyd's and in this way derive more appropriate loads. These *Agreed Loading* must naturally be set individually for each different construction. An *Agreed Loading* is generally used in a design based on the first principals of strength of the material together with direct calculations and FEA. This approach enables optimisation of virtually all parts of the structure with regards to weight and strength. This more optimised structure would still be able to fulfil the class rules as long as the calculations follow procedures defined by the classification societies. The method allows the designer to make use of the materials full potential but extensive calculations are required to ensure the reliability of the structure. Designs that include futuristic features or deal with areas that might be outside the scoop of the empirical rules should be designed using this concept.

During the construction of the concept section, there was constantly a dialog with Lloyd's Register in London to discuss the application of class rules. One of the main consequences of the discussions with Lloyd's was that for a ship such as *M/S Undine* it is possible to use the rules applying to passenger ships without service restrictions, to decide deck loads and scantlings for parts of the deckhouse. This was deemed possible mainly due to the large difference in height between the water line and the deck in question and also the fact that the weather decks are not to carry any cargo.

For direct calculations the global loads from hogging and sagging were found to be rather low and the design driving parameters were the stresses and deflections from local loads and also the natural frequency analysis.

9.6 Materials

When combining different materials onboard a ship, several aspects should be considered. In this case where aluminium is to replace steel special attention must be paid to the problems of stability, deflection and vibration. This is mainly due to the fact that the E-modulus of aluminium is one third of the E-modulus of steel. Experience shows that the governing design factor is deflection rather than the usual tensile stress. Also, differences in yield stress, linear expansion due to temperature, structural collapse temperature and various forms of corrosion are important.

The steel used to build the concept ship *M/S Undine* was mainly mild steel of grade A. This is a common quality in the ship building industry. General material properties for mild steel of grade A are listed below.

Density:	$\rho_{\text{steel}} = 7850$ kg/m^3
Modulus of elasticity:	$E_{\text{steel}} = 210\,000$ N/mm^2
Yield strength $R_{p0,2:}$	$R_{p0,2\ \text{steel}} = 235$ N/mm^2
Tensile stress R_m:	$R_{m\ \text{steel}} = 360$ N/mm^2

The aluminium alloy to be used for the deckhouse is EN-AW-6082 T6. The advantages compare to other alloys are high yield strength and the ability to produce thin walled extruded profiles. Disadvantages are higher cost than eg EN-AW-6005 and corrosion resistance which is slightly less than e.g. alloys from the 5XXX series.

Material properties for EN-AW-6082 T6:

Density:	$\rho_{\text{alu}} = 2700$ kg/m^3
Modulus of elasticity:	$E_{\text{alu}} = 70\,000$ N/mm^2
Yield strength $Rp_{0,2:}$	$R_{p0,2\ \text{alu}} = 240 - 260$ N/mm^2
Tensile stress R_m:	$R_{m\ \text{alu}} = 270 - 310$ N/mm^2

9.7 Joining Methods for Metals

The different industrial methods and techniques to join metals are numerous and the methods can be divided into four major categories according to below.

- Welding
- Brazing
- Mechanical fastening
- Adhesive bonding

Since WP3c will be devoted to study the deckhouse section of the concept ship, basically without introducing novel manufacturing techniques only the welding methods were considered.
For the structure versions Alu –1, Alu –2 and Alu –3 bimetallic explosive welded joints will be used to join aluminium with steel. This technique is common in ship building industry and also approved by classification societies.

The proposal in this project for joining aluminium to aluminium is to use a combination of Friction Stir Welding (FSW) and MIG welding. Large plate panels are pre-manufactured using Friction Stir Welding and assembled onboard using MIG. FSW is achieved by letting a cylindrical shouldered tool with a pin rotate and slowly be forced into the joining area between the two pieces that are to be joined. FSW contribute to a relatively small heat affected zone, smaller distortion and better material properties and is cost effective.

9.8 Scantlings – definitions and assumptions

There are a number of different ways of building an aluminium deckhouse. In WP3c three different aluminium deckhouse versions, Alu –1, Alu –2 and Alu –3, are investigated.
In order to limit the design work the following statements were assumed:

Alu –1

- The structure is designed using aluminium without combination of other materials as e.g. polymer composites.
- The structure is built with a framework carrying a weather tight shell.
- The scantlings follow class rules hand calculations.

Alu –2

- The structure is designed using aluminium without combination of other materials as e.g. polymer composites.
- The structure is built with a framework carrying a weather tight shell.
- The design is performed by direct calculations and optimisation using FE-software. The calculations follow the class rules.

Alu –3

- The structure is designed using aluminium without combination of other materials as e.g. polymer composites.
- The secondary structure is eliminated as far as possible, instead hollow profiles are used as transverse beams and they also provide the necessary structural stiffness.
- The design is performed by direct calculations and optimisation using FE-software. The calculations follow the class rules.

This report do concentrate on result from the version Alu –2, as the version pointed out the most interesting results according to strength-weight ratio.

9.9 Bimetallic Joint, Deckhouse to Upper Deck

To join the steel deck and aluminium side of deckhouse, bimetallic strips will be used. The strips and plates will be welded onto the steel deck to fit the geometry of side plates and side frames, see figure below.

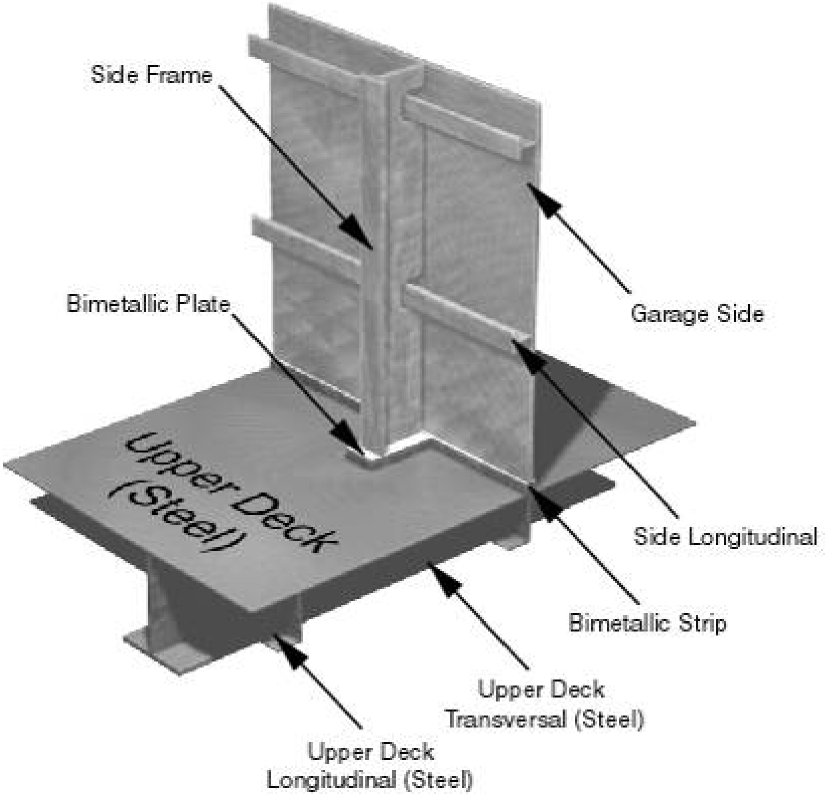

Figure 9-5 General view of fitting of sides to Upper deck

The sections of the deckhouse are then fitted to the bimetallic strips and plates. The side plate and frames will be MIG welded to the bimetallic strips and plates.

Longitudinals and shell plates are extruded as one piece and then Friction Stir Welded into panels. The transversal framework is built out of extruded T-bars and is joined to the panels by MIG welding. The FSW joining technique result in a plate joint with almost no HAZ, therefore plates will be considered as heat affected only in the area of the joint to the frames and at the transversal joint between panels. At the longitudinal panel joints the cross section area of the plate profile will be slightly increased to compensate for the loss of strength in the material by MIG welding. Plate and longitudinals will partly be considered as unwelded material, frames will be considered as welded material. Also see figures below.

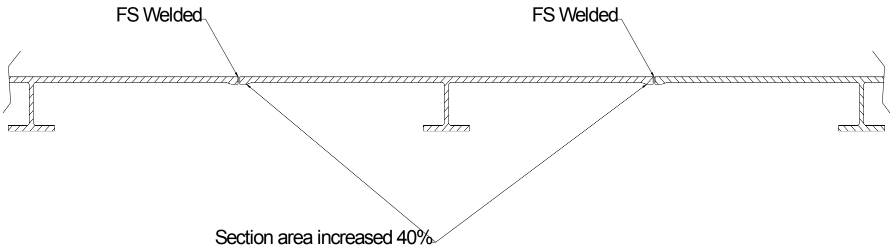

Figure 9-6 View of profile and weld line locations

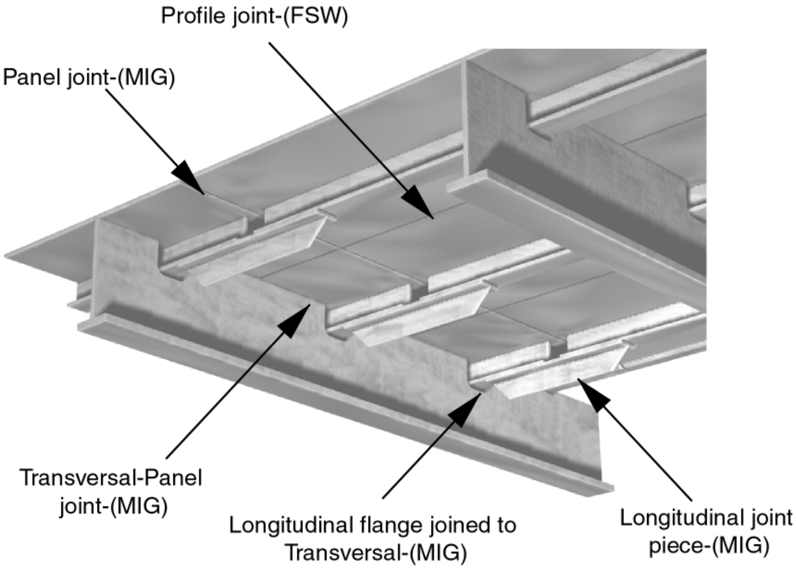

Figure 9-7 View of panel and weld line locations

Primary structure, deck beams and side frames, are proposed to be built in a transversal/vertical direction. Secondary structure, plate and stiffeners, are built in longitudinal direction. The structure results in a large transversal section area. The steel structure below Upper Deck matches the position of deckhouse side frames. The deck load and weight of structure will be transformed from the transverse deck beams to side frames and forwarded down to the hull's steel structure. A longitudinal alignment of the extruded profiles also reduces the number of transversal welds in deck and sides.

9.10 Insulation of the Concept Section

The structure onboard M/S Undine should, when fitted with additional fire insulation, fulfil the SOLAS fire safety requirements using SOLAS method I C. The SOLAS code allows the use of aluminium in fire divisions onboard ships since the aluminium is classed as *steel or equivalent*. All of the A-, B- and C-class divisions that might be needed onboard a ship like *M/S Undine* can be manufactured in aluminium and still be approved by the SOLAS code. However in the SOLAS code it is stated that the temperature of the structural core of an aluminium bulkhead or deck is not to rise more than 200° C above the ambient temperature during a standard fire test. This implies that an aluminium deckhouse must be fitted with additional fire insulation, compared to an equivalent steel structure, to keep the temperature of the structural core at an acceptable level.

There are several different types of products on the market and different solutions on how to install the insulation. For the concept section the insulation solution using insulating blankets is proposed. This is due to the reasonable price and the fact that most shipyards have a vast experience from these types of insulations. They are comparatively easy to install and are easily adapted to the ship's structure. The blankets will be mounted onto the structure with a distance of 100 mm to the longitudinals. The air gap between insulation and the structure is incorporated in the insulation system and give the possibility to reduce the insulation thickness with approximately 25%. In the calculations of insulation weight and cost Thermal Ceramics insulation system "FireMaster Marine

Plus" is used. As an example, a A60 deck is approved with 50 mm insulation, but if an air gap of 100 mm is used it is possible to reduce the insulation thickness to 38 mm.

9.11 Calculations and result

Global and local loads were considered according to the Lloyd's *Rules and Regulations for the Classification of Ships*. The global loads were found not to be the dimensioning load for the deckhouse. The local loads and their response was investigated and agreed with Lloyds. All versions of the superstructure were subject to the same deck and side loads. Deck loads were based on the rule loads for primary structure and the side loads were based on the stagnation pressure of a hurricane, see figure below.

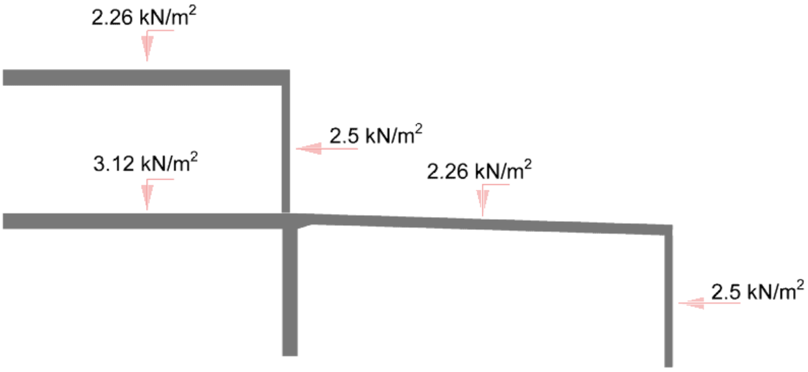

Figure 9-8 Deck loads used to check stress levels in the deck and side plates

9.11.1 Stresses

A model of the concept section was developed and calculations were performed using a quarter model to reduce calculation times.

9.11.1.1 Result

Using direct calculations the dimensions of stiffeners, beams and plates were determined primarily by looking at the resulting stresses and deflections. Since aluminium has an elasticity modulus that is a third of what steel has the main issue was still the large spans and associated deflections for the transverse beams. Stress levels were once again not the driving design factor. If large holes are to be made in the web of primary structure elements to allow pipes, cables etc. to pass through, this must be especially considered. The stress levels are determined to a level below the requirements (125 N/mm^2 for heat affected material) of Lloyds' regulations, however singularities remain to be considered in the design of local reinforcements.

9.11.2 Deflection

Lloyd's recommendations regarding deflections when using direct calculations were to consider the beam fixed in both ends and when deck load and gravity load applied the beam was allowed to deflect one 1000th of the beams span. The Lloyds criteria together with the components in the model which interact with each other need to be verified. This corresponds in the assembled aluminium model to a criterion of an allowed maximum deflection of one 400th of the length of the beam in question.

9.11.2.1 Result

When designing the refined aluminium versions it became obvious that the large spans that the transversal beams must cover is the *design driver*. Stress levels can be kept at an acceptable level with some what thinner beams but to keep the vertical deformations within the prescribed limitations it was necessary to increase the dimensions on virtually all components.

9.11.3 The Structure's Natural Frequencies

To analyse the natural frequencies for the Deckhouse FE software was used.

9.11.3.1 Result

From the frequency analysis results it is evident that some of the frequencies are close to what is considered allowed, but the whole interval is above the limitations (10Hz).

9.11.4 Buckling

As the goal was to reduce the weight of the section as much as possible the resulting dimensions on beams and plates are more slender then on the original version. This increases the risk of instability and buckling issues and therefore this was also investigated using the previously described model. During the buckling analysis the local loads were considered and also the compressive stresses originating from the global sagging moment were applied as a separate load case. To verify the results they were compared with analytical solutions.

9.11.4.1 Result

Loads from the global sagging condition result in compressive stresses of around 15 MPa. With analytical formulas and pure compression load the plate between longitudinals has a critical buckling stress of 55 MPa and the longitudinal around 40 MPa. This implies that buckling from global loads is not likely for the deckhouse. This was further verified by the FE buckling analysis for Alu –2 which state a buckling factor of 2.4.

9.11.5 Dimensions

The most interesting results according to weight are output from the version Alu -2, scantlings are presented in the table below.

Table 9-1 Version Alu -2 structure dimensions

STRUCTURE PART	LOCAL DIM [MM]
(1) BD weather deck transversal	430x10+100x28
(2) BD Deck Transv Carlings	n/a
(3) BD weather deck longitudinal	54,5x3+30x4
(4) BD weather deck plate	4
(5) BD Deck Girder	n/a
(6) GD side frame	150x8+80x10
(7) GD Side Vertical Stiffener	n/a
(8) GD side plate	4
(9) GD Side Window Frame	n/a
(10) GD Side Carlings	n/a
(11) GD Pillar	n/a
(12) GD bulkhead #126	
(13) GD side longitudinal	54,5x3+30x4
(14) GD acc. deck longitudinal	54,5x3+30x4
(15) GD accommodation deck plate	4
(16) GD acc. deck transversal	470x10+100x20
(17) GD Garage pillar	H-244x9+244x14
(18) GD weather deck longitudinal	54,5x3+30x4
(19) GD weather deck plate	4
(20) GD weather deck transversal	280x8+100x15
(21) UD side frame	150x8+80x10
(22) UD side plate	4
(23) UD side longitudinal	54,5x3+30x4
(24) GD Girder	500x18+030x28
(25) Bimetallic Plate	40x15+40x10

9.11.6 Structural and Insulation Weight

During the whole design process continuous weight calculations have been made. Output from the weight calculations for the concept section were extrapolated to account for the whole deckhouse with the alternative general arrangement

9.11.6.1 Result

The result from the weight calculation of the sections is presented in the following tables and figures.

Table 9-2 Weight of five different versions of the concept section

Version	Structure [kg]	Percent of steel -1	Percent of steel -2	Insulation [kg]	Structure + Insulation [kg]	Percent of steel -1	Percent of steel -2
Steel -1	40268	100%	115%	2234	42 501	100%	118%
Steel -2	35054	87%	100%	1003	36 057	85%	100%
Alu -1	18613	46%	53%	1689	20 302	48%	56%
Alu -2	11024	27%	31%	1689	12 713	30%	35%
Alu -3	13611	34%	39%	1689	15 300	36%	42%

As the table above show, the weight of the optimized version Alu –2 is most favourable. Including insulation the weight is approximately 30 % of the original steel version. The optimization of the aluminium structure saved approximately 39% compare to the Alu –1 version.

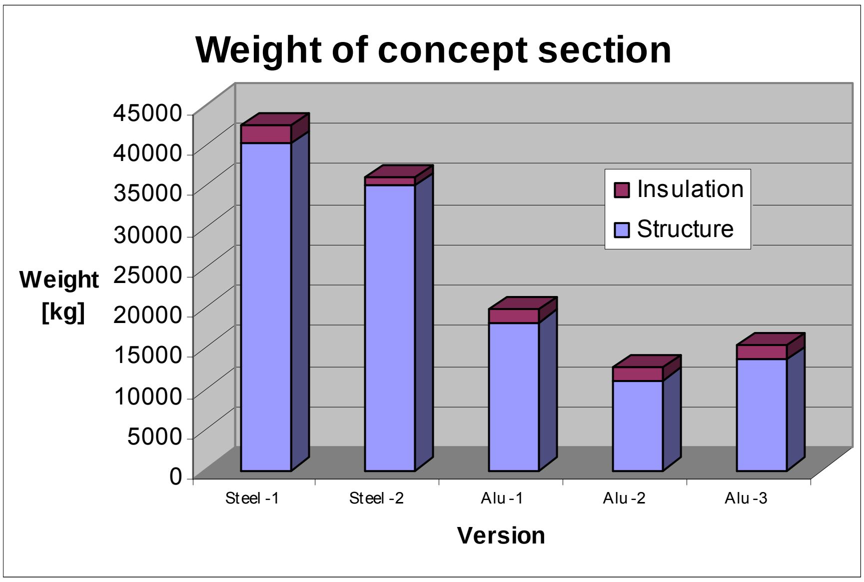

Figure 9-9 Weight of the five different versions of the concept section.

9.12 Economical Aspects

To find out if building a Deckhouse out of aluminium is of interest or not from ship owner point of view, the relation between cost and profit was investigated.

- The investments were defined as costs for structure and insulation when building a Deckhouse with extended Garage in aluminium minus cost of the original Deckhouse in Steel.
- The profit is defined as income from increased number of cars onboard during the transport.
- The revenue is defined as profit minus investment.

9.12.1 Result

Based on input from weight the calculations of, production cost and insulation cost the investment for the concept section is defined in table below. The calculation is based on a steel structure cost of 2.5 $/kg and aluminium cost of 15 $/kg.

Table 9-3 Cost for five different versions of the concept section

Version	Structure weight [kg]	Structure cost [$]	Insulation cost [$]	Structure & Insulation cost [$]	Percent of Steel -1	Percent of Steel -2
Steel -1	40268	100669	1944	102613	100%	114%
Steel -2	35054	87634	2086	89721	87%	100%
Alu -1	18613	279195	8114	287309	280%	320%
Alu -2	11024	165353	8114	173467	169%	193%
Alu -3	13611	204165	8114	212279	207%	237%

As table above show, the cost for the Alu –2 version, including insulation, is approximately 169 % of the original steel version, Steel –1. The optimization of the aluminium structure saved approximately 40% compare to the Alu –1 version.

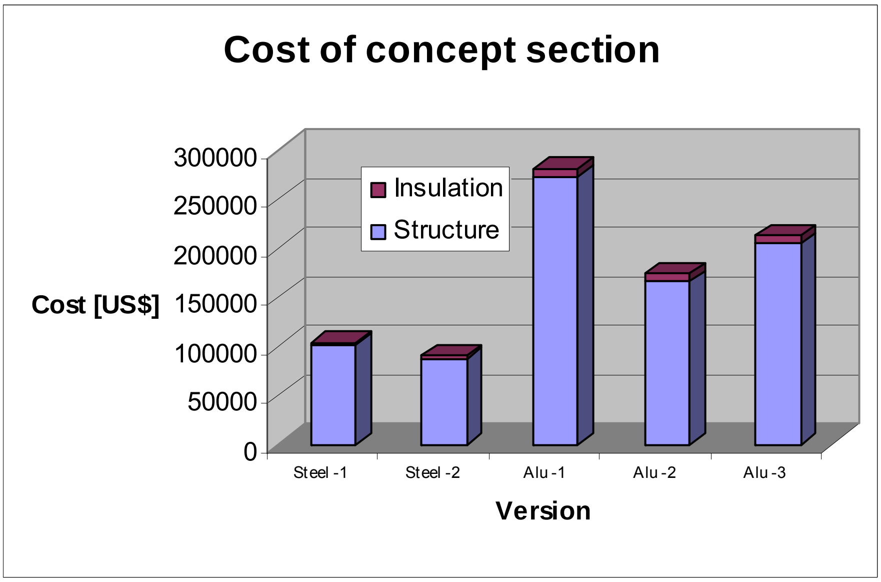

Figure 9-10 Cost for five different versions of the concept section

The result above was extrapolated to contribute to the whole deckhouse using structure version Alu –2, with a garage extended with 58.4m to accommodate an additional 180 RT43 units.

The following output is used for the **investment** calculation.

I Steel Structure material + production + insulation cost: 1 576 954 $
II Aluminium Structure material (Alu –2 version) + production + insulation cost including extended Garage (58.4m): 3 320 240 $

Additional investment caused by changing to the aluminium structure is calculated as:
II – I = 1 743 286 $.

The **profit** is**,** based on an increased load capacity of 180 vehicles, approximately assumed to be 2 400 000 $ after a period of 5 years.

The **revenue** is based on above 2 400 000 $ – 1 743 286 $.= 656 714 $.
The amount indicates that there is relatively large economical revenue from building an aluminium deckhouse using structure version Alu –2, with a garage extended with 58.4 m to accommodate an additional 180 RT43 units. In addition to the economical benefits, the total weight of the deckhouse including the added weight of RT43 units is lowered with 220 tonnes. This could also be described by, that in theory, the Garage could be lengthened with approximately 115m, which would correspond to 350 RT43 units and a revenue of 2 300 000 $. However, the actually deck layout and deckhouse geometry of Undine needs to be totally changed to give space to more than 180 RT43 units.

As can be seen in figure below, the "break even" point for Alu –2, based on aluminium structure cost of 15 $/kg, version is approximately corresponding to a garage extended 35m, which in turn would be able to accommodate approximately 100 RT43 units.

From the same figure it is also obvious that with the Alu –2 version the investments in the economical example above, will not generate a profit with an aluminium cost of 20 $/kg.

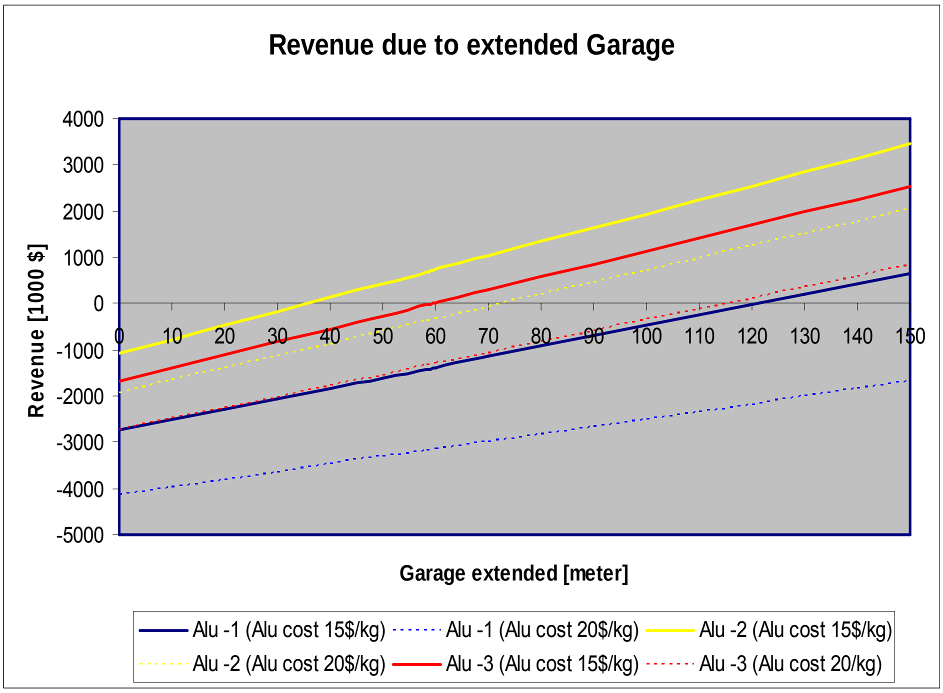

Figure 9-11 Revenue due to extended Garage

9.13 Conclusions

Below some conclusions and thoughts from the sub project output are presented:

- Based on structure cost results in the report and information regarding profit from pay load, positive revenue from changing material from steel to aluminium in a deckhouse of a PCTC vessel is to be expected within a period of 5 years. The result indicates that the Garage of the concept ship ought to be extended in order to load maximum number of vehicles according to what is geometric possible on the Upper Deck area, and reduce fixed ballast.

- The revenue is strictly depending on cost from material + production hours, which is subject to large fluctuating at the moment (year 2007). Therefore the revenue shall be considered carefully with regards to up to date cost.

- With maximum number of vehicles loaded on upper deck, according to what is geometric possible, the centre of gravity of the vessel is lowered and fixed ballast can be removed.

- The aluminium structure on a Ro-Ro deck is to be built with few pillars due to the cargo handling. This result in large span on supporting beams, girders and transversals, where large section modulus are required to keep deflection and natural frequencies within the limits. This will result in a heavier structure than on e.g. a passenger high speed vessels where more pillars and supports can be used in order to shorter the beam span. On a Ro-Ro deck a better strength-weight ratio might be performed if transversals and girders are built of steel, and the shell with stiffeners are built out of aluminium.

- For aluminium the design driver for all stiffeners and beams is the deflection. The max deflection is based on steel structure, with a modulus of elasticity of three times of aluminium. There might be possibilities to allow aluminium beams to deflect more than steel. Regards shall be taken rather to fatigue and onboard comfort than to deflection criteria and stress levels.

- The version Alu -2 indicates the most interesting weight saving compare to the original steel version. However the plate thickness proposed in the design is less than the Lloyds minimum requirements. This might result in a discussion with the class administration regarding activities and cargo handling in the deckhouse area. The structure design in this report does not cover point loads from handling e.g. some deck cargo.

- Improvements for Alu -2 version with the aim to lower the weight has been investigated The two most interesting ways are:
  - Carbon fibre reinforce the flanges on transversals and girders, expected weight reduction is 10% compare to the Alu -2 section.
  - Inclined sides to shorter the transversals span, expected weight reduction is 17% compare to the Alu -2 section.

- The investigation do cover a general structure design, detail design is not performed within this project. All details, reinforcements, brackets, doublings, production solutions might slightly increase the total structure weight.

- The ship yards who build the PCTC vessels are ordinary steel builders, lack of experience end routines in dealing with aluminium design is to be expected.

Therefore a pre design, built by experienced aluminium manufacturers, which is assembled and mounted on site, probably the best way to go.

- At the moment (year 2007) it is a lack of yard capacity. This result in that new design, as an aluminium deckhouse on a steel ship, is not the favourite object for the yards to build. They rather want to build vessels similar to previous ones for best profit. Therefore it might be difficult to find a yard with capacity to build such a vessel, with regards to relevant cost.

10 Case study WP3d; a RoPax with a composite superstructure

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Kockums AB

Nomenclature

AP	Aft Perpendicular
B_{MAX}	Breadth (max)
B_{WL}	Breadth (designed waterline)
BL	Baseline (The upper surface of the flat keel)
CL	Centre Line (A longitudinal line at the centre of the ship)
D (main deck)	Moulded depth (from main deck)
DNV	Det Norske Veritas
FEA	Finite element analysis
FEM	Finite element method
GRP	Glass-fibre reinforced plastic
HDT	Heat distortion temperature
HSLC	High Speed Light Craft
KAB	Kockums AB
L	Defined as L_{PP} in this report
LCG	Longitudinal centre of gravity
L_{OA}	Length over all
L_{PP}	Length between perpendiculars
L_{WL}	Length at designed waterline
NSC	Naval Surface Craft
Ships	Rules for Ships
SWL	Summer Load Waterline
T	Draught
V	Speed

10.1 Introduction

The objective with this report is to replace an existing steel superstructure with a GRP superstructure placed on a Stena Ro-Pax ferry in the LASS project.

The load cases in this report are taken from DNV Rules for Ships (Ships) and the hull scantling calculations in this report is based on DNV HSLC and NSC. The type of craft is chosen as unrestricted R_0.

The main particulars of the craft are:

Table 10-1 Main particulars of the ship

PROPERTY	DIMENSION	UNIT
L_{OA}	188.3	m
L_{PP}	170	m
B_{WL}	28.7	m
D	15	m
T	6	m
Δ	19889	m^3
C_B	0.6794	-
Displacement	$12\ 500 \cdot 10^3$	kg
V	22	knots

The different decks are defined as being part of the superstructure according to (Pt.3 Ch.4 Sec.1) of DNV's HSLC rules as follows:

Deck 7	Superstructure
Deck 8	Superstructure
Deck 9	Superstructure
Deck 10	Deckhouse -Long
Deck 11 /Bridge	Deckhouse –Short

Although structural design in the superstructure is based on a GRP-Sandwich, the scantlings have been calculated based on the commercial DNV HSLC & NSC (the January 2006 edition rules) with adequate safety margins. For the time being, no further optimisation is made.

The use of GRP-Sandwich gives a lightweight superstructure with flat panel surfaces. The weight reduction, given by using composite superstructure aids seaworthiness to the craft, this is done by lowering the neutral axis of the ships structure. The choice of material is also positive as it has low corrosive capabilities.

10.2 Description of the Stena Ropax

Figure 10-1 Image of the Stena Ropax. © Stena Line AB

The Stena Ropax is a 188.3 meter long and 12 500 tonnes heavy cargo and passenger ferry operating between Hoek in Holland and Harwich in Great Britain. Its superstructure can be seen in the figure above as it begins just above the name "Stena RoRo".

10.2.1 Existing steel superstructure

The existing steel structure consists of deck plates connected and stiffened by longitudinals, verticals, girders and stiffeners. The interior of the superstructure is upheld by pillars and corrugated plates see figures below. Observe that some dimensions may differ slightly from deck to deck.

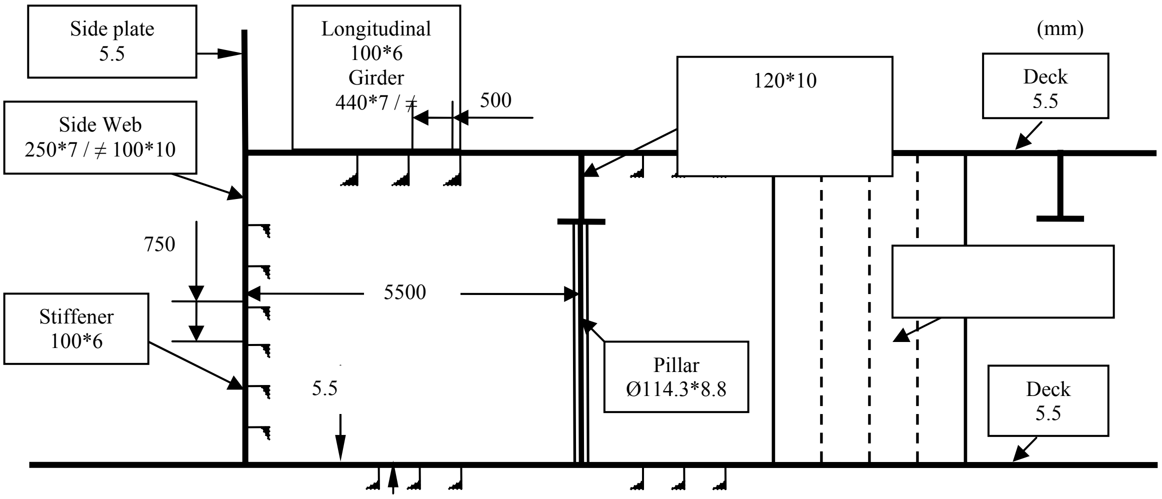


Figure 10-2 A cross section of the superstructure with girders, longitudinals, pillar, corrugated plate and stiffeners

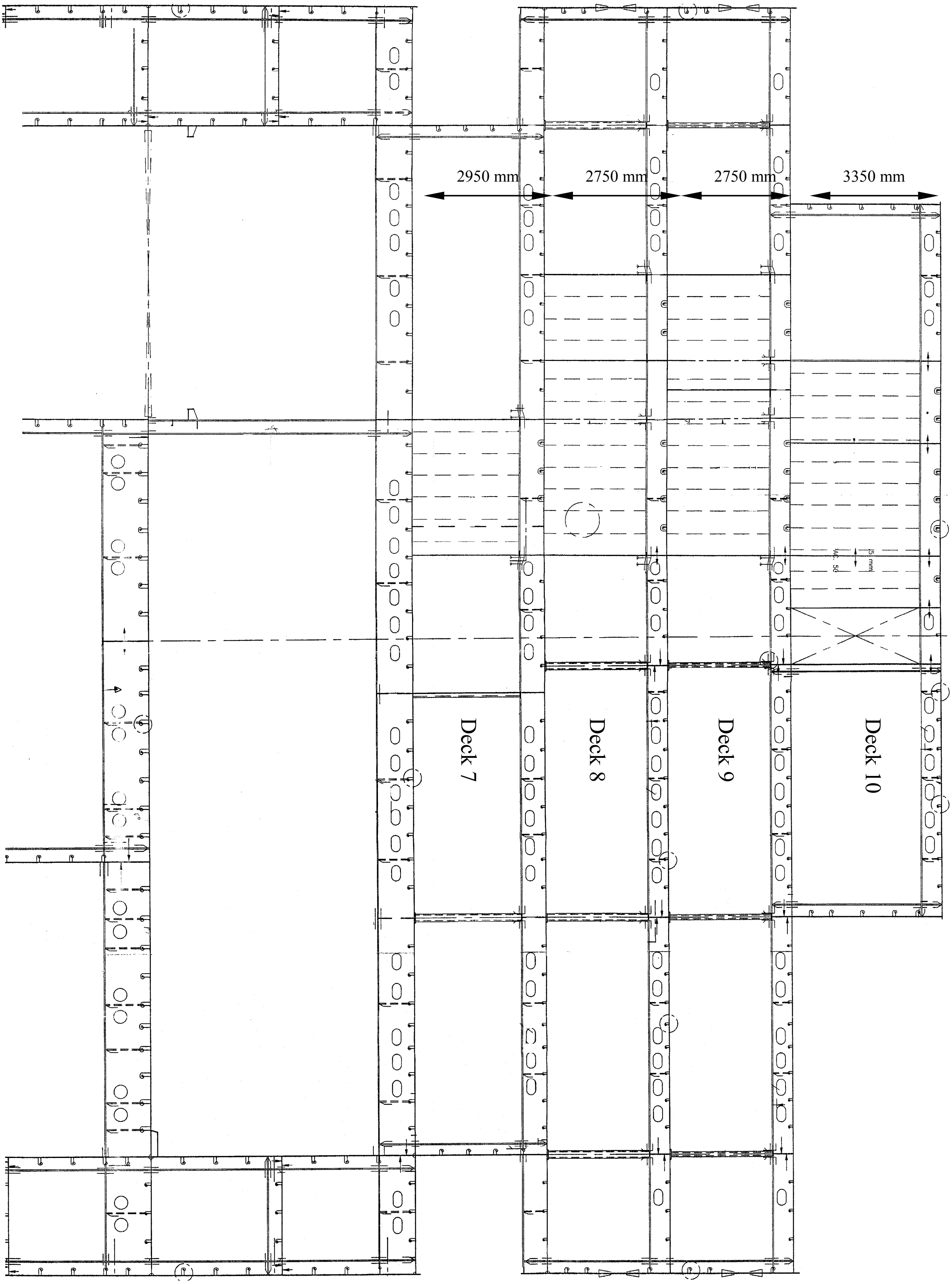


Figure 10-3 Entire midship cross section of the Stena Ropax (Picture is tilted 90° right).

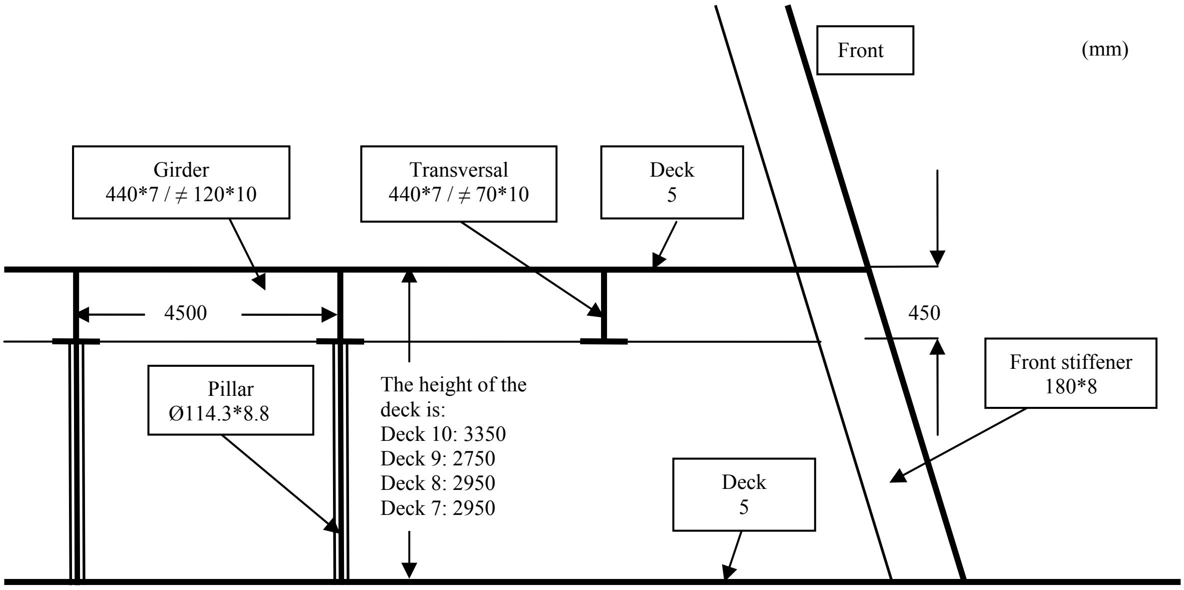


Figure 10-4 A part of a cross section of the superstructure in CL with girder, transversals, pillars and plates.

The superstructure consists of deck seven (steel deck) through deck 11 plus the bridge deck. The bridge deck is not included in this report. Areas in blue represent cabins, areas in green represent gangways and yellow is service areas. Deck eight consists mainly of passenger cabins and corridors.

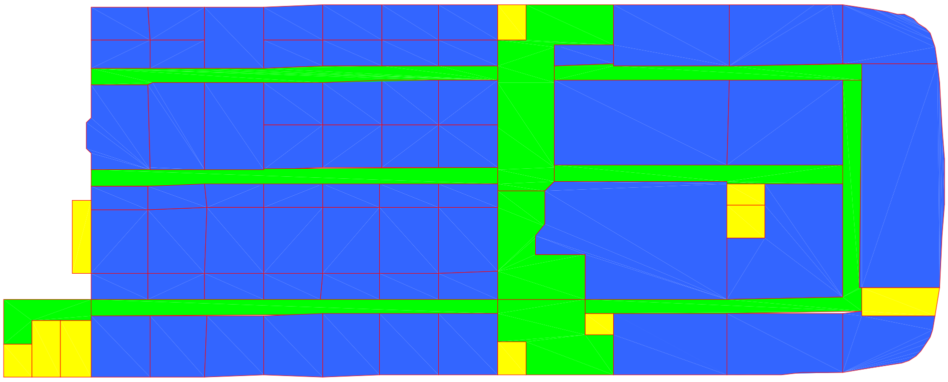


Figure 10-5 Areas of deck 8

Deck 9 has almost the same geometry as deck 8 except for the forward part used for the crews mess room in colour orange.

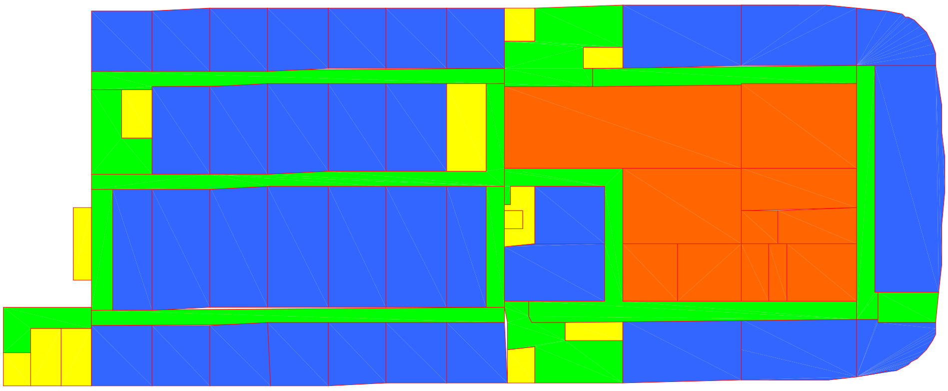


Figure 10-6 Areas of deck 9

The upper deck is used solely for crew with cabins and mess rooms.

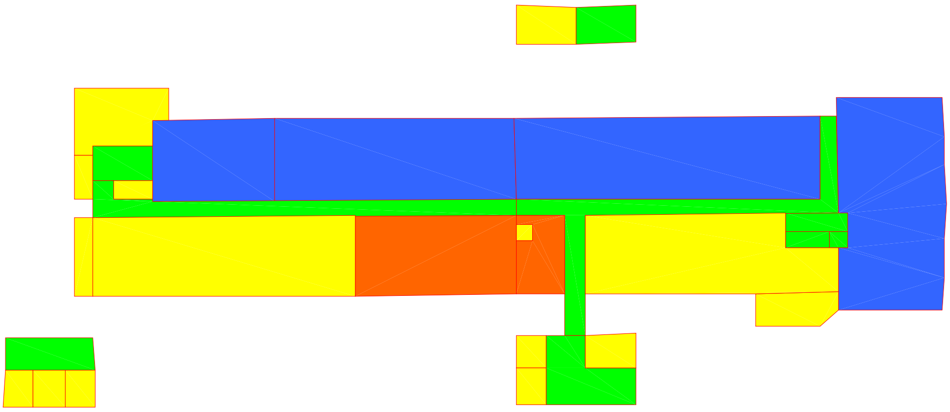
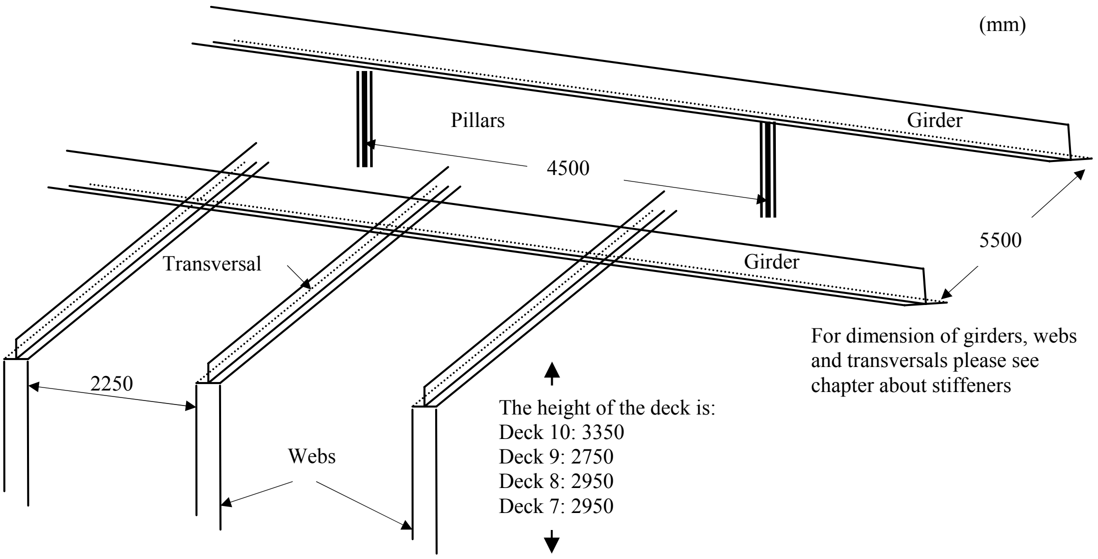


Figure 10-7 Areas of deck 10+11

10.3 Future sandwich superstructure

The future superstructure has almost an identical geometry compared to the present one except that the stiffeners at the side plates are removed and that half of the longitudinals are taken away, see figure below.



For dimension of girders, webs and transversals please see chapter about stiffeners

The height of the deck is:
Deck 10: 3350
Deck 9: 2750
Deck 8: 2950
Deck 7: 2950

Figure 10-8 Suggested geometry of the future sandwich superstructure with girders, longitudinals, transversals, webs and pillars. Internal plates and deck plates are not depicted

10.3.1 Materials

The development of materials and sandwich structures is an ongoing process. Values given below are well established but may be changed as new materials and manufacturing methods are developed.

10.3.1.1 Core material

The core material used in this report is Divinycell H-grade expanded PVC foam. The materials used are approved by DNV. Material properties for H-grade is given below.

Table 10-2 Definitions of the core materials used

Property	Unit	H 45	H 60	H 80	H 100	H 130	H 160	H 200	H 250
Nominal Density	Kg/m^3	48	60	80	100	130	160	200	250
Tensile Modulus E	MPa	55	75	95	130	175	170	250	300
Shear Strength τ_u	MPa	0.56	0.76	1.15	1.6	2.2	2.6	3.5	4.5
Shear Modulus G	MPa	15	20	27	35	50	73	85	108
Shear Strain ε	%	12	20	30	40	40	30	40	30

For sun and heat exposed areas, core material with higher temperature resistance will be used. In this report though, calculations are performed using the ordinary H-grade core. Core materials with higher temperature resistance and the same mechanical properties are available.

10.3.2 Laminate material in flat panels

The laminate material is based on the following design.

Table 10-3 Definitions of the laminate materials used

Property	Unit	GRP
Nominal Density	kg/dm^3	1.8
Tensile Modulus E	GPa	17
Tensile strength $\sigma_{nu,tensile}$	MPa	290
Compressive strength $\sigma_{nu,compressive}$	MPa	220
Fibre volume	%	50

The GRP is defined by:
Fibre: Multiaxial Quasi Isotropic stitched glass fibre fabric
Matrix: Polyester
Fabrication technique: Vacuum infusion

Assuming the GRP is injected a material consisting of 50 %V Glass-fibres with a polyester matrix a weight fraction of 69 %W can be achieved.

10.3.3 Allowable stresses and deflections for sandwich panels

For simplified calculation methods for sandwich panels based on rule formula in Pt.3 Ch.4 Sec.5, allowable stresses and deflections according to Pt.3 Ch.4 Sec.5 B500 shall be used.

Table 10-4 Allowable stresses and deflections for sandwich panels

STRUCTURAL MEMBER	Σ_N	T_C	W/B
Side structures	$0.3\sigma_{nu}$	$0.4\tau_u$	0.02
Deck structures	$0.3\sigma_{nu}$	$0.4\tau_u$	0.02
Bulkhead structures	$0.3\sigma_{nu}$	$0.4\tau_u$	0.02
Superstructures	$0.3\sigma_{nu}$	$0.4\tau_u$	0.02
Deckhouses	$0.3\sigma_{nu}$	$0.4\tau_u$	0.02
All structures exposed to long time static loads	$0.2\sigma_{nu}$	$0.15\tau_u$	0.01

σ_{nu} = the ultimate tensile stress for skin laminates exposed to tensile stresses
= the smaller of the ultimate compressive stress and the critical local buckling stress, according to B300, for skin laminates exposed to compressive stresses.
τ_u = the minimum ultimate shear stress of sandwich core material given on the type approval certificate.

10.3.4 Allowable stresses and deflections for beams

According to Pt.3 Ch.4 Sec.7 B602 maximum allowed design stress, σ_d, in beams shall be $0.3\sigma_u$. σ_u = ultimate laminate strength (tensile or compressive).

According to Pt.3 Ch.4 Sec.7 B603 maximum allowed design shear stress, τ_d, in stiffeners and girder webs shall be $0.25\tau_u$. τ_u = ultimate laminate shear stress

10.4 Design loads

This section presents the different loads, local and global, that are used for the dimensioning work on the superstructure. The figures used below are:

Table 10-5 Figures used for dimensioning

PROPERTY	DIMENSION	UNIT
m	$12\,500\cdot10^3$	kg
L	170	m
B	28.7	m
D	15	m
T	6	m
Δ	19889	m^3
V	22	knots
g_0	9.81	m/s^2
k	0.8	-
C_B	0.6794	-
k_r	11.2	m
GM	2	m
CG	14	m
R_R	7	m

10.4.1 Design acceleration

The wave coefficient used is:

$$C_W = 10.75 - \left[(300 - L)/100\right]^{3/2} = 9.27$$

(Pt.3 Ch.1 Sec.4:B201)

The service area notation is set to R_0 which gives no reduction of C_W.
With parameters

$$C_V = \frac{\sqrt{L}}{50} = 0.26$$

(maximum) and

$$C_{V1} = \frac{V}{\sqrt{L}} = 1.69$$

is the acceleration factor a_0 chosen to:

$$a_0 = \frac{3C_W}{L} + C_V C_{V1} = 0.60$$

(Pt.3 Ch.1 Sec.4:B203)

The surge, sway/yaw and heave acceleration is given by:¨

$$\mathrm{a_x} = 0.2\mathrm{g_0 a_0 C_B} = 0.80\, m/s^2$$ (Pt.3 Ch.1 Sec.4:B301)

$$\mathrm{a_y} = 0.3\mathrm{g_0 a_0} = 1.77\, m/s^2$$ (Pt.3 Ch.1 Sec.4:B302)

$$\mathrm{a_z} = 0.7\mathrm{g_0}\frac{\mathrm{a_0}}{\sqrt{\mathrm{C_B}}} = 5.00\, m/s^2$$ (Pt.3 Ch.1 Sec.4:B303)

The period of roll is taken as

$$\mathrm{T_R} = \frac{2\mathrm{k_r}}{\sqrt{\mathrm{GM}}} = 15.8\, s$$ (Pt.3 Ch.1 Sec.4:B401)

With $\mathrm{k_r} = 11.2\, m$ and metacentric height $\mathrm{GM} = 2\ \mathrm{m}$.

The roll angel (single amplitude) is given by

$$\phi = \frac{50\mathrm{c}}{\mathrm{B}+75} = 0.33\, rad$$ (Pt.3 Ch.1 Sec.4:B401)

Which gives a tangential roll of

$$\mathrm{a_r} = \phi\left(\frac{2\pi}{T_R}\right)\mathrm{R_R} = 0.38\, m/s^2$$ (Pt.3 Ch.1 Sec.4:B403)

With $R_R \approx 7\, m$ as the distance in m from the centre of mass to the axis of rotation in both roll, pitch and yaw. The pitch angle is given by

$$\theta = 0.25\frac{a_0}{C_B} = 0.17\, rad$$ (Pt.3 Ch.1 Sec.4:B501)

The tangential pitch is

$$\mathrm{a_P} = 120\,\theta\frac{R_P}{L} = 0.94\, m/s^2$$ (Pt.3 Ch.1 Sec.4:B503)

This gives three combined accelerations, a transversal (a_t), a longitudinal acceleration (a_l):

$$a_t = \sqrt{a_y{}^2 + \left(g_0 \sin\phi + a_{ry}\right)^2} = \left\{a_{ry} = a_r\right\} = 3.8\, m/s^2$$ (Pt.3 Ch.1 Sec.4:B701)

$$a_l = \sqrt{a_x{}^2 + \left(g_0 \sin\theta + a_{px}\right)^2} = \left\{a_{px} = a_p\right\} = 2.6\, m/s^2$$ (Pt.3 Ch.1 Sec.4:B801)

and a vertical (a_v) acceleration taking into consideration $\mathrm{k_v}$ a longitudinal distribution factor.

$$a_V = \frac{k_V g_0 a_0}{C_B}$$ (Pt.3 Ch.1 Sec.4:B601)

For different positions, $\mathrm{k_v}$ varies as seen in figure below.

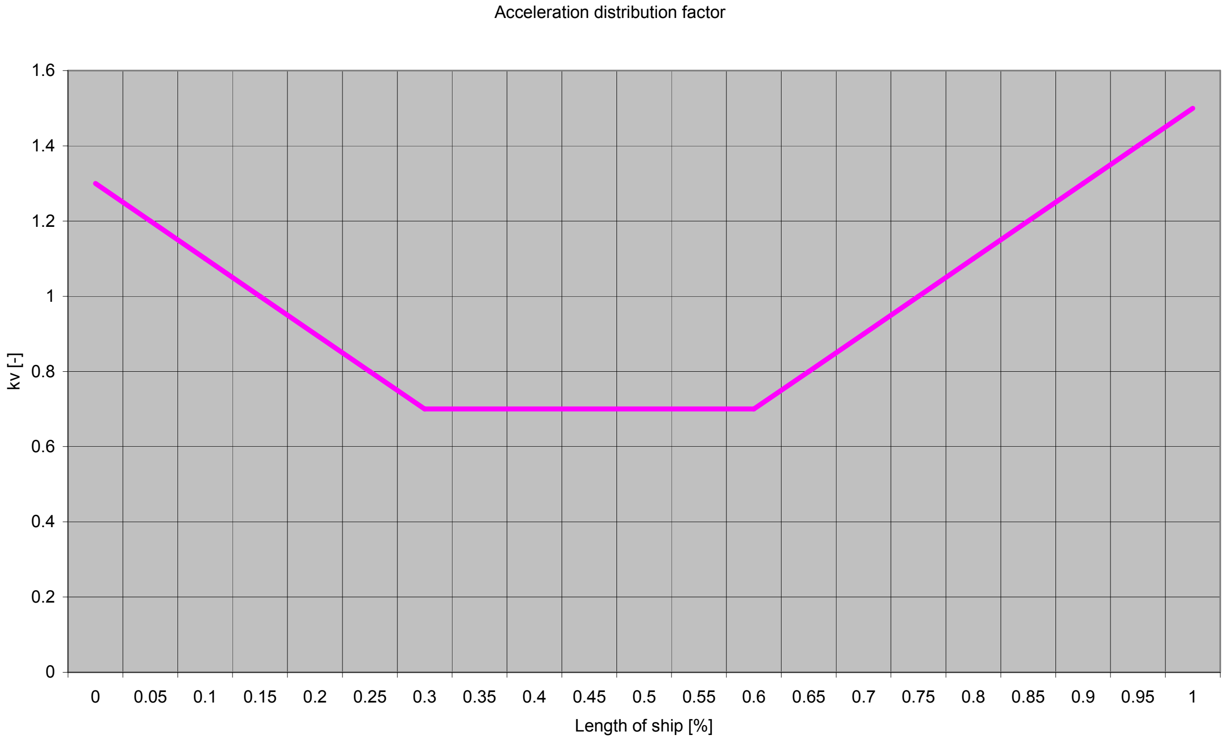


Figure 10-9 Distribution factor k_v throughout the superstructure

This gives following acceleration over the ship's side:

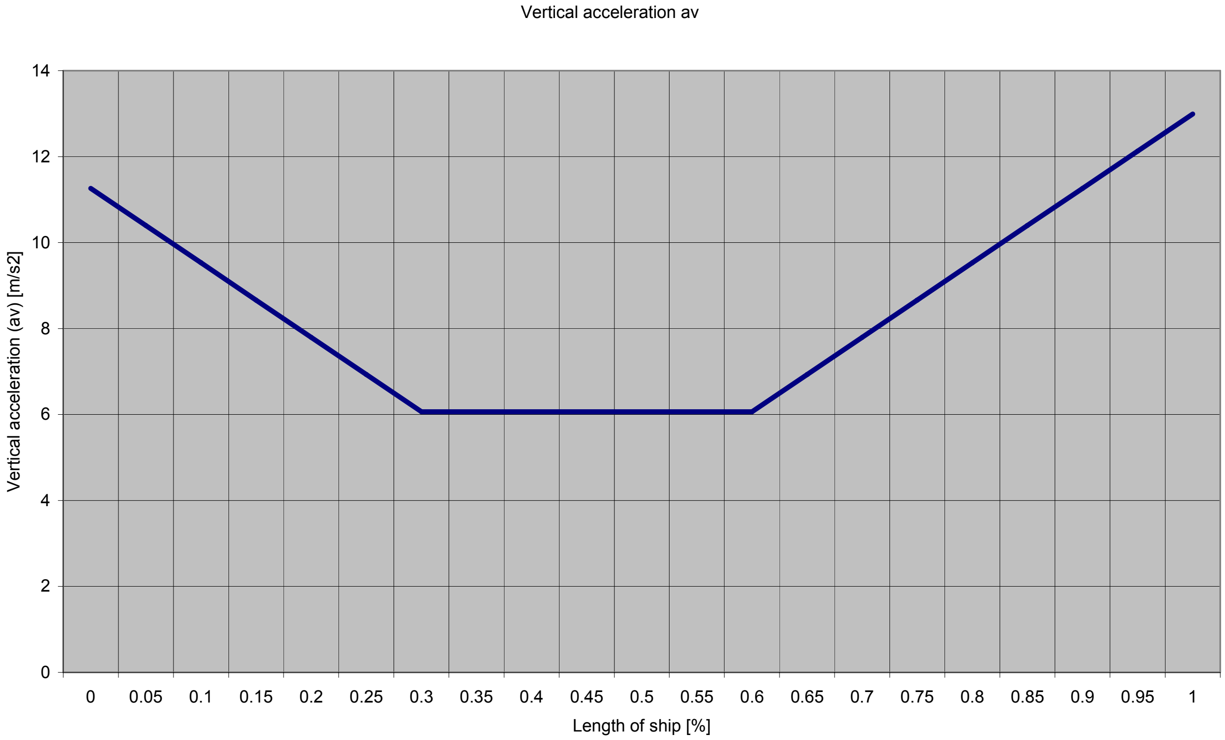


Figure 10-10 Vertical acceleration throughout the superstructure

It can be concluded that the vertical acceleration is the largest acceleration affecting the superstructure acting together with earths gravity producing as much as $9.81+13\ m/s^2 = 23\ m/s^2$ at the forward part of the ship.

10.4.2 Hull girder loads

The two moments used are Still water bending moment (M_{SO}) and Wave induced bending moment (M_W). The two moments are added to produce the total bending moment.

10.4.3 Longitudinal bending

The moments apply to two types of bending; Hogging and Sagging. These two modes are applied to the Stena Ropax.

10.4.4 Hogging & Sagging

The total sagging and hogging bending moments are

$M_{SO,SAGG} = -0.065 C_W L^2 B (C_B + 0.7)$ *[kNm]* (Pt.3 Ch.1 Sec.5:B105)

$M_{W,SAGG} = -0.11 \alpha C_W L^2 B (C_B + 0.7)$ *[kNm]* (Pt.3 Ch.1 Sec.5:B201)

$M_{SO,HOGG} = C_W L^2 B (0.1225 - 0.015 C_B)$ *[kNm]* (Pt.3 Ch.1 Sec.5:B105)

$M_{W,HOGG} = 0.19 \alpha C_W L^2 B C_B$ *[kNm]* (Pt.3 Ch.1 Sec.5:B201)

In seagoing conditions is $\alpha = 1$.
For stress analysis is a factor $k_{wm} = 1$ added to the equation between 0.4L and 0.65L from AP and linearly towards the sides.

$M_W = k_{WM} M_{WO}$ (Pt.3 Ch.1 Sec.5:B202)

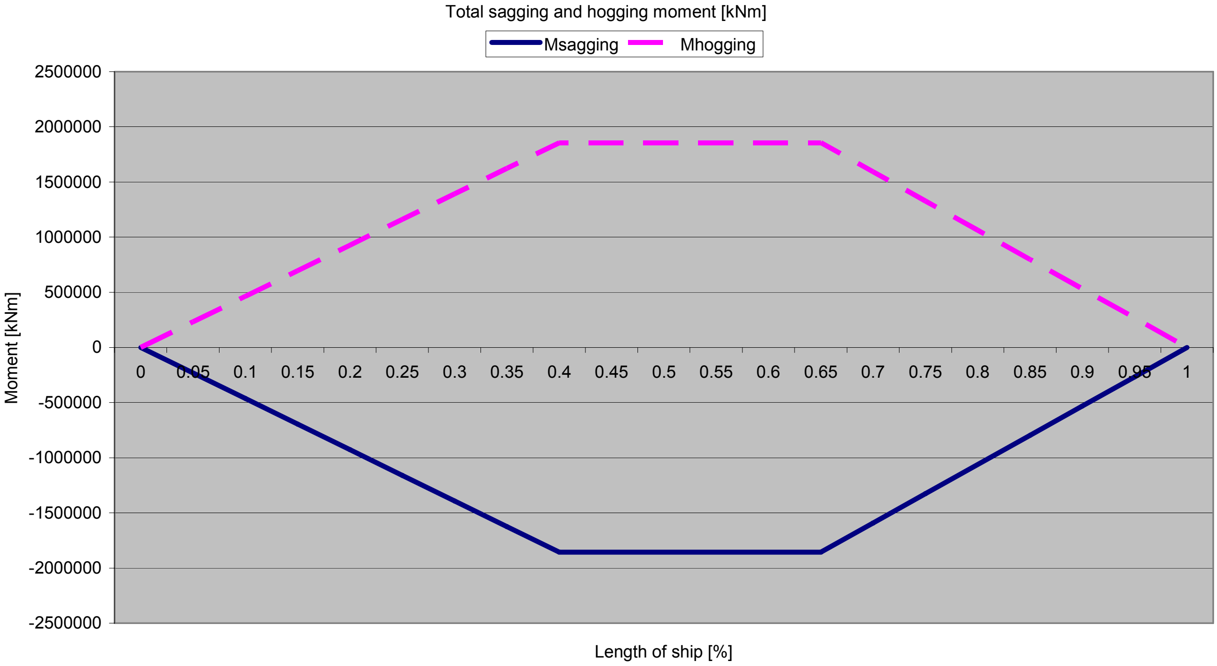


Figure 10-11 Total sagging and hogging [kNm] using the factor k_{wm}

This gives

$M_{SAGG} = -1855600$ *[kNm]* (Pt.3 Ch.1 Sec.5:B105&B201)

$M_{HOGG} = 1855600$ *[kNm]* (Pt.3 Ch.1 Sec.5:B105&B201)

10.4.5 Shear force from longitudinal bending

The vertical shear force from longitudinal bending is calculated as

$$Q_{WP} = 0.3\beta k_{wqp} C_W LB(C_B + 0.7) \quad [kN] \qquad \text{(Pt.3 Ch.1 Sec.5:B203)}$$

$$Q_{WN} = -0.3\beta k_{wqn} C_W LB(C_B + 0.7) \quad [kN] \qquad \text{(Pt.3 Ch.1 Sec.5:B203)}$$

As the factors k_{qwp} and k_{qwn} varies throughout the ship is the shear forces found in table below.

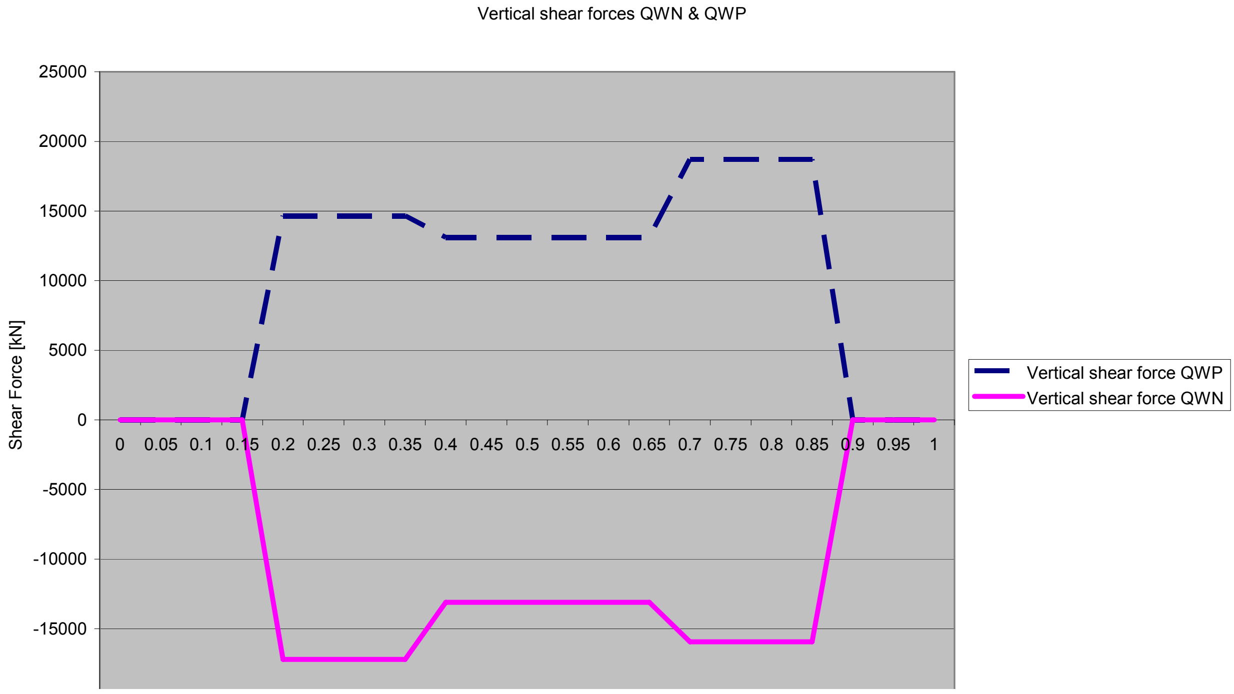


Figure 10-12 Vertical shear forces acting on the craft

The maximum vertical positive shear forces affecting the superstructure is $Q_{WP} = 19383\,kN$ Q_{WP}=18 712 kN at $0.7 \le x/L \le 0.85$ and the maximum vertical negative shear forces affecting the superstructure is Q_{WP}=-17 215 kN at $0.15 \le x/L \le 0.35$.

10.5 Local loads

10.5.1 Sea pressure on superstructure sides, front and aft

The sea pressure used in this report is found in DNV Rules for Ships part 3, chapter 1 sections 7 table B1 concerning the sides and aft ends of the superstructure (p_3) and chapter 10, table B1 for the deckhouse and front bulkheads (p_2 and p_{11}).

Deck seven through ten has a design pressure of

$$p_2 = 12.5 + 0.05L = 22\,kPa \qquad \text{(Pt.3 Ch.1 Sec. 10:C100)}$$

on the front bulkheads and

$$p_3 = 6.25 + 0.025L = 11\,kPa \qquad \text{(Pt.3 Ch.1 Sec.7: Table B1)}$$

on the sides and aft ends.

The pressure acting on the side can be reduced to, according to (Pt.3 Ch.1 Sec.10:C100, Table C1 addendum 2) 2.5 kN/m^2 at 1.7C$_W$ above SWL. In this case same as the draught $T=6m$ equalling $1.7 \times 9.6 + 6 = 16.32 + 6 = 22.32\,m$ above BL. Therefore is the pressure acting on the deckhouse on deck 11 reduced to *2.5 kPa*.

$p_{11} = 2.5\,kPa$ (Pt.3 Ch.1 Sec.10:C100)

10.5.2 Pressure on decks

DNV's Rules for Ships states that the interior decks of a ship shall withstand a pressure of

$p_5 = 0.35\left(g_0 + 0.5\,a_v\right) = \{\max\} = 5.7\,kPa$ (Pt.3 Ch.1 Sec.8:Table B1)

The weather decks (deck 10 partly and deck 11 entirely) shall be made to withstand 13 kPa (Pt.3 Ch.1 Sec.4:Table C1)

10.6 Summary of design loads

10.6.1 Global loads

The design longitudinal bending moment is
M=1 855 600 kNm in sagging (Pt.3 Ch.1 Sec.5:B201)
The maximum vertical shear force is positive
Q=18 712 kN (Pt.3 Ch.1 Sec.5:B203)

10.6.2 Local loads

The loads for various parts of the superstructure can be found in Table 10-6 below.

Table 10-6 Pressures on the superstructure

DECK [NO.]	HEIGHT ABOVE WATERLINE [M]	AFT PRESSURE [KPA]	SIDE PRESSURE [KPA]	FRONT PRESSURE [KPA]	DECK PRESSURE [KPA]
11 (exterior)	26.800	-	-	-	13
10 (exterior)	23.450	-	-	-	13
10 (interior)	23.450	-	-	-	5.7
10-11	24.825	2.5	2.5	2.5	-
9 (interior)	20.700	-	-	-	5.7
9-10	22.075	11	11	22	-
8 (interior)	17.950	-	-	-	5.7
8-9	19.325	11	11	22	-
7-8	16.475	11	11	22	-

10.7 Scantling Calculations

10.7.1 Structural design philosophy

The design philosophy for the composite superstructure can be summarised according to the following list:

- Steel superstructure is replaced by an equivalent GRP structure.
- Deigned according to Det Norske Veritas using the load cases from Rules for Ships (DNV Rules for Ships) and using the Rules for classification of high speed, light craft and naval surface craft (DNV HSLC & NSC) for GRP and sandwich calculations.
- The original stiffening arrangement is to be kept while plates and longitudinals are replaced and rearranged by an equivalent GRP structure.
- Superstructure panels are designed to be produced using a vacuum infusion process.
- Weight optimised superstructure subordinating in favour of yield ability.
- Restrict the translation of global loads in the superstructure.
- Make use of existing hull structure for load translation.
- The superstructure is not to carry any global loads.

10.7.2 Design principles

The scantling calculations for the FRP superstructure are based on DNV HSLC (Pt 3 Ch 4:”Hull structural design, fibre composite and sandwich construction”), together with actual material data and structural design loads.

The calculations presented in this section are to decide panel scantlings, i.e. spacing in the girder system, and a suitable combination of face thickness and core material type/thickness. Note that loads applied in this section are design pressures, i.e. local loads

10.7.3 Minimum laminate reinforcement

The amount of reinforcement (g/m^2) in face laminates in the panels should not normally be less than

$$W \geq W_0 \left(1 + k\left(L - 20\right)\right) \qquad \text{for } L > 20 \text{ m} \qquad \text{(Pt.3 Ch.4 Sec.5:A106)}$$

W = mass of reinforcement per unit area (g/m^2)

Given by (Pt.3 Ch.4 Sec.5:Table A2) the minimum thickness for the GRP is 1.96 mm outside of the superstructure, the structural bulkheads with the accommodation deck are 0.66 mm and 0.88 mm at the weather decks and the watertight bulkheads.

Table 10-7 Minimum requirements for glass reinforcement

STRUCTURAL MEMBER	*W_0 [G/M^2]*	*K*	*W [G/M^2]*	*GRP [MM]*
Weather deck (not for cargo)	1600	0.0	1600	0.88
Accommodation deck, if adequately protected	1200	0.0	1200	0.66
Structural bulkheads	1200	0.0	1200	0.66
Watertight bulkheads	1600	0.0	1600	0.88
Superstructure and deckhouse, outside	1200	0.013	3540	1.96

10.7.4 Minimum core material

Minimum core material properties required are listed in (Pt.3 Ch.4 Sec.5: Table A2) and corresponds to a Divinycell H60, see Table 10-8 below.

Table 10-8 Minimum requirements for core materials

STRUCTURAL MEMBER	*SHEAR STRENGTH [N/MM^2]*	*COMPRESSION STRENGTH [N/MM^2]*
Weather deck (not for cargo)	0.5	0.6
Accommodation deck, if adequately protected	0.5	0.6
Structural bulkheads	0.5	0.6
Watertight bulkheads	0.5	0.6
Superstructure and deckhouse, outside	0.5	0.6

10.7.5 Panel strength calculation method

The panel calculations presented below refers to DNV HSLC (Pt.3 Ch.4 Sec.5). Factors needed for calculation e.g. C_x for different panel length/breadth ratios are retrieved from figures in DNV HSLC.

The normal stresses in the skin laminates are calculated as followed

$$\sigma_n = \frac{160 \cdot p \cdot b^2}{W} \cdot C_N \cdot C_1 \qquad \text{(B201)}$$

The maximum core shear stress at the midpoints of the panel edges is given by

$$\tau_c = \frac{0.52 \cdot p \cdot b}{d} \cdot C_S \qquad \text{(B202)}$$

The critical local buckling stress for skin laminates in compression (wrinkling) is given by

$$\sigma_{cr} = 0.5 \cdot \sqrt[3]{E \cdot E_c \cdot G_c} \qquad \text{(B301)}$$

The deflection at midpoint of a flat panel is given by

$$w = \frac{10^6 \cdot p \cdot b^4}{D_2} \cdot \left(C_6 C_8 + \rho C_7\right) \qquad \text{(B401)}$$

Modulus of elasticity for sandwich structure with symmetric face laminates

$$D_2 = \frac{E_{lam} t d^2}{2(1-\nu^2)} \qquad \text{(B401)}$$

where $\nu = 0.3$ for a typical laminate

10.7.6 Stiffener strength calculation method

The stiffener calculations presented in this chapter refer to DNV HSLC (Pt.3 Ch.4 Sec.7:) and it follows general beam theory. A general composite stiffener is shown in Figure 10-13 below. The stiffener consists of top flange, web and a corresponding effective panel flange. Dimensions used in this part can be found in the figure below.

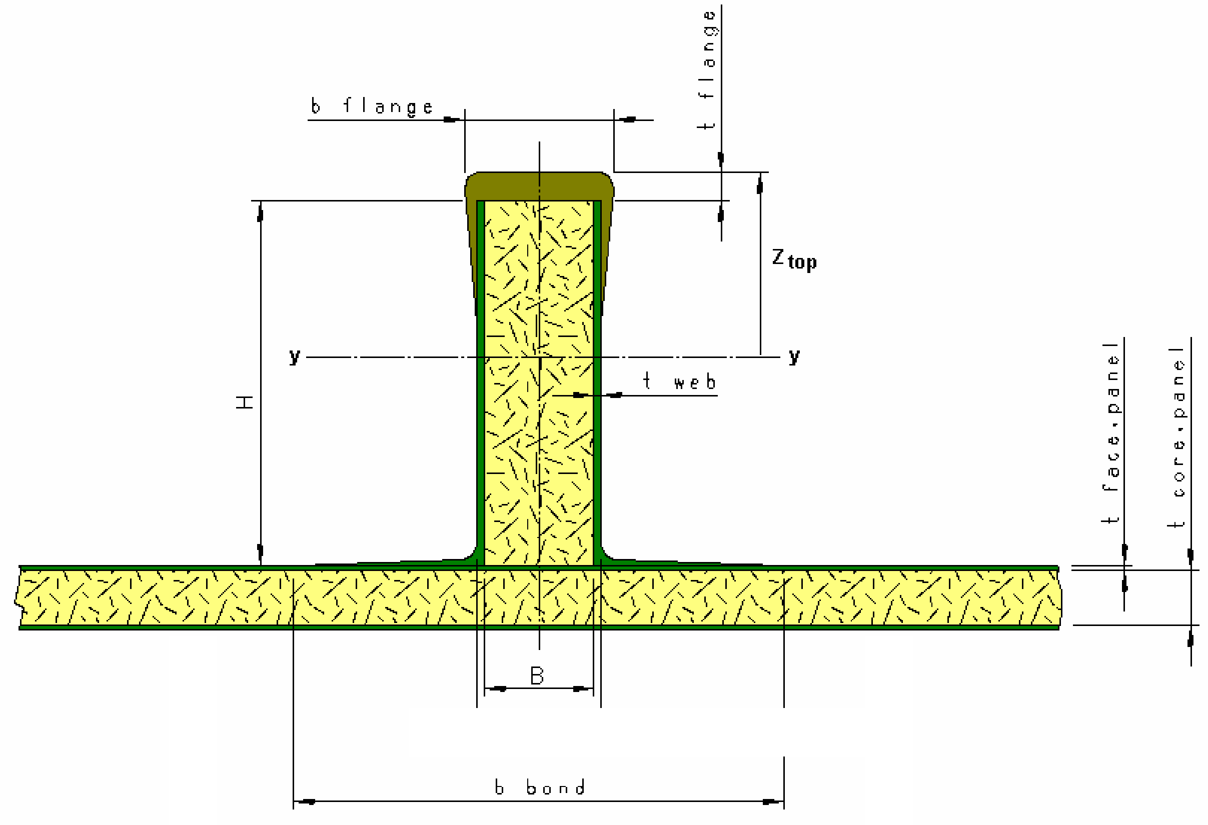


Figure 10-13 General stiffener with flange, web and corresponding effective panel flange

The effective breadth of flange is taken as the stiffener's breadth for the bottom (opposite stiffener side) face laminate. For the top (stiffener side) face laminate the effective breadth of flange is taken as:

$$\frac{b_{eff}}{b} = \frac{1}{1 + 3.3\dfrac{E}{G}\left(\dfrac{b}{l}\right)^2} \qquad \text{(Pt.3 Ch.4 Sec.7:B300)}$$

where *b* is the panel breadth between beams, *l* is the length of the beam with E and G as the Young's modulus and the shear modulus of the GRP. The geometry of the superstructure is similar throughout which means that a general stiffener scheme is set up.

Table 10-9 General stiffener scheme for all decks.

MEMBER	SPAN L [M]	SPACING [M]	B [M]	E [GPA]	G [GPA]	B_{EFF} [M]
Transversal	5.5	2.25	2.25	17	6.5	0.92
Web	3	2.25	2.25	17	6.5	0.39
Girder	4.5	5.5	5.5	17	6.5	0.40

The bending moment induced by a pressure load acting on the stiffener is calculated as:

$$M = \frac{p_{design}\, b\, l^2}{c_1} \qquad \text{(Pt.3 Ch.4 Sec.5:B201)}$$

where

p_{design} = design pressure (kPa)
b = breadth of load area (m)
l = length of stiffener (m)

The factor c_1 may be found from textbook formula for standard load cases and support conditions. The most common factors to be used for superstructure calculations are listed below:

Table 10-10 Factor c_1 for different load cases

LOAD CASE	C_1 AT ENDS	C_1 AT MIDSPAN
Sea pressure loads on continuous members	12	24
Sea pressure on beams with freely supported ends	0	8

The distribution of shear loads along the stiffener may be found from textbook formula for standard load cases and support conditions.

When calculating the section modulus of the stiffeners, the effect of possible variations in the modulus of elasticity throughout the section should be taken into account.

The effective section modulus is not to be taken less than:

$$Z = \frac{M}{0.3\,\sigma_u} \cdot 10^3 \qquad \text{(Pt.3 Ch.4 Sec.5:B602)}$$

where

M = bending moment in kNm
σ_u = ultimate laminate normal stress (MPa)

The effective shear area (stiffener web area) is not to be taken less than:

$$A_w = \frac{10 \cdot Q}{0.25\,\tau_u} \qquad \text{(Pt.3 Ch.4 Sec.5:B603)}$$

where
Q = shear force in kN
τ_u = ultimate laminate shear stress (MPa)

10.7.6.1 Standard stiffeners

A rational approach to the girder / web frame calculations is to create a set of pre-defined stiffeners. (See appendix-report ”WP3d-calculations”).

Height H of 100 mm, a breadth B of 50 mm. The web consists of three layers QX450 and the flange consists of four layers QX850. The flange material overlaps the web with 50 mm. Local variations may occur.

Height H of 200 mm and a breadth B of 50 mm. The web consists of three layers QX450 and the flange consists of four layers QX850. The flange material overlaps the web with 80 mm. Local variations may occur.

A Height H of 400 mm and a breadth B of 100 mm is the strongest of the standard stiffeners. The web consists of three layers QX450 and the flange consists of four layers QX850. The flange material overlaps the web with 150 mm. Local variations may occur.

See Figure 10-14 for a thorough geometry of the stiffeners. The core is surrounded by a 5 to 10 mm thick laminate with a flange top of 5 to 10 mm.

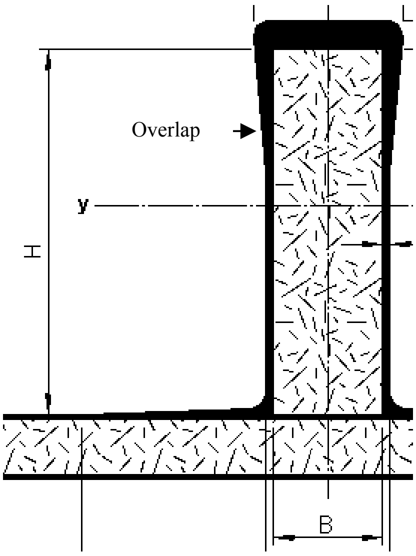


Figure 10-14 General geometry of a standard stiffener built up of GRP (dark colour) around a PVC core (dash pattern).

10.7.7 Scantlings

10.7.7.1 Superstructure

The pressure requirements on the superstructure sides alter over the side of the ship. The sea pressure is at its highest at the front and decreases linearly. For global bending behaviour and manufacturing the scantlings of the panels is the same over the whole side. The panel scantlings presented above are designed for local loads. The superstructure panels must also be able to sustain global deformation and to make sufficient contribution to the global section modulus. Therefore the panel scantlings can be changed if so found needed. The superstructure front is considered unprotected and must therefore be designed according to higher pressures and safety margins.

Table 10-11 Pressure and material thickness of the panels in the superstructure

Deck	Area	Panel size [m2]		Pressure [kPa]					Material				Decisive load case
		b [m]	h [m]	Aft	Side	Front	Deck	Design Pressure	Divinycell H-	Thickness [mm]	GRP	Thickness [mm]	
11	Exterior	2.3	14	-	-	-	13	13	80	55	QXLT850	2.0	Dynamic pressure
10	Aft	5.5	3	2.5	-	-	-	2.5	60	55	QXLT850	0.7	Sea Pressure
10	Side	2.3	3	-	2.5	-	-	2.5	60	55	QXLT850	0.7	Sea Pressure
10	Front	5.5	3	-	-	2.5	-	2.5	60	55	QXLT850	0.7	Sea Pressure
10	Exterior	2.3	5.5	-	-	-	13	13	80	55	QXLT850	2.0	Dynamic pressure
10	Interior	2.3	5.5	-	-	-	5.7	5.7	60	55	QXLT850	0.7	Static pressure
9	Aft	5.5	3	11	-	-	-	11	80	55	QXLT850	3.3	Sea Pressure
9	Side	2.3	3	-	11	-	-	11	60	55	QXLT850	1.3	Sea Pressure
9	Front	5.5	3	-	-	22	-	22	130	55	QXLT850	5.2	Sea Pressure
9	Interior	2.3	5.5	-	-	-	5.7	5.7	60	55	QXLT850	0.7	Static pressure
8	Aft	5.5	3	11	-	-	-	11	80	55	QXLT850	3.3	Sea Pressure
8	Side	2.3	3	-	11	-	-	11	60	55	QXLT850	1.3	Sea Pressure
8	Front	5.5	3	-	-	22	-	22	130	55	QXLT850	5.2	Sea Pressure
8	Interior	2.3	5.5	-	-	-	5.7	5.7	60	55	QXLT850	0.7	Static pressure
7	Aft	5.5	3	11	-	-	-	11	80	55	QXLT850	3.3	Sea Pressure
7	Side	2.3	3	-	11	-	-	11	60	55	QXLT850	1.3	Sea Pressure
7	Front	5.5	3	-	-	22	-	22	130	55	QXLT850	5.2	Sea Pressure

The interior corrugated plate is replaced by GRP but is not calculated in the report. The pillars are not replaced and not calculated but can be replaced by equivalent GRP structures. The scantling calculations can be found in appendix-report ”WP3d-calculations”.

Standard stiffeners are created as mentioned above and fulfils the minimum cross sectional area $A_{W,MIN}$.

Table 10-12 Definition of standard stiffeners

MEMBER	HEIGHT H [M]	BREADTH B [M]	$A_{W,MIN}$ [CM^2]	A_W [CM^2]	WEIGHT [KG/M]
A1	0.1	0.05	6	10	3.7
A2	0.2	0.05	15	20	11.0
A3	0.4	0.05	37	40	21.7

All standard stiffeners are built-up of glass fibre webs with glass fibre flanges around a PVC Divinycell H60 core. See appendix-report ”WP3d-calculations”.

10.7.8 Global strength verification

10.7.8.1 Aim

This chapter aims to prove that verification of global strength is unnecessary since the bending moment has no larger influence on the superstructure.

10.7.8.2 Introduction

Since only the superstructure will be designed in composite materials and it is situated above the neutral axis, all laminates will be subjected to the same stress situation during load, compressive or tensile strain.

The following maximum longitudinal bending moment and shear force are calculated:

$M_{SAGGING} = 1\ 855\ 600\ kNm$

$Q_{POSITIVE} = 18\ 712\ kN$

For the superstructure, the sagging bending moment is the dimensioning load case because it will subject the structure to compressive strain.

10.7.8.3 Longitudinal bending moment and section modulus

The longitudinal bending moments affecting the hull girder are assumed to have no larger influence on the superstructure as it is placed in the front part of the craft, front of L/2. The section modulus of a superstructure deck should be added if it applies with the definition of a strength deck. Applied on the superstructure the definition is as follows

“A superstructure deck which within 0.4L amidships has a continuous length equal to or greater than”

for monohull vessels 3(B/2+H) (Pt.3 Ch.1 Sec.1:B205)

“shall be regarded as the strength deck”.

H = height in m between the uppermost continuous deck and the superstructure deck in question. As the height H in this case is 2.95 for deck eight and 2×2.95 for deck nine and so on is none of the decks regarded as a strength deck. There is therefore no section modulus added.

10.8 Further work

The work described in this document shall be regarded as an initial scantling calculation. The presented design represents a robust design able to further optimisation. A FEA analysis of the entire superstructure can be made to further lessen the weight of the superstructure. Different fibre angles can be used in different parts to optimise the structure.

10.9 Appendix-report

In Appendix-report "WP3d-calculations" is given the calculations in more details for the scantlings and pressures of the Stena Ropax composite constructions.

Case studies WP3e and WP3f - Introductory comments

Application cases studied in WP3e and WP3f were both added to LASS in 2006, approximately 15 months after the project started. The intention was to include two highly interesting objects for lightweight construction and it was in direct response to requests from Swedish industry. In connection to the expansion six more industries were added to the Technical Platform as “associated” LASS partners. The intention was to make less detailed studies than for the original four concepts with a main focus on weight savings by replacing conventional steel with aluminium (WP3e) and FRP-composites (WP3f).

Responsible for the new WP designs were Pharmadule-Emtunga AB and Kockums AB respectively. Unfortunately for the project, was Pharmadule-Emtunga after some time reconstructed and divided into two new companies: Pharmadule AB and Emtunga Offshore AB and in relation to this found it difficult to continue their participation in LASS. Therefore, the study was not fully completed. The results obtained regarding a new lightweight offshore LQ (living quarter) module were, however, highly promising and very interesting panel designs were made based on the LASS-partner SAPA’s know-how on extruded aluminium profile constructions.

Due to the interrupted participation of the WP3e-leader, no report will be included on the LQ except for an abstract and a power-point presentation made by Emtunga Offshore at the LASS-conference in October 2007.

11 Case study WP3e; An aluminium off-shore living quarter

Peo Svärd
Emtunga Offshore AB

Abstract given for the LASS-conference held in Borås, 071031 The full PowerPoint presentation from the conference is given as an appendix-report “Emtunga-presentation at the LASS conference”.

11.1.1 Light weight material for Living Quarters

A living quarter (also called LQ) serves an offshore platform or a complete oil field with a number of properties as shown below.

• Accommodation for crewmembers	• Recreation
• Protection for Fire and gas as well as blast over pressure loads - Safe area	• Central Control Room
• Dining area	• Airport with control tower, baggage handling, sky lobby, etc
• Galley	• Medical centre
• Laundry	• Office

The design and fabrication for a living quarter characterises by a number of temporary construction phases as shown below. These temporary construction phases tends to drive the structural design ending up in material used for temporary phases are dead load during its live time.

• Assembly phase
• Load out
• Sea transport
• Installation (Lifting/skidding/etc.)

Emtunga Offshore AB (Emtunga) provides the market with key turn living quarters on a EPC contract basis. The living quarters are designed the modular way which means that the living quarter are spitted into smaller modular sections that are fabricated at ground inside a construction hall. This gives advantages in terms of QA, HSE, lead time, standardized design and construction.

The weight of a living quarter is predominantly driven by the structural discipline and the architectural disciplines which stand for 80-90 % of the total living quarter weight. Furthermore, the structure is partly driven by temporary construction phases which add on additional structural material useless for the in-place service.

The effort in this particular project has been focused on using aluminium material for steel structure and light weight wall panels. The Table below shows pros and cons for aluminium structure and light weight wall panels.

Aluminium	
Advantage	*Disadvantage*
• Light weight. Saves 25% of the structural weight	• 2,5-3 times more expensive
• “Build-in” functions making it cheaper for construction	• Need additional fire protection - expensive
	• Long lead time
Light weight wall panels	
Advantage	*Disadvantage*
• Saves typically 40 ton	• Acoustic properties
	• Certification

Structural aluminium panels for walls and floor have been designed in this project using hand calculation and 3D computer analysis provided by SAPA. The computer analyses have taken shear capacity and blast capacity into consideration. Wall panels can be designed using open (one plate with stiffener) or closed sections (two wall plates). The closed section gives the opportunity to bolt outfitting directly at the wall and still have a gas tight wall since the outer wall serves as gas and fire protection.

The majority of cost in a typically living quarter EPC project comes from the fabrication phase. The closed section adds an additionally weld to connect the panels to the roof/floor beam and column at each module which means more time consuming fabrication and consequently more expensive. Therefore, open sections with T stiffeners have been preferable during this study so far. The T stiffeners are also used for attaching/bolting outfitting equipment to the wall panels.

12 Case study WP3f; composite materials in a trollmax bulk cargo vessel

Håkan Sandell
Kockums AB

As a part of the LÄSS project a study concerning use of composite materials in selected parts of small cargo vessels has been performed by Kockums AB. The parts of concern are the cargo hatches, a grain bulkhead, and the deckhouse. The aim is to decrease the structural weight in order to increase the pay-load. The study will result in a base line for the composite structures, from which it will be possible to estimate the weight, the material cost and the manufacturing cost. No detail design concerning battening or interlinking of hatch sections will be performed.

Figure 12-1 Type of vessel studied

12.1 Requirements

The known requirements are that the cargo hatch and the grain bulkhead must have a robust design. The surfaces must be flat in order to achieve an easy cleaning. The deformation when loaded must be limited in order to maintain the water tightness of the cargo hatch. The grain bulkhead is not water tight but it may be unpractical with large deformations for this structural element.

For the deckhouse the prime goal is to decrease the structural weight. All composite details must be easy to manufacture and to repair and the material cost must be low.

12.1.1 Cargo hatch design loads

The design loads for the parts of current interest are based on the DNV Rules for Ships.

12.1.1.1 Deck cargo pressure

The design pressure for the cargo hatch cover is based on DNV Rules for Ships Pt.3 Ch.1 Sec.4 C401. The deck cargo on the hatch covers, 1,6 ton/m^2, will cause a design pressure of:

$$p = \rho\left(g_0 + 0{,}5 \cdot a_V\right)H$$

$\rho H = 1{,}6 \text{ ton/m}^2$

$a_V = 6{,}34 \text{ m/s}^2$ (Vertical design acceleration, DNV Rules for Ships Pt.3 Ch.1 Sec.4 B601).

$p = 20{,}8 \text{ kPa}$.

12.1.1.2 Water pressure

The design water pressure of the foremost hatch, FR #113, will be

$$p_1 = a\left(p_{dp} - \left(4 + 0{,}2k_s\right)h_0\right)$$

$a = 1{,}0$

$p_{dp} = 41{,}01 \text{ kPa}$ (DNV Rules for Ships Pt.3 Ch.1 Sec.4 C201)

$k_s = 4{,}66$ (DNV Rules for Ships Pt.3 Ch.1 Sec.4 C201)

$h_0 = 3{,}1 \text{ m}$

$p_1 = 25{,}83 \text{ kPa}$.

The design water pressure of the hatch at FR #103, will be

$$p_1 = a\left(p_{dp} - \left(4 + 0{,}2k_s\right)h_0\right)$$

$a = 1{,}0$

$p_{dp} = 32{,}06 \text{ kPa}$ (DNV Rules for Ships Pt.3 Ch.1 Sec.4 C201)

$k_s = 3{,}33$ (DNV Rules for Ships Pt.3 Ch.1 Sec.4 C201)

$h_0 = 3{,}1 \text{ m}$

$p_1 = 17{,}59 \text{ kPa}$.

The design load for the foremost hatch, at FR#113, is water pressure **25,83 kPa**.
The design load for the rest of the cargo hatch sections are the deck cargo pressure **20,8 kPa**.

12.1.2 Grain bulkhead design loads

Design pressure for the three grain bulkhead sections, DNV Rules for Ships, Pt.3 Ch.2 Sec.8 B100,

$$p_2 = k \cdot \rho_c \cdot g_0 \cdot K \cdot h_c$$

$k = 1{,}3$

$\rho_c = 0{,}7 \text{ t/m}^3$ (dry cargo dencity)

$g_0 = 9{,}81 \text{ m/s}^2$

$K = \sin^2\alpha \tan^2(45 - 0{,}5\delta) + \cos^2\alpha = 0{,}49$

$\alpha = 90^\circ$

$\delta = 20^\circ$

$h_c = 7$ m for the lowest section

$h_c = 5$ m for the middle section

$h_c = 3$ m for the top section

$p_2 = 30{,}6$ kPa for the bottom section,

$p_2 = 21{,}9$ kPa for the middle section,

$p_2 = 13{,}2$ kPa for the top section.

12.1.3 Deckhouse design loads

The design loads for the external deckhouse bulkheads are determined from DNV Rules for Ships Pt.3 Ch.1 Sec.10.

Table 12-1 External deckhouse bulkhead design loads

	FRONT	SIDES	AFT
Raised quarter deck	50,9 kPa	20,8 kPa	17,7 kPa
Boat deck	12,9 kPa	9,1 kPa	8,4 kPa
Bridge deck	8,4 kPa	8,4 kPa	8,4 kPa

Design loads for deckhouse decks are derived from DNV Rules for Ships Pt.3 Ch.2 Sec.7.

Table 12-2 Deckhouse deck designload

	DESIGN PRESSURE
Wet Boat deck	14,3 kPa
Accommodation deck	4,5 kPa
Deckhouse top	4 kPa

12.2 Structural design

Design of the composite structures is based on the DNV Rules for High Speed, Light Craft and Naval Surface Craft.

In this study the focus is set on the weight aspects, material cost and the manufacturing costs. A typical sandwich structure may have a high stiffness compared to its weight but the robustness can be a weak point if a non suitable core material is used. The cross linked PVC core material, used in a large number of marine applications, may be referred to as expensive and has no favourable fire resistance properties. Due to the “Sandwich effect”, the flexural rigidity of a composite sandwich structure is generally referred to as poorer, compared to a stiffened single skin structure.
In this study we will give up the sandwich design in structures where a high level of flexural rigidity and great robustness is desirable. This means the cargo hatch and the grain bulkhead.

In the deckhouse it will be feasible to use sandwich. A typical sandwich panel design for the deckhouse could be glass fibre reinforced polyester in the skin laminates and balsa as core material. Balsa is used for the high “shear modulus/density” ratio, which means that the panels will have less deflection for a certain thickness and weight. It is also regarded to as a sandwich core with better fire resistant properties compared to e.g. PVC foam.

12.3 Cargo hatch scantlings

KAB has no input concerning the cargo hatches that are used at the present. Because of this there are a number of assumptions made. The dimension of each section is measured directly from the general arrangement drawing, supplied by the ship-owner. A typical hatch is assumed to be 10,4 x 6,5 m, with the height 0,4 m.

The proposed cargo hatch design is a traditional stiffened single skin structure. It will consist of a number of joined square hollowed sections. The sections can be pultruded or manufactured by vacuum infusion on a mould. The laminate design, which means the save of weight, can be more optimised when vacuum infused. The size of the cross section may be limited when pultruded.

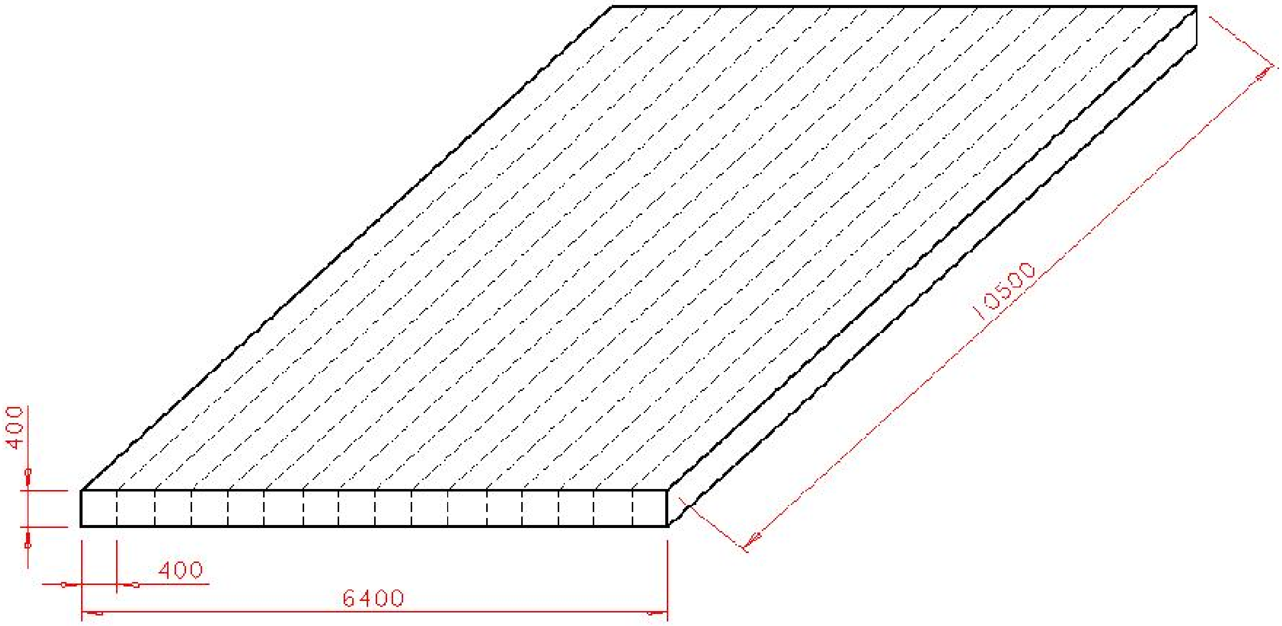


Figure 12-2 Typical cargo hatch cover, built up by a number of square hollowed sections

To avoid local deflections and to create a tough upper skin laminate a layer of high absorbent fibres is used, “Lantor Soric XF6”. The layer thickness is 6 mm and the fibres are located in the middle of the skin laminate. This will increase the thickness and the bending stiffness of the skin laminate.

12.3.1 FEM analysis

A FEM analysis is performed to get knowledge of the hatch deflections. The hatch will be built up with a number of similar sections. Each section will be designed to carry itself and the design pressure. The FEM model consists of only one single square hollowed section. The analysis is performed with ANSYS® and the element used in the FEM analysis is Shell 181, a 4-node finite strain shell.

The classification rules requirements for the composite structures are taken from DNV HSLC&NSC Pt. 3 Ch.4

12.3.1.1 Minimum requirements and design values

Minimum amount of reinforcement in the hatch top side laminate is, according to DNV HSLC&NSC Pt. 3 Ch.4 Sec. 6 A202,

$W = 5400(1 + 0{,}013(84{,}99 - 20)) = 9963 \text{g/m}^2$.

The maximum allowable deflection of the laminate is,

$w \leq 2 \cdot t$

where t is the laminate thickness

The requirement for the bending stress is,

$\sigma_d \leq 0{,}3\sigma_{nu}$

The shear stress criteria is,

$\tau_d \leq 0{,}25\tau_{nu}$

A section of the FEM model that will comply with the classification rules can be designed as showed below. For this typical section the allowable local deflections of the different parts are:

$$w_{top} \leq 2 \cdot (8{,}94 + 6) = 29{,}88 \text{ mm}$$

$$w_{bottom} \leq 2 \cdot 8{,}31 = 16{,}62 \text{ mm}$$

$$w_{sides} \leq 2 \cdot 1{,}89 = 3{,}78 \text{ mm}$$

The top and bottom laminate design tensile stress will be:

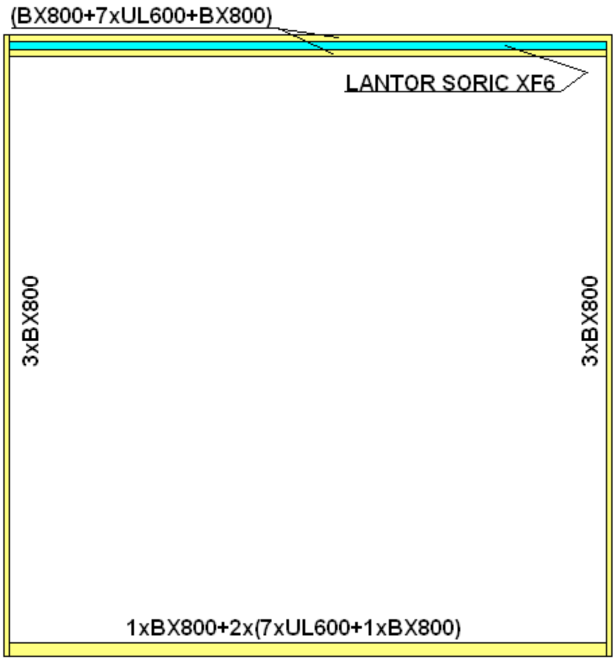
$\sigma_{d,tens} \leq 0{,}3 \cdot 527 = 158 \text{ MPa}$,

and the design compression stress will be:

$\sigma_{d,compr} \leq 0{,}3 \cdot 395 = 118 \text{ MPa}$

The design shear stress in the web laminates will be:

$\tau_d \leq 0{,}25 \cdot 330 = 82{,}5 \text{ MPa}$.



12.3.1.2 Model

The model is a square hollowed beam with section 400 x 400 mm and length 10500 mm. The fabric lay up is shown in the section on the previous page. The model consists of shell elements, Shell 181.

12.3.1.3 Loads

The load is a uniform pressure of 25830 Pa, acting on the top surface of the beam. This is the design pressure for the foremost of the hatch sections.
To include the effect of structural weight the model is accelerated in the vertical direction. The acceleration is according to DNV Rules for Ships Pt.3 Ch.1 Sec.4 C501, derived to $(9{,}81+0{,}5*a_v)=9{,}81+0{,}5*6{,}34=12{,}98 \text{ m/s}^2$.

12.3.1.4 Boundary conditions

The boundary condition used in the model is simply supported beam ends. At the ends rotations are free and the translations are prevented in all directions. These boundary conditions are expected to simulate the reality with a sufficient correctness.

12.3.1.5 Results

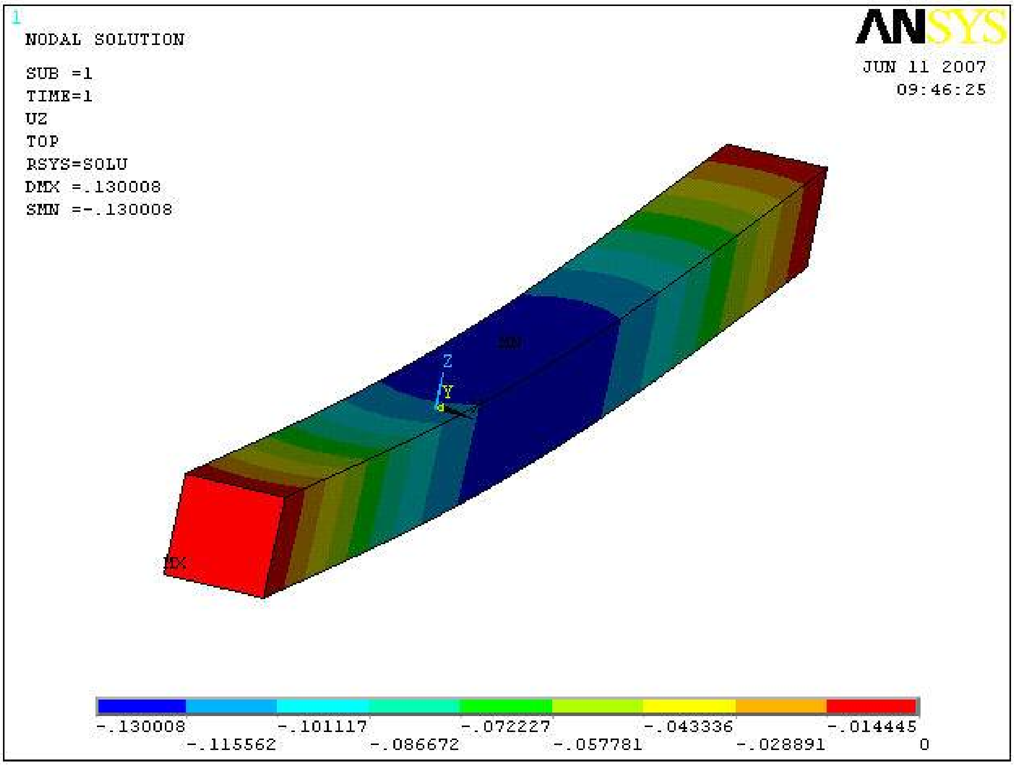


Figure 12-3 Total vertical deflection of the hatch section

The total global deflection of the model is 130mm which means approximately 1,25%. The DNV HSLC&NSC have no restriction of the global deflection of a single skin structure. The requirement on a sandwich panel is a maximum deflection of 2%, which means 210mm.

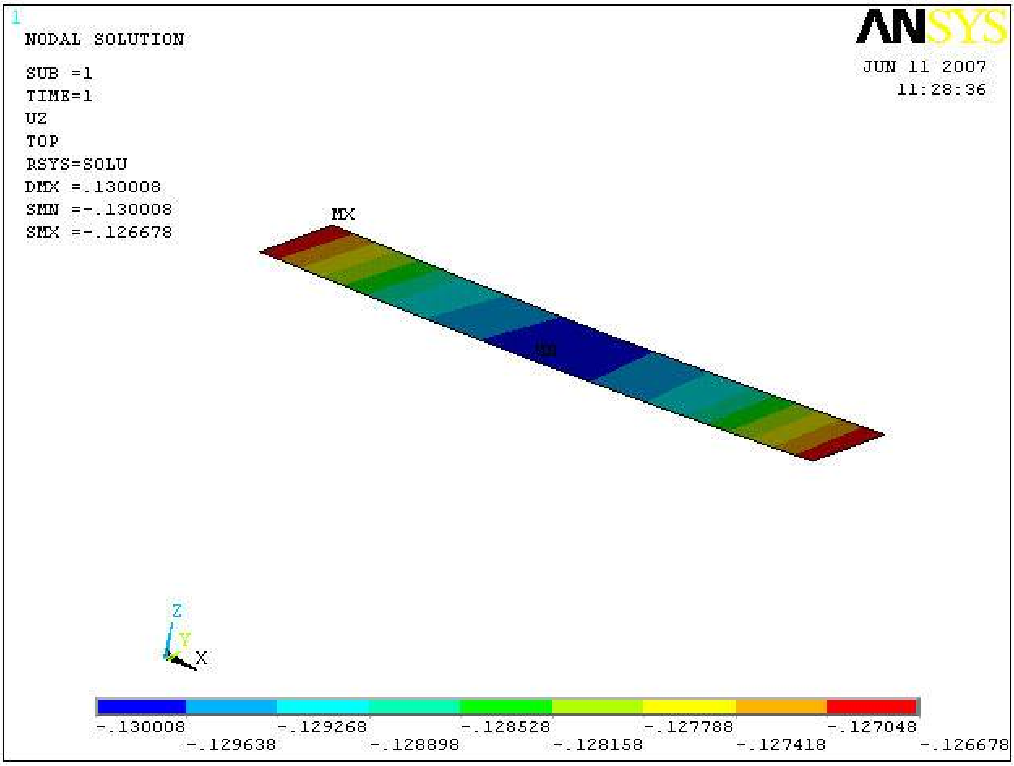
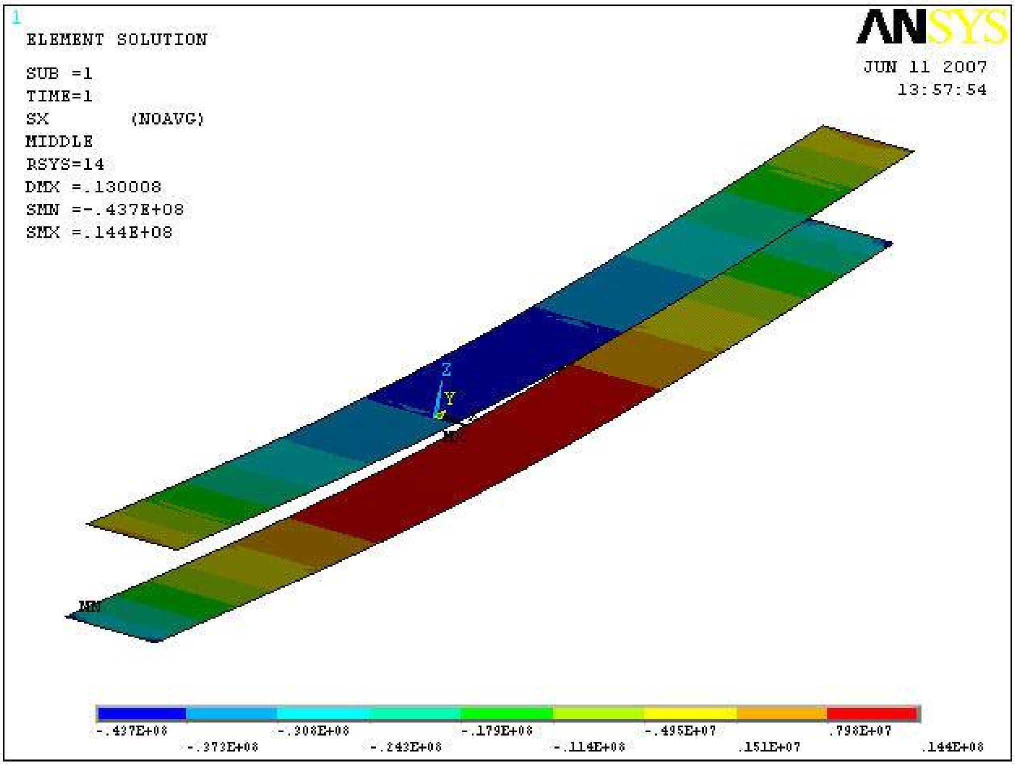


Figure 12-4 Local bending deflection in the top side laminate

The largest local bending deflection can be found in the top side laminate. The figure shows a shred of the midpoint area of the top side laminate. The shred is taken in the transverse direction of the beam. From the figure it can be seen that the local deflection is 3,33mm.

The maximum allowed local deflection is set to w=2t, where t is the laminate thickness, in this case t=14,94mm, including the Lantor soric ply of 6mm. The allowable local bending deflection will then be 29,88mm.

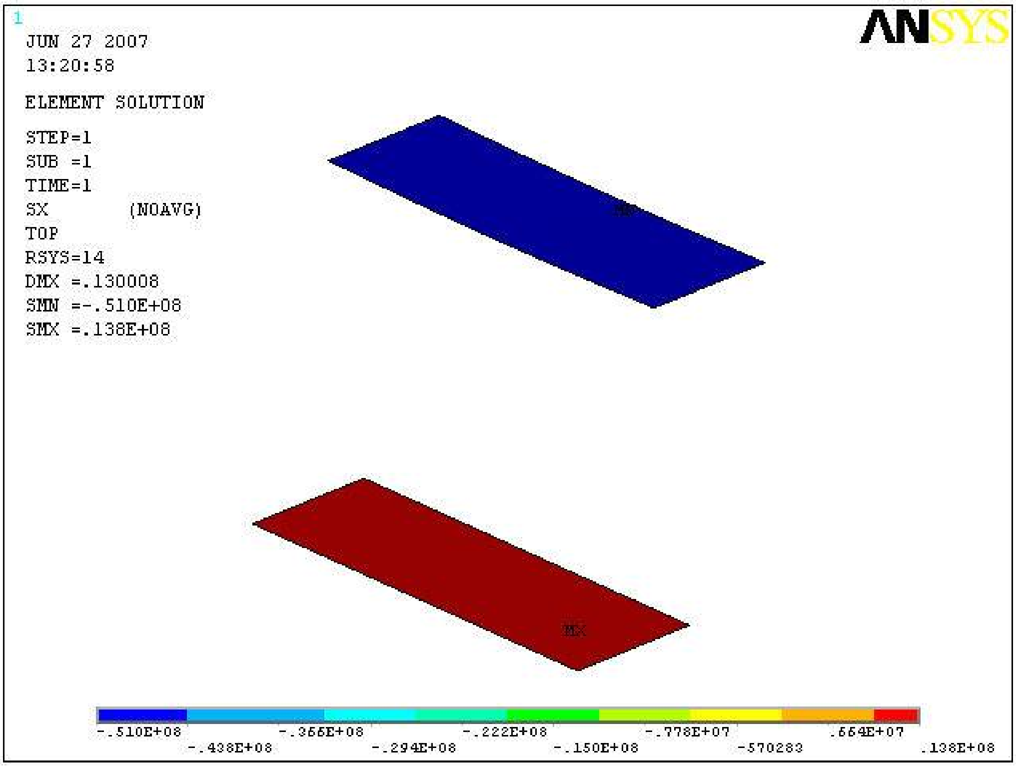
This means that the deflection is within the rule limitations.



```
ELEMENT SOLUTION
SUB =1
TIME=1
SX       (NOAVG)
MIDDLE
RSYS=14
DMX =.130008
SMN =-.437E+08
SMX =.144E+08
```

Figure 12-5 Stress in middle layer of top and bottom flange laminate

The stress level in the middle layer of the top and bottom laminates is illustrated in the figure. The maximum compression stress is located in the bottom laminate at the beam ends. This is due to the boundary condition with prevented translations.



```
JUN 27 2007
13:20:58
ELEMENT SOLUTION
STEP=1
SUB =1
TIME=1
SX       (NOAVG)
TOP
RSYS=14
DMX =.130008
SMN =-.510E+08
SMX =.138E+08
```

Figure 12-6 Stress level at mid span

The stress level at mid span of the hatch is more interesting in this study. A shred section of this area shows the bending stress at the mid span in the top layer of the laminates.

The compression stress in the top side laminate is 51MPa. The maximum allowed compression stress is set to 118MPa.

The tensile stress in the bottom side laminate is 14MPa. The maximum allowed tensile stress is set to 158MPa.

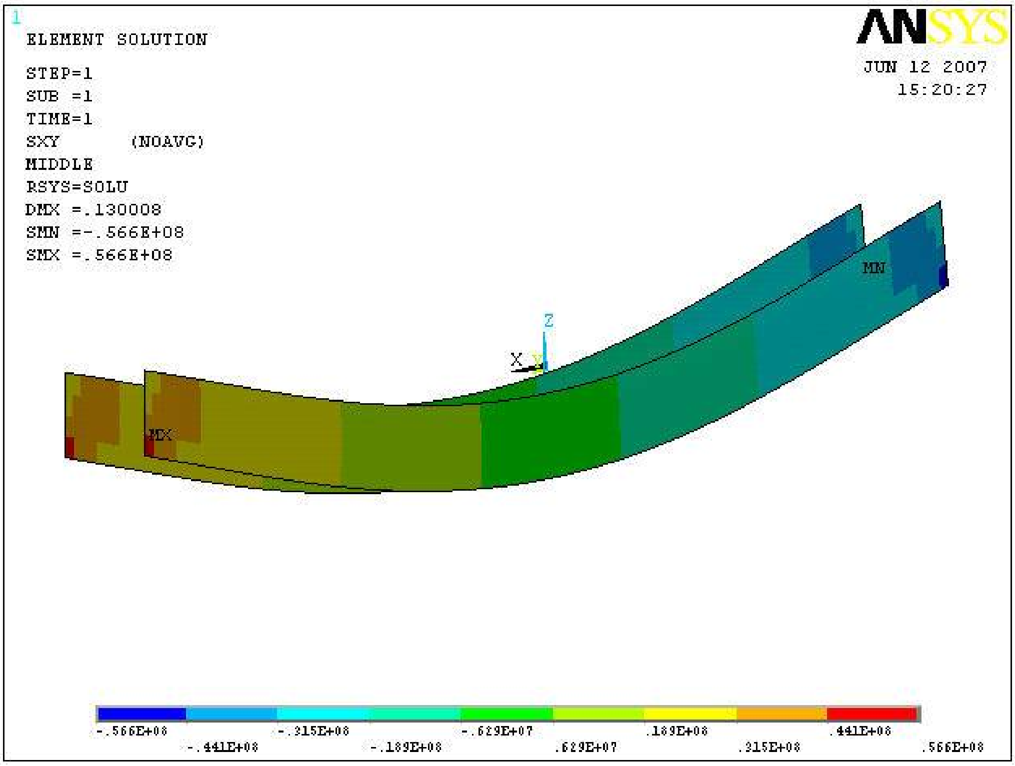


Figure 12-7 Web laminate shear stress, according to DNV criterion

The shear stress shown in above is corresponding to the well known transverse force distribution over a beam subjected to a uniform pressure over the span. Maximum occurs at the ends and no shear at mid span. Maximum shear stress is 57MPa and the maximum allowed shear stress is 82MPa.

12.3.1.6 Summary

The FEM analysis gives the following results for stresses and deflections.

Table 12-3 Stress and deflections; FEM-results

	ACTUAL VALUES	DESIGN VALUES
Tension stress	14 MPa	158 MPa
Compression Stress	51 MPa	118 MPa
Shear Stress	57MPa	82 MPa
Local deflection	4 mm	30 mm
Global deflection	130	208 mm

The result above tells us that the crucial design criteria are the deflection. Large deflections may be unsuitable.

12.3.2 Hatch weight estimates

The estimated weight of each square hollowed section in the cargo hatch is given in Table 12-4.

Table 12-4 Weight of hollow sections in cargo hatch

PART	NO OF	LENGTH (M)	WIDTH (M)	THICKNESS (MM)	KG/M^2	KG/M	WEIGHT (KG)
Top Face plate	1	10,4	0,4	15	19		79
Web plate	2	10,4	0,4	2	3,5		30
Bottom face plate	1	10,4	0,4	9	15,4		64

The weight of this square hollowed section is approximately 180kg. One cargo hatch section will be built up by 16 of these, so the total weight for one hatch section 10,4x6,4 will be approximately 2880kg.

A steel hatch will have the approximate weights shown in the table below:

Table 12-5 Weight of steel hatch

PART	NO OF	LENGTH (M)	WIDTH (M)	THICKNESS (MM)	KG/M^3	WEIGHT (KG)
Face plates	2	10,4	6,4	4	7800	4154
Trans. sides	2	10,4	0,4	4	7800	260
Long sides	2	6,4	0,4	4	7800	160
Stiffeners	10	10,4	0,4	4	7800	1300
Stiffeners	3	6,4	0,4	4	7800	240

Total weight of each hatch section is approximated to 6114 kg. The weight saving will then be 53%. There are nine hatches on the ship so the total save of weight will be 29 ton**.**

The weight of sealing-, tightening-, and battening- device is not included in the calculations above. However it estimated that these weights are remains the same independently of the hatch cover material.

If necessary the cargo hatch can be covered with a wear protection of suitable thickness. If a wear plate, stainless steel with thickness 1,5mm is used, the weight will be increased by approximately 800 kg for each hatch section. It is recommended to use a wear protection material with a lower modulus of elasticity than the glass fibre laminate.

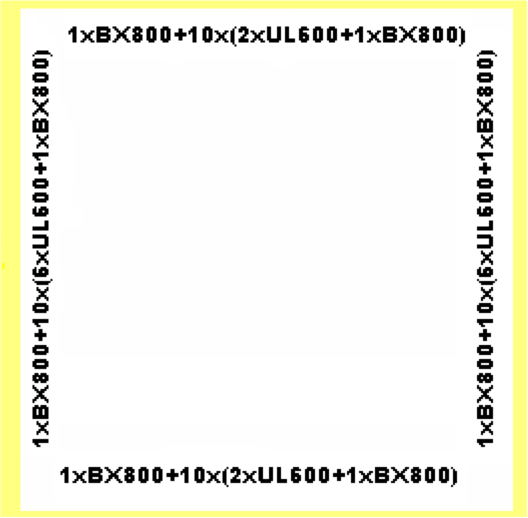
This study shows that it will be feasible to supply a vessel like this with cargo hatches made of glass fibre reinforced polyester. In further studies it will be necessary to focus on the weather tightness of the hatch, and suitable wear protections for the top side laminate.

12.4 Grain bulkhead scantlings

In this study a grain bulkhead made of glass fibre reinforced polyester has been assumed. The design is based on an easy manufacturing and low material costs. The dimensions of each section are based on the detail drawings supplied by the ship-owner.
A bulkhead section will be 11,6 x 1,93 m. The thickness of the bulkhead is 0,24 m.

The design follows the same principle as the cargo hatch cover i.e. a number of square hollowed sections on top of each other.

Minimum amount of reinforcement in the laminates is, according to DNV HSLC&NSC Pt. 3 Ch.4 Sec. 6 A202, for non watertight or tank bulkheads:



$$W = 2500(1 + 0{,}0(84{,}99 - 20)) = 2500\text{g/m}^2.$$

The maximum allowable deflection of the laminate is,
$w \leq 2 \cdot t$
where t is the laminate thickness

The requirement for the bending stress is,
$\sigma_d \leq 0{,}3\sigma_{nu}$

The shear stress criteria is,
$\tau_d \leq 0{,}25\tau_{nu}$

A little trial and error ended up in the following design, 1xBX800+10x (6xUL600+1xbx800) in the flange laminates and 1xBX800+10x(2xUL600+1xBX800) as web laminates. This means a great amount of unidirectional fabrics in the flange laminates and more bi axial, ±45°, fabrics in the web laminates. The UL600 fabrics in the web increase the bending stiffness without taking any space from the hold.

The estimated weight of each square hollowed section in the grain bulkhead is given in Table 12-6.

Table 12-6 Weight of hollow sections in grain bulkhead

PART	NO OF	LENGTH (M)	WIDTH (M)	THICKNESS (MM)	KG/M^2	KG/M	WEIGHT (KG)
Face plate	2	11,6	0,24	30	64		356
Web plate	2	11,6	0,24	16	30		167

A bulkhead section consists of 8 hollowed sections. The weight of the main structural parts in a bulkhead section will then be 4200 kg.

The steel weight of the main structural parts in each grain bulkhead section used at the present is shown in Table 12-7.

Table 12-7 Steel weight of main structural parts in grain bulkhead

PART	NO OF	LENGTH (M)	WIDTH (M)	THICKNESS (MM)	KG/M^3	KG/M	WEIGHT (KG)
Face plate	2	11,6	1,925	6,5	7800		2265
UPE 240	2	11,6				30,2	701
HP 240x10	3	11,6				26,4	919
HP 240x10	3	1,925				26,4	153

The total weight is then supposed to be 4038 kg for each section of the bulkhead, and a total weight of 12114 kg for the steel main structure in the complete bulkhead.

The composite bulkhead in this example has a larger weight than the steel bulkhead. The calculated bending deflection of the composite bulkhead will be approximately 0,4m. An analysis of the steel grain bulkhead gives the bending deflection 0,3m.

In this study the bending deflection and flexural rigidity is the limiting factor. If the requirements of the grain bulkhead are more explicit it will be possible to further optimise the design. Designing against a strength requirement will result in a significant decrease in weight for this bulkhead. It is recommended to perform further studies.

12.5 Deckhouse scantlings

Minimum requirements for amount of reinforcement in the sandwich panel skin laminates used in the deckhouse structure are taken from DNV Rules for HSLC&NSC Pt.3 Ch.4 Sec.5 A106.

Table 12-8 Minimum reinforcement requirement

	MINIMUM AMOUNT REINFORCEMENT (G/M^2)	MINIMUM NUMBER OF PLIES (FABRIC 800 G/M^2)
Outside deckhouse	2214	3
Accommodation decks	1600	2
Weather decks	1600	2
Structural bulkheads	1200	2

The core material used in the superstructure is balsa with density 100kg/m^3 for all panels except the first tier of the front bulkhead where the density 279kg/m^3 is used. The higher design pressure level is demanding an increase in core material density for this area.

The fabrics used in the panels are biaxial 0/90 800g/m^2, (BLT800). The panel design in the different parts of the deckhouse is listed below.

Table 12-9 Deckhouse panel design

RAISED QUARTER DECK	***SKIN LAMINATE***	***MAXIMUM PANEL FIELD SIZE***	***BALSA CORE DENSITY (KG/M^3)***	***BALSA CORE THICKNESS (INCH)***	***SANDWICH PANEL WEIGHT (KG/M^2)***
Front	5xBLT800 / 5xBLT800	2,6 x 2,1 m	279	2”	**26**
Sides	3xBLT800 / 3xBLT800	2,6 x 2,3 m	101	2”	**13**
Aft	3xBLT800 / 3xBLT800	2,6 x 3,2 m	101	2”	**13**
Bulkheads	2xBLT800 / 2xBLT800		101	1”	**8**
Funnel	3xBLT800 / 3xBLT800		101	2”	**13**
Boat deck	*Skin Laminate*	*Maximum Panel field size*	*Balsa Core density (kg/m^3)*	*Balsa Core thickness (inch)*	***Sandwich panel weight (kg/m^2)***
Front	3xBLT800 / 3xBLT800	2,2 x 5,7 m	101	1,5”	**11**
Sides	3xBLT800 / 3xBLT800	2,2 x2,4 m	101	1”	**10**
Aft	3xBLT800 / 3xBLT800	2,2 x 2,5 m	101	1”	**10**
Acc. deck	3xBLT800 / 3xBLT800	4,0 x 5,4 m	101	2”	**13**
Bulkheads	2xBLT800 / 2xBLT800		101	1”	**8**
Funnel	3xBLT800 / 3xBLT800		101	2”	**13**

BRIDGE DECK	*SKIN LAMINATE*	*MAXIMUM PANEL FIELD SIZE*	*BALSA CORE DENSITY (KG/M^3)*	*BALSA CORE THICKNESS (INCH)*	*SANDWICH PANEL WEIGHT (KG/M^2)*
Front	3xBLT800 / 3xBLT800	1,0 x 20,0 m	101	1”	**10**
Sides	3xBLT800 / 3xBLT800	1,0 x 20,0 m	101	1”	**10**
Aft	3xBLT800 / 3xBLT800	1,0 x 20,0 m	101	1”	**10**
Acc. deck	3xBLT800 / 3xBLT800	4,0 x 5,4 m	101	2”	**13**
Wet deck	3xBLT800 / 3xBLT800	4,0 x 5,4 m	101	2”	**13**
Bulkheads	2xBLT800 / 2xBLT800		101	1”	**8**
Deckhouse top	3xBLT800 / 3xBLT800	4,0 x 5,4 m	101	2”	**13**
Funnel	**3xBLT800 / 3xBLT800**		**101**	**2”**	**13**

12.5.1 Deckhouse weight estimates

The approximate structural weight of the deckhouse is presented below. All equipment such as windows, doors, doorframes etc. is excluded in this weight calculation.

The design presented is based on minimum requirements in accordance to the classification rules. This is to be regarded as a baseline for a weight study.

Section	Infusion panels			Stiffeners	
	Net Weight [kg]	No.	Net Area [m2]	Net Weight [kg]	Net length [m2]
Raised quarter deck	2648	3	202	0	0
Boat deck	2514	3	213	0	0
Bridge deck	1881	2	156	0	0
Total	7043	8	571	0	0
Resin fill	525				

Component	Weight	Area	Length
Overlap	176	23	
Attachment laminate	317		
Joints	623		367
Girders	0		0
Pillars	0		0
S/C-joint	400		40

CORE	Net [m2]	Net [kg]	unforeseen	Net [m2]	Net [kg]
279/2"	24	79,2	5%	25	83
101/2"	367,5	1102,5	5%	386	1158
101/1,5"	17	74,8	5%	18	79
101/1"	162	1158	5%	170	1216

GRP	Net [kg]	unforseen	Net [kg]
BLT800	3963	5%	4161
BX450	0	5%	0
Resin	2647	5%	2779

Str.Adh	Net [kg]	unforseen	Net [kg]
FI177	144	5%	151

Steel	Net [kg]	unforseen	Net [kg]
Pillar	0	5%	0
Foundation	400	5%	420

Insulation	Net [kg]	unforseen	Net [kg]
Fire	2853	5%	2995

COMPOSITE WEIGHT [ton]	**10,1**
FIRE INSULATION [ton]	**3,0**
VCG [mm. above BL]	**11539**

12.5.2 Comparable steel deckhouse weight

The weight of a steel deckhouse can be estimated in the following manner.

Steel plates:
Assumed average plate thickness: 4mm
Total Plate Area: 571m2
Plate weight: **17816 kg**

Stiffeners:
Assumed stiffener type: HP100x6
Stiffener weight: 7,33 kg/m
Stiffener spacing: 500mm
Stiffeners, side-, aft- and front bulkheads: 2111kg+1503kg+1049kg=**4663kg**
Stiffeners, decks: 1613kg+1239kg=**2852kg**

Estimated steel weight: **25,5 ton**

Since the composite weight above is 10,1 ton, the weight saving ratio, in this example, is estimated to be approximately 60% or 15,4 ton.

12.6 Summary

The study shows that it may be feasible to use composite material in the cargo hatch and the deck house structure without any major changes in the design. The grain bulkhead design needs to be adjusted to achieve the most benefit from changing material to composite. Further studies within the area will result in a more optimised design with better weight saving ratio.

In this project a balsa core was used in the deckhouse. The reason for this is that this material has been used for several years within the marine application industry. The thickness of the balsa used in this example is not a standard thickness. Today there are several other core materials, approved by classification societies. Such materials are different foams based on phenol, PVC, etc.

Balsa core are often regarded to as a better material in a fire protective point of view. This have also been verified in fire tests on sandwich panels with a core thickness of 1,75 inch. The ships for whom those panels where intended to are considerable larger. In the design of this Trollmax ship a thinner core, 1 inch, has been used. This means a reduction in weight but significant properties concerning fire, noise, vibrations, etc. must be further studied.

In this example a single skin design has been studied for the cargo hatch. It may be possible to use a sandwich design with a suitable core, this has not been studied.

13 LCCA and LCA for lightweight constructions at sea

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13.1 Introduction

Within the Swedish LÄSS project the influence of lightweight design has been studied for several concept ships. Both aluminium material and fibre composite material in form of sandwich (from here designated composite) is included as replacement of conventional steel material for structural design. The overall goal for the project is to improve the efficacy of marine transport by reducing the weight of ships by 30 %, with unchanged performance, and with a total cost reduction of 25 % over the life cycle.

The use of composite has increased since the middle of 1980ies in shipbuilding, especially in military ships in order to reduce acquisition and maintenance cost and to improve performance both structural and operational[1].

To change material and manufacturing methods from well know materials and manufacturing methods means a sort of system change which needs to be carefully considered. At the same time also demands on decrease of product development times combined with a more complex market, with increasing costs for fuel, puts even more pressure on the producer. Thereby it becomes more and more important to consider the value for money in a long time perspective. This can be done by studying a system or a product with a life cycle cost analysis, LCCA. Here the cost over the entire life for a product can be studied, not just the acquisition cost which traditionally has been of large interest. The costs included as well as design and production, are for example distribution cost, operation cost, maintenance cost and cost for disposal.

For a ship structure, steel is the most economical material when just looking at the manufacturing cost. But from a life cycle perspective the cost for operation and maintenance are as important as the acquisition cost. A decrease in structural weight, by using a light weight material, can result in reduced fuel consumption, increased payload, increase of speed and increased range. All these factors then will affect the cost during operation. Also environment will benefit through lower emissions due to reduced fuel consumption. This has been demonstrated in a life cycle study for the hull structure of a high speed ferry[2] where cost and energy consumption was compared for three structural materials, steel, aluminium and composite.

LCCA will here be investigated and compared for the following four ship structures:

- High speed craft; hull structure in aluminium (origin), composite
- High speed ferry; superstructure, aluminium (origin), composite
- Ro-Ro ship; superstructure in steel (origin), aluminium
- Ro-Pax ferry; superstructure, steel (origin), composite

13.2 Description of life cycle cost analysis

Several different models of LCCA exist. One interesting definition of life cycle cost analysis, LCCA is the following[3]:

"Life cycle cost analysis may be defined as a systematic analytical process for evaluating various designs or alternative courses of actions with the objective of choosing the best way to employ scarce resources."

In this type of LCCA the environmental costs are especially considered. With the increasing interest in environmental issues this type of LCCA increases and is named life cycle environmental cost analysis. In a conventional LCCA, as used in this study, the cost analysis aims to cover costs over the complete life cycle for a system or a product and as a result try to reduce the overall cost. Though, this does not mean that a conventional LCCA will not be beneficial for the environment, which already has been mention in the study of the high speed ferry[2].

In this work the LCCA model of Woodward is used[4] with some minor changes in the methodology. The origin methodology includes eight steps:

1. Establish operation profile
2. Establish utilisation factors
3. Identify all cost elements
4. Determine the critical cost parameters
5. Calculate costs at current price
6. Escalate current prices at assumed inflation rates
7. Discount all costs to the base period
8. Sum discounted cost to establish the present value

In this study the operation profile is together with maintenance considered as the utilization factors. The critical cost parameter, step 4, is not considered in this study. In the origin model this means to include time periods of downtime for failure. In this LÄSS-study a sensitivity analysis is included which is not included in the Woodward model.

The utilization factor for the studied structures differs. For the high speed craft and the high speed ferry the decrease in weight is utilized as decreased fuel consumption. For the Ro-Ro ship and the Ro-Pax ferry the decrease in weight instead is used to increase the load capacity. This means that the different versions have the same fuel consumption.

13.2.1 Time value of money

Money has a time dependent value, meaning that the sum of money paid today for a product or service does not have the same value in the future, due to inflation. On the other hand well invested money will grow.

Therefore it is of importance to specify the year when the money is spent. Here all costs are first presented at current price (present cost). The future cost of an investment is calculated considering the inflation rate and time in form of year as t, see Equation 1.

$$\text{Future cost} = \text{present cost}\ (1 + \text{inflation rate})^t \qquad \text{Equation 1}$$

Then the future cost, needs to be discounted back to a base period resulting in the present value which determines the amount of money needed today to pay for future cost, including the interest rate, see Equation 2.

Present value = future cost $(1 + \text{interest rate})^{-t}$ Equation 2

By combining Equation 1 and 2 the present value is determined from the present cost, see Equation 3.

Present value = present cost $(1 + \text{inflation rate}/1 + \text{interest rate})^{t}$ Equation 3

.

The inflation rate used in these studies is set to 3%, which is the target for inflation plus 1%, defined by the Swedish central bank[5]. The target for inflation is 2%.

Based on Euribor, Euro Interbank Offered Rate[6], the interest rate is set to 4% based on the period spring 2007. Most of the cost used in this study is date from spring 2007. Euribor interest rate is based on the average interest rates at which a panel of 57 European banks lends money to one another.

13.2.2 Time period of cost and break-even analysis

The distribution of costs is spread over the life cycle starting with initial costs. These are including design, planning and development of manufacturing devices. These costs are spread over the first year. During the second year the costs for production of the structure follows. Next follows the time period of operation which is constant during the assumed operation life. On top of this cost comes the maintenance cost, starting from year two of operation. Finally the ship is disposed resulting in a cost assumed for one year. The base period for the cost is set to the start of the year.

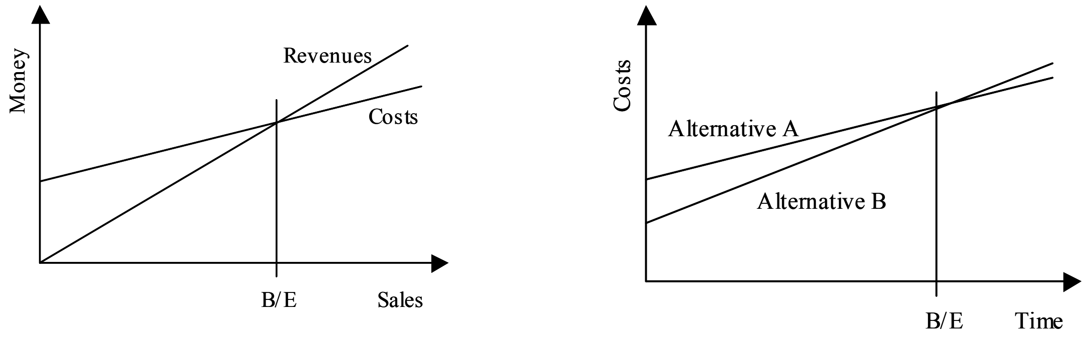


Figure 13-1 Alternatives for assessment of break-even point, B/E[2].

The break-even point is usually defined as the point where the income and the cost are the same, the profit is zero, see Figure 13-1, to the left. However, for comparing different alternatives the time when the costs for the two versions are equal defines the break-even point, as illustrated in Figure 13-1 to the right.

13.3 High speed craft

This 24 m high speed craft for transport of passenger is based on an existing military ship with hull in aluminium material. This ship, developed by the Swedish Defence Material Administration, was converted to civil passenger use[7], Figure 13-2.

Based on this reference ship new versions of hulls were designed in composite material[8]. All hulls are designed according to the DNV HSLC-code with the same specification and thereby comparable. The reduced structural weight for this high speed craft is utilized as lower fuel consumption.

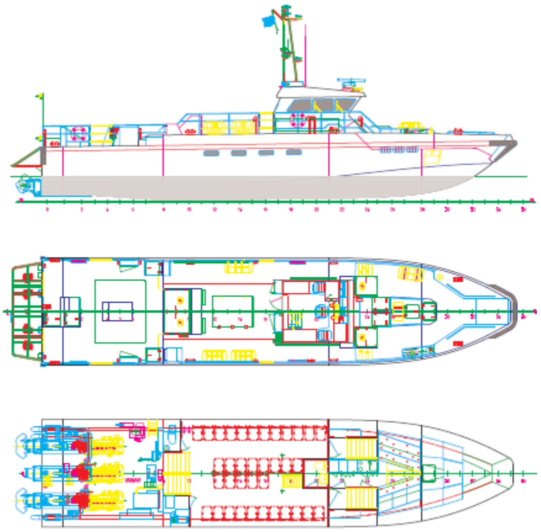


Figure 13-2 High speed craft, civil version with three jet propulsions.

The following versions are included in the LCCA:

- Version 0 – Aluminium – three water jet propulsions
- Version 1 - Sandwich with glass/vinylester – three water jet propulsions
- Version 3 - Sandwich with carbon/vinylester – three water jet propulsions
- Version 3A – as version 3 but with two water jet propulsions, 33% reduced fuel tank

The ship specifications include the building of totally 20 ships for each version and with economical life length set to 20 years.

13.3.1 Data for life cycle cost analysis

The life cycle cost is divided in four main parts; initial cost, production cost, utilization cost and cost for disposal. These parts are then further divided into cost for design, structural material, equipment, fuel etc.

Production cost for both aluminium and composite versions was provided by the Swedish Shipyard, Swede Ship Composite AB. This cost calculation is based on manufacture of a series of 20 ships. In

Table 13-1 a summary of the manufacturing cost for one ship is presented. More detailed information is found in Appendix A, Table A-I and Table A-II. The cost was calculated with 4% interest rate and 5% inherent profit.

Initial costs include cost for development and different equipment for manufacturing. Materials cost contains structural material and material for insulation. The equipment cost is decreased for version 3A due to two engines compared to three for the other versions. Cost for disposal of waste from manufacturing is not included.

Table 13-1 Production cost for one complete ship.

Cost element [kSEK]	Version 0	Version 1	Version 3	Version 3A
Initial	350	250	250	250
Material (gross)	858	1 015	1 605	1 540
Man-hour total	4 265	2 110	2 090	2 090
Equipment	11 400	11 000	11 000	8 500
Certification	500	500	500	500
Total production	**17 373**	**14 875**	**15 445**	**12 880**

The fuel consumption was calculated from the utilization cycle in combination with the ship performance, see Appendix A, Table A-III and Table A-IV. The ship performance was based on measured data from the military ship in combination with calculations.

Costs for the operation phase of the ship includes, fuel consumption and maintenance over 20 years, Table 13-2 Cost for fuel, diesel, is set to 10 SEK/liter based on Swedish statistics[9]. Maintenance cost is estimated from experience, were the higher cost for the aluminium hull is explained by problems with fatigue and corrosion.

Table 13-2 Cost for operation over 20 years.

Cost element [kSEK]	Version 0	Version 1	Version 3	Version 3A
Fuel	138 900	134 620	128 580	110 200
Maintenance	3 000	2 200	2 200	2 200
Total use	**141 900**	**136 820**	**130 780**	**112 400**

The rest value after 20 years of service was estimated by the Swedish Shipyard. Composite hulls have the same value after 20 years as when it was new. Regarding the value for the aluminium hull it has decreased with 30% or more from the origin value.

13.3.2 Cost at current price

In Table 13-3 the overall result with cost at current price for the four life cycle phases is presented. These phases are initial, production, operation and rest value.

Table 13-3 Total cost at current price for high-speed craft versions, including rest value.

Cost element [kSEK]	Version 0	Version 1	Version 3	Version 3A
Initial	350	250	250	250
Production	17 023	14 625	15 195	12 630
Operation	141 900	136 820	130 780	112 400
Rest value	-12 161	-14 875	-15 545	-12 980
Total	**147 112**	**136 820**	**130 680**	**112 880**

Figure 13-3 illustrates the accumulation of costs for the four versions.

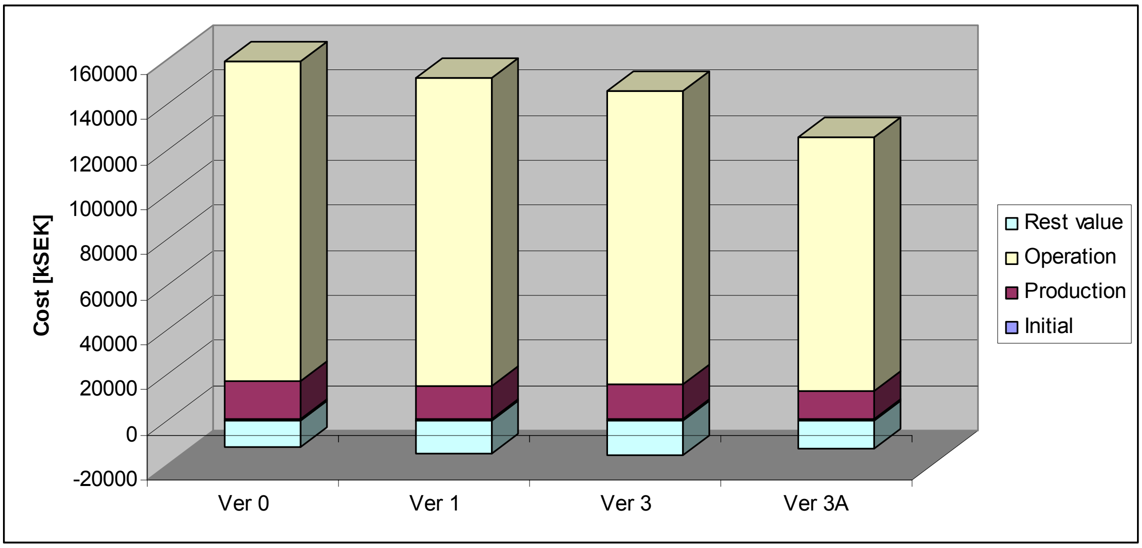


Figure 13-3 Life cycle cost at current price for different versions of high-speed craft.

The lowest life cycle cost at current price is presented by version 3A, which presents 15-20% lower operation cost due to decreased fuel consumption. Since the structural weight (including insulation) is decreased with more than 40%, comparing ver. 0 to ver. 3A the engine power is reduced. This results in secondary effects as reduced fuel tank which also reduces weight and production cost.

13.3.3 Present value of future cost

Here the time value of money is calculated based on the current price as described in 13.2. Calculated data is found in Appendix A Table A-IV and Table A-V.

The accumulated present value over all life cycle phases for the four versions of the high speed craft is illustrated in Figure 13-4.

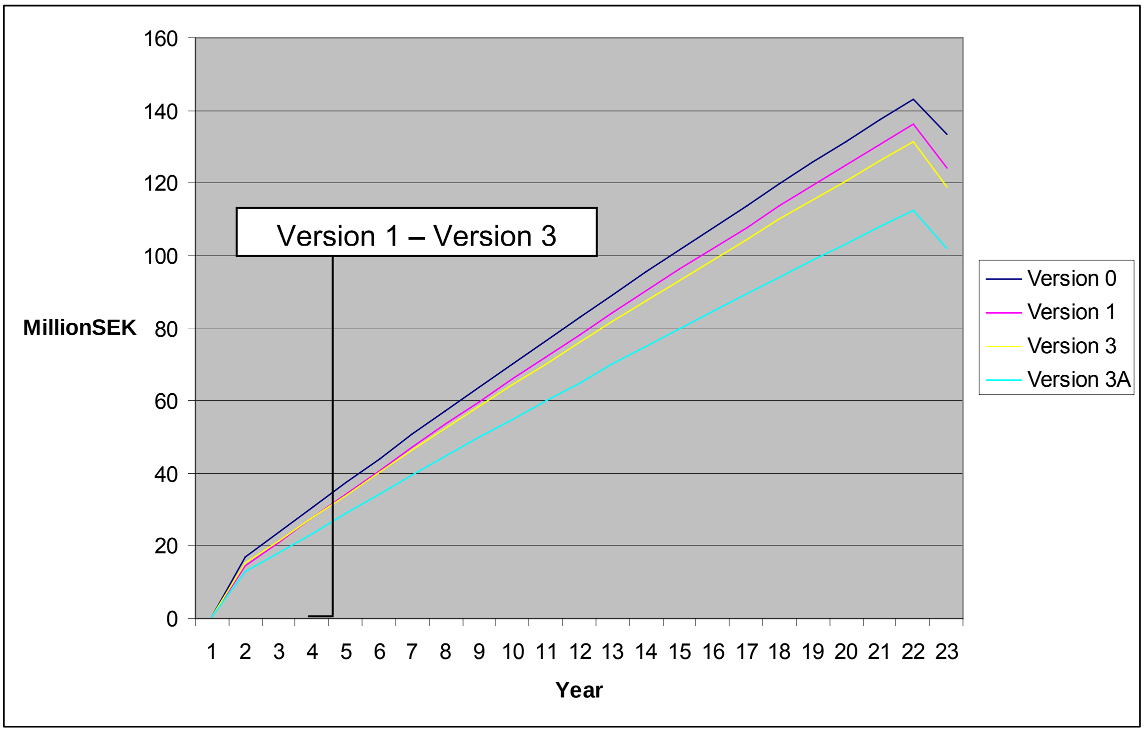


Figure 13-4 Accumulation of costs at present value in million SEK.

The accumulated cost for version 3A is lower than all of the other ship versions during the complete life cycle. A break-even point is identified according to the method described by the graph to the left in Figure 13-1. This point appears around year 4,5 comparing version 1 (sandwich/glass fibre) and version 3 (sandwich/carbon fibre). This is just after the start of operation phase since the cost for production of version 3 is slightly higher than for version 1.

13.3.3.1 Sensitivity analysis

A sensitivity analysis is meant to investigate the influence of different input parameters within the LCC. Here the influence of an increase in fuel cost is investigated. The fuel consumption is very large and stands alone for around 95% of the total LCC at current price, with fuel cost 10 SEK/litre. Since the fuel cost in the near future will increase it is of large concern to decrease the consumption. Comparing version 0 to version 3A the fuel consumption is decreased with around 20% during operation, see Table A-IV in Appendix A. One other very important fact is that the environmental effects decrease with lower fuel consumption.

In Figure 13-5 the influence of a fuel cost of 20 SEK/litre is illustrated. Data is presented in Appendix A, Table A-VI and Table A-VII. Compared to Figure 4.3 the total LCC is almost doubled. The break-even point between version 1 and version 2 is decreased from 4 years to 3 years, in favour for the carbon fibre sandwich with lower fuel consumption.

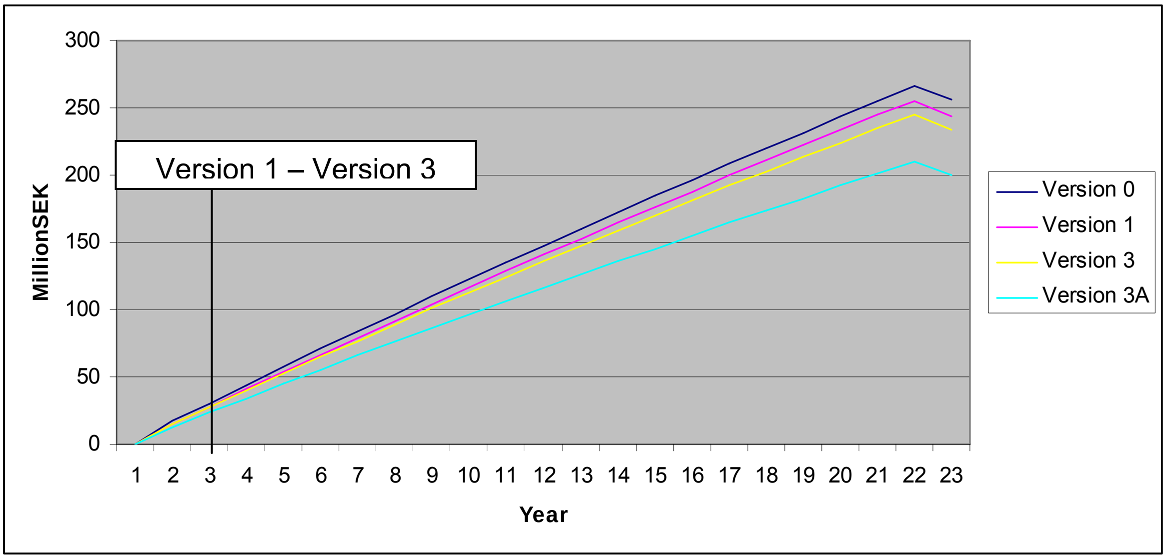


Figure 13-5 Accumulation of costs at present value in million SEK

The influence of other cost parameters is not studied since the difference between version 0 and version 3A is so obvious. A more thorough analysis was made regarding the influence of production cost including the share of different materials as insulation material and structural material, showing clearly the decrease in production cost with 26% for version 3A compared to version 0[10]. Even if the production cost for the optimised carbon sandwich version 3A increases with 50% the total life cycle cost is lower.

13.4 High-speed ferry – superstructure

In this second LCCA the superstructure of a high-speed ferry is studied. The ship Stena Carisma, is one of several ships within the HSS series, developed and owned by the Swedish shipping company Stena Line. These ships are catamarans with a maximum length of 124 meter, transporting passengers and cars.

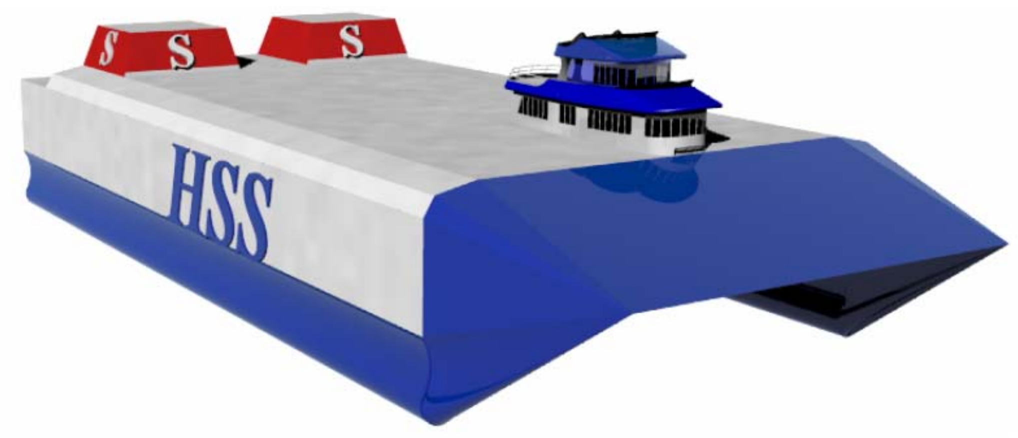


Figure 13-6 Stena Carisma high speed ferry.

A structural analysis of a section of the superstructure of Stena Carisma or HSS 90 ferry has been made[11]. This ferry is 88 meter long and travels between Gothenburg in Sweden and Fredrikshavn in Denmark. The structural requirement is to save weight by using composite materials. Thereby fuel can be saved to decrease costs and environmental impact during operation.

The following versions of the superstructure are included in the LCCA:

- Version 0 – Aluminium
- Version 1 - Sandwich with glass/vinylester and PVC core
- Version 2 - Sandwich with carbon/vinylester and PVC core

The operation time for the structures is 25 years. In this study only the structural material and the insulation material is included. The furnishing and equipment is assumed to be the same for all versions and is not included since the study is a comparison. Also the hull is the same for all versions and not included in the study.

13.4.1 Data for life cycle cost analysis

Cost information for the aluminium superstructure, which is the origin material, was given by Stena and also collected from earlier work on a high speed ferry, [2], as well as information from SSPA Sweden AB who worked with the Ro-Ro ship in the following chapter. For the two composite versions, a cost analysis for the production was made by Kockums AB, Karlskronavarvet, who is a possible manufacturer of a superstructure in sandwich material due to several years of experience.

In Figure 13-4 the costs for manufacturing of the three versions is presented, more detailed information can be found in Appendix B, Table B-I and Table B-II.

The initial cost comprises design for all versions and for the composite version also cost for the manufacturing equipment. Material cost includes structural material and insulation. The aluminium structure needs insulation against noise while the composite structure needs insulation against fire. For the aluminium structure the material price also includes man-hour cost. The initial cost for version 0 is set to 10% of manufacturing cost. Cost for disposal of manufacturing waste is not included.

Table 13-4 Cost for manufacture of superstructure for high speed ferry.

Cost element [kSEK]	Version 0	Version 1	Version 2
Initial	560	946	946
Material (brutto)	5 781	4 214	10 259
Man-hour total	-	12 016	11 966
Total production	**6 341**	**17 176**	**24 667**

Information about fuel consumption was received from Stena Line and is the total fuel consumption for the complete ferry. The fuel cost is set to 350 USdollar/ton, which was the price in spring 2007. According to Stena Line the maintenance cost is zero for the aluminium superstructure. The same is assumed for the composite versions. Total cost for operation is presented in Table 13-5.

Table 13-5 Cost during operation for high speed ferry.

Cost element [kSEK]	Version 0	Version 1	Version 2
Fuel	615 550	547 844	480 128
Total operation	**615 550**	**547 844**	**480 128**

After 25 years of operation the structure is supposed to be phased out. For the aluminium structure material recycling is used for the aluminium, receiving 500 Euro/ton, September 2008[12] and landfill for the insulation generating a cost of 1000 SEK/ton[13]. For the composite structure material recycling does not yet exists, instead incineration with energy recovery is assessed as a possible alternative[14]. The insulation material is assumed to be put on landfill. Though, the best alternative for this material would be material recycling if possible. The cost for disposal of the composite structure is based on information from scrapping a Danish composite ship[15], with the cost of 180 Euro/ton (year 2006). In this cost activities as cutting, incineration and landfill is included. In Table 13-6 the cost for disposal is presented. Regarding environment regulations, there has been a lot of focus on disposal issues especially concerning landfill. More details for disposal cost are presented in Appendix B, Table-IV.

Table 13-6 Cost for disposal of superstructure

Cost element [kSEK]	Version 0	Version 1	Version 2
Disposal	-234	113	95
Total disposal	**-234**	**113**	**95**

13.4.2 Cost at current price

In Table 13-7 and Figure 13-7 the summation of all cost elements at current price is presented for the three versions of the superstructure. The costs are divided into the four phases; initial, production, operation and disposal.

Table 13-7 Total cost of superstructure for high speed ferry.

Cost element [kSEK]	Version 0	Version 1	Version 2
Initial	560	946	946
Production	5 781	16 230	22 225
Operation	615 550	547 844	480 128
Disposal	-234	113	95
Total cost	621 657	565 133	503 394

In Figure 13-7 only the cost for production and operation are visible since the other two, initial cost and disposal cost, comprise less than 1% of the total cost.

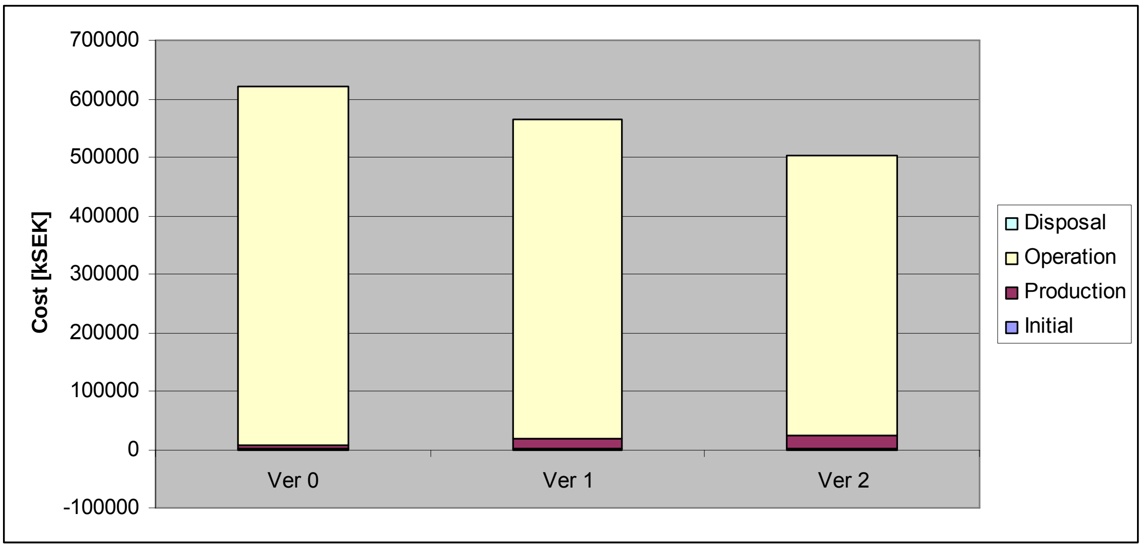


Figure 13-7 Total cost at current price for three versions of high speed ferry superstructure.

Totally dominating is the operation cost with 99% of the total cost for the origin superstructure. This part is slightly lower for the composite version with about 95% for the carbon composite superstructure due to higher production cost. But to remember is that the production cost as well as initial and disposal cost, is calculated for the superstructure without machinery, furnishing etc. while the operation cost is for the complete ferry.

13.4.3 Present value of future cost

In this chapter the present value of future cost is calculated as described in 13.2. The result from the summary of the present value of future cost is illustrated in Figure 13-8. All numbers behind the result are presented in Appendix B Table B-V. Highest total accumulated cost is shown by version 0, the aluminium superstructure. Though, this structure presents the lowest costs until around year 5 at the break-even point.

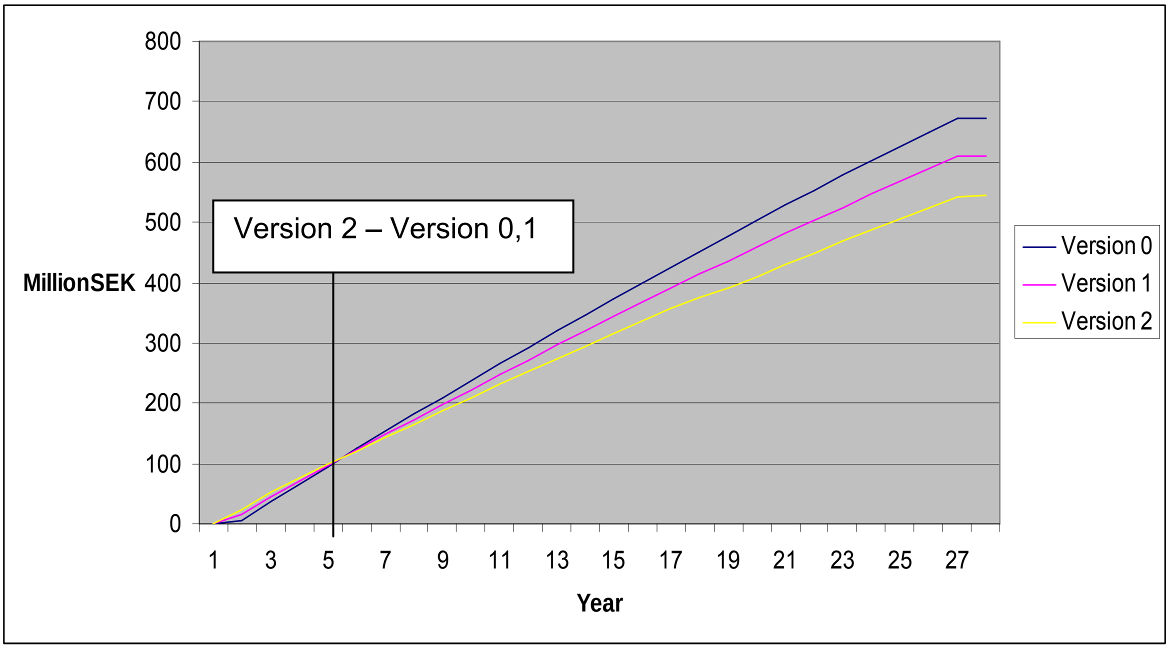


Figure 13-8 Accumulation of costs at present value in million SEK. Fuel price = 350 $/ton

At the break-even point the costs for both sandwich structures increases slower since the fuel consumption is less than for the steel structure. The lowest accumulated cost is shown by version 2, the carbon fibre sandwich structure before the break-even point.

13.4.3.1 Sensitivity analysis

As for the high speed craft also here the influence of fuel cost is of large interest. A future price of 700 $/ton is investigated, a doubling from the analysis in earlier part. The result is presented in Figure 13-9 and figures behind is found in Table B-VI in Appendix B. The break-even point has now moved from around 5 years (year 3 of operation) to 4 years (year 2 of operation). Since the fuel price has large influence the total accumulated cost is also doubled.

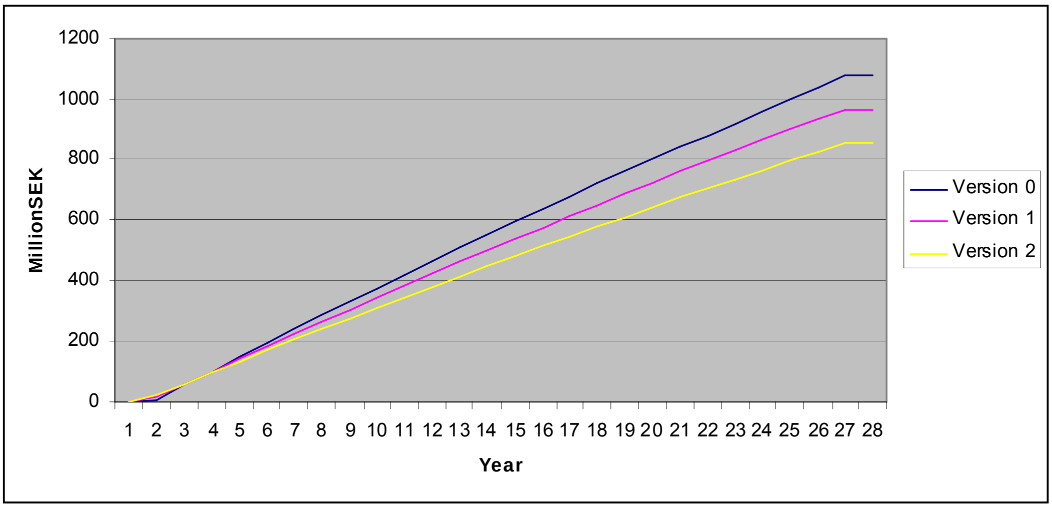


Figure 13-9 Accumulation of costs at present value in Million SEK. Fuel price = 700 $/ton.

Also the influence of material cost is investigated, comparing version 0 to version 2. For version 2 the carbon fibre price is increased with 100%, fuel price 350 $/ton. In Figure 13-10 and Table B-VII, the result show the break-even point at year 6,5, (year 4,5 of operation). Comparing with Figure 5.3 the difference is 1,5 year. This only illustrates how material price can influence the position of the break-even point. An other possible scenario is an increase of aluminium price which then will favour version 2 compared to version 0.

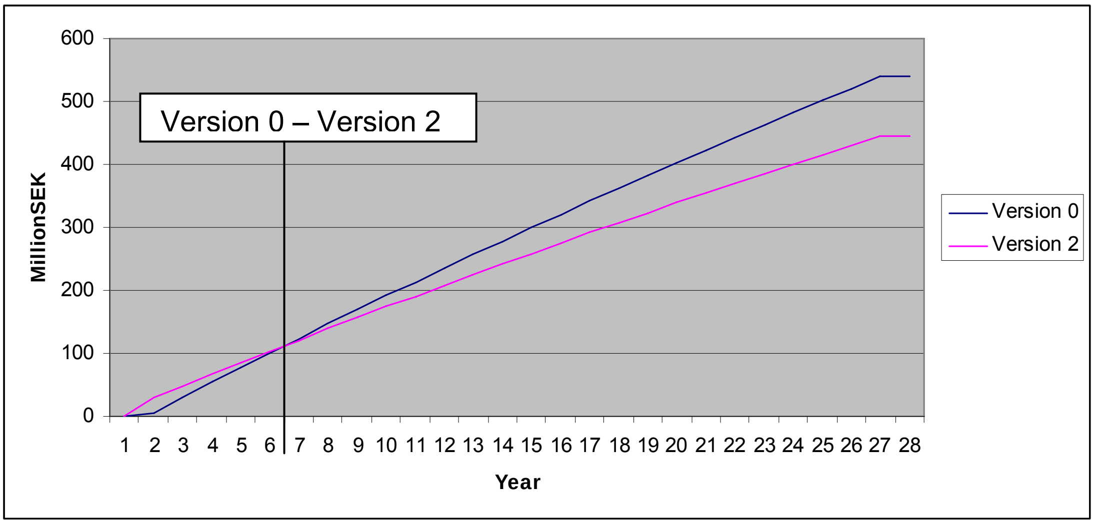


Figure 13-10 Accumulation of costs at present value in Million SEK, carbon price increased. Fuel price = 350 $/ton.

13.5 Ro-Ro ship – superstructure

Also here the study is restricted to the superstructure and in this case the ship is of Ro-Ro type. The specific ship, MS Undine see Figure 6.1, is a car carrying ship of 200 m length, built for Wallenius Marine AB.

Figure 13-11 Ro-Ro ship for car transport.

For this structure the consequences of replacing the origin structural material, steel with aluminium is investigated. Design studies were made for several concepts[16] and in this LCCA the following versions are included:
Version 0 – Steel-2
Version 1 – Aluminium-2

Length of period for operation time is set to 35 years for the two versions. The saved weight is here used to increase the payload capacity which results in an LCCA with the same fuel consumption for the two superstructures. In this case the saved weight in the aluminium version is utilized with an extended garage of the superstructure and increased payload.

13.5.1 Data for life cycle cost analysis

Information about cost for the origin steel structure and the new aluminium concept was based on structural design analysis made by SSPA[16] and also through discussions and meetings with Wallenius Marine AB and SSPA.

In table 6.1 initial cost and cost for manufacturing are presented. The initial cost, development, design etc., is estimated to 10% of the structural material cost. In material cost the following costs are also included, man hour, water cutting and 15% material waste.
The cost for steel is set to 2,5 $/kg and the cost for aluminium is set to 15 $/kg[16].

Table 13-8 Cost for manufacture of superstructure for Ro-Ro ship.

Cost element [kSEK]	Version 0	Version 1
Initial	956	2 505
Material (structural)	9 561	25 051
Insulation	132	171
Total production	**10 649**	**27 727**

More detailed information about cost is found in Appendix C, Table C-I.

During the operation phase only fuel consumption is included in this study. The maintenance is assumed to include the same activities as repainting, cleaning etc. for the two versions resulting in the same cost and therefore not included in this analysis. If the complete ship would have been studied the maintenance could have differed due to fatigue and corrosion of the hull. These problems are not expected to occur at the same extent for the superstructure.

The fuel consumption is the same for the two versions since the saved weight is utilized as increased payload., see Table 13-9. The fuel cost used is 350 $/ton, which was the cost when the ship production costs was analyzed.

Table 13-9 Cost for operation of Ro-Ro ship.

Cost element [kSEK]	Version 0	Version 1
Fuel	1 203 383	1 203 383
Total operation	**1 203 383**	**1 203 383**

Regarding disposal Wallenius Marine AB has the intention of reuse of their structures as much as possible, since this is the best option considering environmental effects and perhaps also when it comes to economy. This means that the superstructure must be refurbished etc. but this cost is considered to be the same for both versions, steel as well as aluminium.

As already mentioned the saved weight for the light weight structures is utilized through an increase in payload. Therefore the saved weight is calculated and added to the amount of payload capacity in the origin structure, see Table 13-10. The ship then transports this payload a specific length over the operation time which is 35 years.

Table 13-10 Payload capacity for the Ro-Ro superstructure.

	Version 0	Version 1
Saved weight [ton]	-	281
Payload capacity [ton]	5 890	6 171
Transport length/year [km]	1,6 E+5	1,6 E+5
Payload/year [tonkm/year]	942,4 E+6	987,4 E+6
Payload 35 year [tonkm]	3,30 E+10	3,46 E+10

The difference in payload capacity over 35 year is around 1 600 million ton.

13.5.2 Cost at current price

In Table 13-11 and Figure 13-10 the summation of all cost elements at current price is presented for the two versions of the Ro-Ro superstructure.

Table 13-11 Total cost superstructure for Ro-Ro ship.

Cost element [kSEK]	**Version 0**	**Version 1**
Initial	956	2 505
Production	9 693	25 222
Operation	1 203 383	1 203 383
Total cost	1 214 132	1 231 110

The dominating cost is the operation cost, clearly illustrated in Figure 13-10, representing more than 99% of the total cost. This is not a completely true figure, it should be slightly lower, since the cost for material and manufacturing of the hull structure is not included..

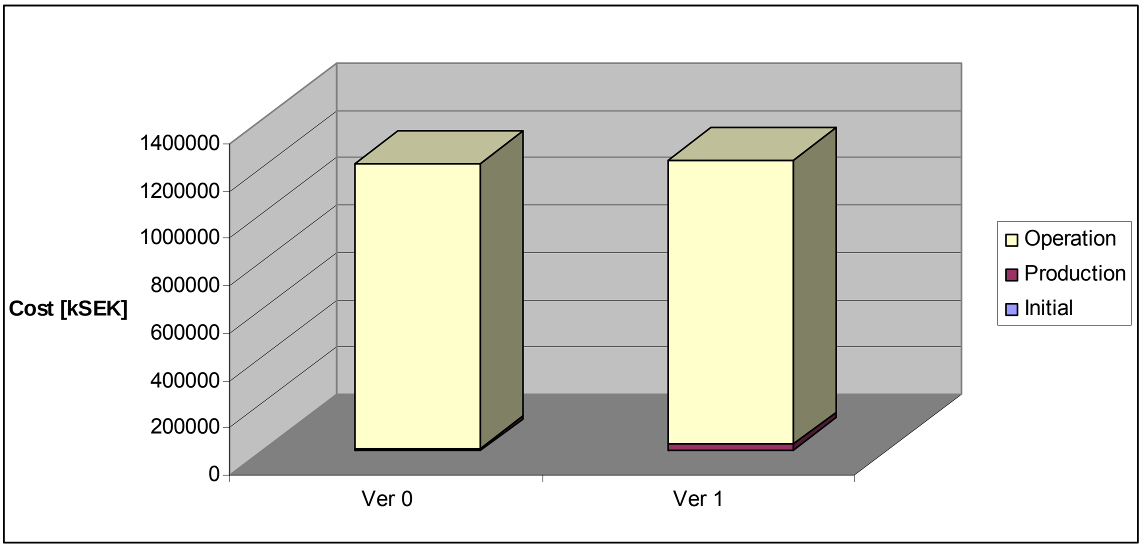


Figure 13-12 Total cost at current price for Ro-Ro ship superstructure.

The cost difference between the origin steel version 0 and the aluminium version 1 is 17,1 million Swedish Crones coming from the higher production cost of the aluminium superstructure. The break-even point is calculated using the method illustrated in Figure 3.1 to the right, comparing cost over the complete life cycle for the two versions, not including revenues. The cost difference is related to the transported gods in form of cost per tonkm. The increased cost for the aluminium version is then related to the increase in payload resulting in the break-even point, see Table 13-12 below.

Table 13-12 Calculation of break-even point.

	Version 0	Version 1
Payload/year [tonkm]	942,4 E+6	987,4 E+6
Payload 35 year [tonkm]	3,30 E+10	3,46 E+10
Total cost [kSEK]	1 213 088	1 229 748
SEK/tonkm	0,0368	0,0355
Cost difference [kSEK]	-	16 660
Break-even [year]	-	13

Without including revenues the break-even point appears at year 13 of operation when the cost difference in life cycle cost is carried by the increase in payload capacity.

Considering revenues the break-even point moves considerably, to around year 4 (3,7) of operation. According to SSPA and Wallenius the revenue/ton with 75% payload rate, is 108 888 $/ton over 35 year, (March 2007). 75% of 281 ton (which is the extra payload capacity for version 1) is 211 ton. The extra revenue/year for the aluminium superstructure then becomes around 4,6 Million SEK (1$ is set to 7 SEK, March 2007).

13.5.3 Present value of future cost

Based on current price the present value of future cost is calculated as described in 13.2. In Figure 13-13 the summation of present value for the two version of superstructure is illustrated. The data for this is found in Appendix C, Table C-III.

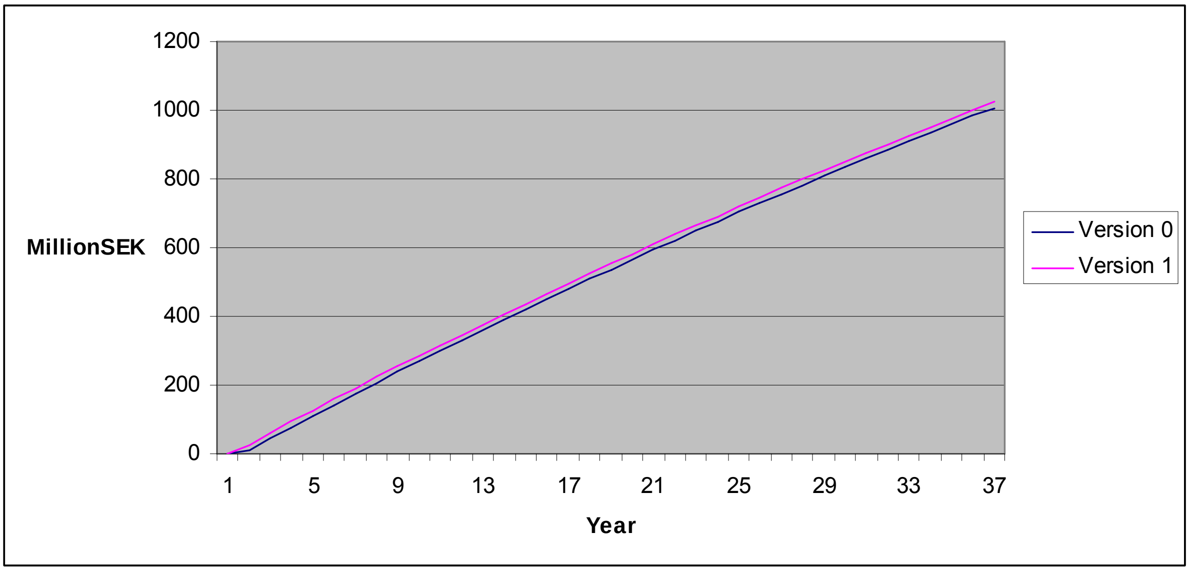


Figure 13-13 Accumulation of costs at present value in million SEK.

Since the fuel consumption is the same for both alternatives and the production cost is lower for version 0, the steel superstructure, also the total accumulated cost is lower and the cost difference is about the same.

13.5.3.1 Sensitivity analysis

No evaluation regarding cost at present value is made considering an increase in fuel price since the fuel consumption is the same for both versions. Instead a discussion about how the fuel price affects the revenues is made. With increased fuel costs the revenues will decrease. Assuming an income decrease of 25% due to increased fuel price but keeping the other costs at the origin level will result in a break-even point of around 5 years (4.96).

If the production cost increases for the aluminium superstructure, version 1, due to increase of material price will increase the cost difference and the break-even point. Assuming a material price increase with 30% for aluminium will result in cost difference of 24 645 kSEK between the two versions. This gives a break-even point between cost and revenue at year 7.

13.6 Ro-Pax ship – superstructure

This LCCA comprises three versions of the superstructure of a Ro-Pax ship, Stena Hollandica. The ship is 188 m in length overall and a displacement of 12 500 tons. The superstructure is approximately 75 m long, 29 m wide and a height of 13 m. This ship is used for transport of cargo and passengers and travels between Hoek Van Holland, Netherlands and Harwich, Great Britian.

Figure 13-14 Ro-Pax ship Stena Hollandica, © Stena Line AB

The following versions of the superstructure are included in the LCCA:

- Version 0 – Steel (origin)
- Version 1 - Sandwich with glass/polyester and balsa wood core
- Version 2 - Sandwich with glass/polyester and PVC core

Operation time is set to 25 years for all versions. The saved weight is used to increase the payload capacity.

13.6.1 Data for life cycle cost analysis

Information about the manufacture cost for the origin steel version and the composite version 1 with balsa core was collected from the European project SAFEDOR[17]. For the composite version 2, structural design and weight analysis were made by Kockums AB, Karskronavarvet[18,19]. These analyses were complemented with a cost calculation regarding manufacturing cost for version 2 also carried out by Kockums. In Table 13-13 cost for manufacture is presented.

Table 13-13 Cost for manufacture of superstructure for Ro-Pax ship.

Cost element [kSEK]	Version 0	Version 1	Version 2
Initial	4 400	7 800	9 285
Material	44 000	78 253	33 853
Manhour total	-	-	59 000
Total production	**48 400**	**86 053**	**102 138**

Initial cost, development and devices for manufacture for the structures is set to 10% of material and man-hour cost. For the steel structure, version 0, man-hour cost is included in material cost. The same is applied for version 1, man-hour is included in material cost. Cost for insulation and deck cover is included in material cost for all versions. More detailed information about cost is found in Appendix D, Table D-I and Table D-II.

Next life cycle phase is the operation with consumption of fuel. Since the decreased structural weight in the composite versions will be utilized as increased payload the fuel consumption is the same for all three versions, see Table 7.2 and Appendix D, Table D-III. The fuel cost is set to 350 USdollar/ton from August 2006. Cost for maintenance is not included since information from Stena point out that there are no large maintenance costs with replacement of steel for the origin superstructure. Normal maintenance is assumed to be the same for all three versions and therefore not included.

Table 13-14 Cost for operation of Ro-Pax ship.

Cost element [kSEK]	Version 0	Version 1	Version 2
Fuel	1 120 000	1 120 000	1 120 000
Total operation	**1 120 000**	**1 120 000**	**1 120 000**

For disposal the same methods and cost as for the high speed ferry and the Ro-Ro ship are used, see chapter 5 and 6. Recycling of metal, here steel, incineration with energy recovery for composite and landfill for insulation materials, see Table 13-15 and Appendix D, Table D-IV.

Table 13-15 Cost for disposal of Ro-Pax superstructure.

Cost element [kSEK]	Version 0	Version 1	Version 2
Steel recycling	-1 280	-	-32
Incineration - Composite + insulation +deck cover	-	792	878
Landfill - Insulation + deck cover	150	-	-
Total disposal	**-1 130**	**792**	**846**

Detailed cost about the fuel consumption and disposal is found in Appendix D, Table D-II and D-III.

In this analysis the saved weight for the light weight structures is utilized as an increase of payload. The saved weight for version 1 and 2 is calculated and added to the amount of payload capacity in the origin structure, see Table 13-16.

Table 13-16 Payload capacity

Weight [ton]	**Version 0**	**Version 1**	**Version 2**
Total weight of superstructure	950	440	488
Saved weight	-	510	462
Payload capacity	5 575	6 085	6 037
Payload/year	1,75E+6	1,91E+6	1,890E+6
Payload 25 year	4,38E+7	4,78E+7	4,74E+7

The payload is the total amount of goods possible to transport for the complete ship, not only the superstructure. These payload capacities are then related to the total cost for the specific versions in next chapter for calculating the break-even point.

13.6.2 Cost at current price

In Table 13-17 and Figure 13-13 the total cost at current price is presented. Here it is obvious how the fuel cost dominates the life cycle cost. But is should be pointed out that this is the fuel cost for the complete ship and the production cost is just for the superstructure; the hull is not included as stated earlier.

Table 13-17 Total cost superstructure for high speed ferry.

Cost element [kSEK]	**Version 0**	**Version 1**	**Version 2**
Initial	4 400	7 800	9 285
Production	44 000	78 253	92 853
Operation	1 120 000	1 120 000	1 120 000
Disposal	-1 130	792	846
Total cost	1 167 270	1 206 845	1 222 984

The initial and disposal cost are very small in relation to the other costs and not visible in Figure 13-13.

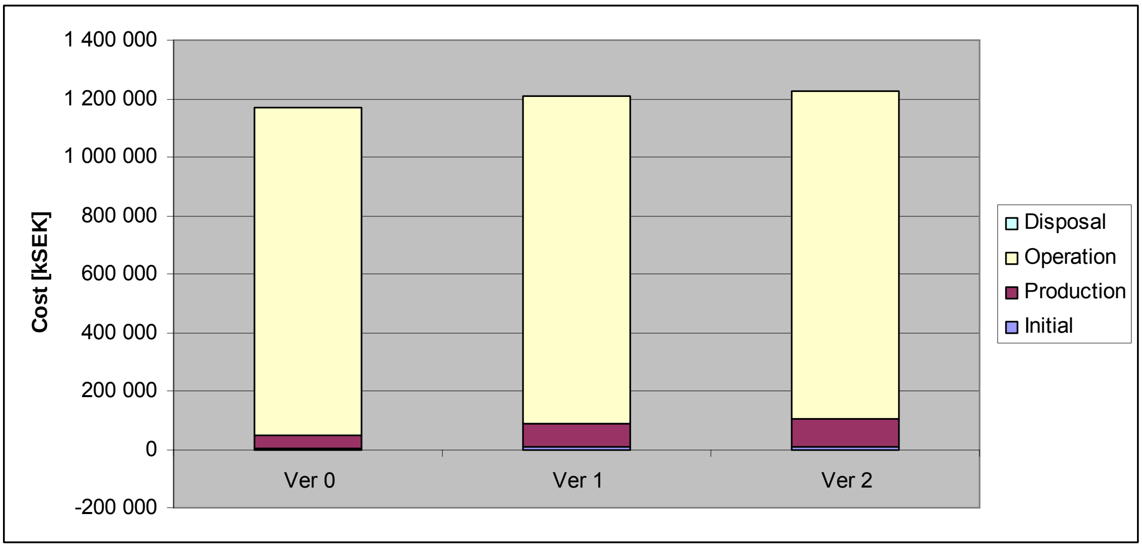


Figure 13-15 Illustration of the total cost at current price for the three superstructure versions of Stena Hollandica.

From Table 13-16 it is seen that the payload capacity increases for the two composite versions as well as the total cost due to higher production cost. This cost increase then must be covered by the increase in payload. The break-even point is calculated without considering the revenues, in accordance with Figure 13-1 to the right where two alternatives are compared.. For the three versions cost per transported ton is calculated, see Table 13-18. Then the difference in total cost of the life cycle is calculated and a break-even point is defined based on the cost for version 0.

Table 13-18 Calculation of break-even point for composite versions.

	Version 0	**Version 1**	**Version 2**
Payload/year [ton/year]	1,75E+6	1,91E+6	1,890E+6
Payload 25 year	4,38E+7	4,78E+7	4,74E+7
Total cost [kSEK]	1 167 270	1 206 845	1 222 984
SEK/ton	26,6	25,2	25,8
Cost difference [kSEK]	-	39 575	55 714
Break-even [year]	-	14,8	36,8

For the balsa composite version the break-even comes after about 15 years and after 37 years for the second composite version with PVC core.

For the Ro-Pax the revenue for the payload is unknown. A break-even of 5 years is assumed. Balancing the cost difference in Table 7.6 against revenue a break-even at year 5 requires an income increase of 7 915 kSEK/year from the payload increase when comparing version 0 to version 1. For the same comparison between version 0 and version 2 a revenue increase from the payload increase of 11 443 kSEK/year is necessary to give a break-even of year 5 of operation.

13.6.3 Present value of future cost

In this chapter the time value of money is calculated to the present value according to the description in 13.2. In Figure 13-16 the accumulated cost of the total life cycle for the three versions of superstructure for Stena Hollandica. Data behind the calculation is found in Appendix D, Table D-V.

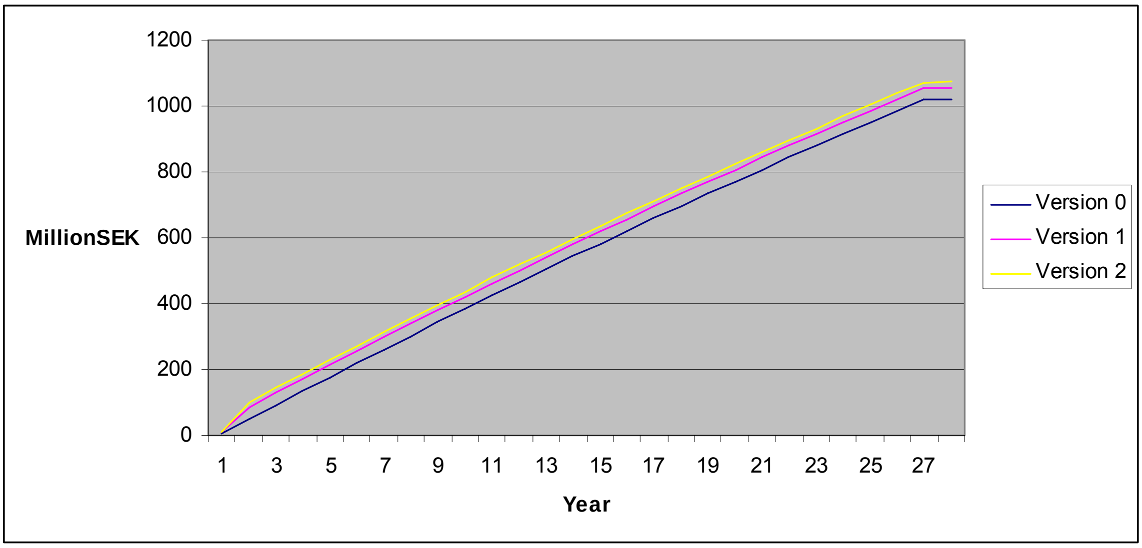


Figure 13-16 Accumulation of costs at present value in million SEK.

The highest total accumulated cost is appearing for version 2, sandwich with PVC core, since this alternative has the largest production cost.

13.6.3.1 Sensitivity analysis

As for the superstructure of the Ro-Ro ship a increased fuel price can result in a revenue decrease, extending the number of years for the break-even point.

13.6.4 LCA for Ro-Pax ship

For the superstructure of the Ro-Pax ship a life cycle assessment, LCA, was made as a master thesis work[20]. Here a comparative LCA study has been made for the three alternatives of superstructures for Stena Hollandica. Since it is a comparative study all equal items, as interior and equipment etc., are not included.

LCA is a standardized tool according to ISO14040-14044, used for studying the overall environmental impact of a product in a life cycle perspective, from cradle to grave (cradle). In an LCA all environmental effects are related to the functional unit. The function of this ship is to transport goods and the functional unit which the impacts are related to in this study is one tonkm.

Three impact categories are considered, these are:

- **global warming**, emissions of mainly gases as carbon dioxide, CO_2 and methane, CH_4 resulting in increased greenhouse effect, i.e. increased temperature and climate change

- **acidification,** emissions of sulphur oxides, SO_X, ammonia, NH_3 and nitrogen oxides, NO_X resulting in acid rain threatening fresh water organisms, marine life and woods

- **abiotic depletion,** natural resource depletion

These categories were chosen since they all causes common problems related to the fuel consumption of the ship. In these areas there are also a large potential for reducing impact by increased efficiency.

The life cycle of the ship is divided into three phases, illustrated in Figure 13-17. The manufacturing phase includes extraction and production of structural material and manufacturing of the superstructure. For the sandwich structures the vacuum injection process is not included due to lack of available data. Fire insulating material is also included since this differs between the structures.

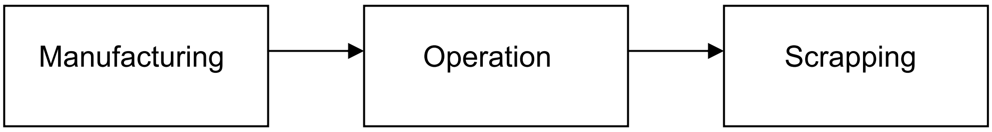


Figure 13-17 Life cycle scenario for the superstructure.

The operation phase, comprise fuel consumption over the operation time with goods transported for the complete ship, not only the superstructure, over the operation time of 25 years. In Table 13-19 the figures for the total transport of goods is presented. The length of transport is the same for the three versions but the payload differs. Since the weight of the sandwich structures is decreased, more goods can be transported with the same fuel consumption as for the steel version.

Table 13-19 Transport of goods over the operation time.

	Version 0	**Version 1**	**Version 2**
Payload capacity [ton]	5 575	6 085	6 037
Transport length/year [km]	308 000	308 000	308 000
Tonkm 25 years	42 927 500 000	46 854 500 000	46 484 900 000

For the steel superstructure maintenance is included with an exchange of steel with 10% during the operation time. Though, information from Stena states that for the steel superstructure there is no repair/exchange of steel[21]. This will not affect the final result since the steel is recycled. For all structures normal maintenance as repainting and cleaning is necessary but not necessary to include since the study is comparative.

Regarding the scrapping which also includes manufacturing waste and the end of life phase for the product, recycling of steel is included. But for the sandwich superstructures several alternatives are studied since no traditional waste treatment method yet exists for these types of structures. The scrap treatment alternatives are:

- recycling, producing new material by grinding
- incineration, producing energy
- landfill

Today the mostly used alternatives are incineration and landfill. Though, material recycling is the most favorable method regarding environmental impact.

In Table 13-20 and Figure 13-17 the result from the LCA of the complete life cycle is presented. The numbers in Table 13-20 shows the emissions for the three impact categories per tonkm, the functional unit.

Table 13-20 Total result for the LCA of superstructures.

Impact Categories	Version 0 Steel	Version 1 Sandwich - balsawood			Version 2 Sandwich - PVC		
	Recycle	Recycle	Incinerate	Landfill	Recycle	Incinerate	Landfill
Global warming [kg CO_2 eq]	0,152	0,127	0,127	0,127	0,128	0,128	0,128
Acidification [kg SO_2 eq]	1,13 10^{-3}	9,43 10^{-4}	9,43 10^{-4}	9,43 10^{-4}	9,51 10^{-4}	9,51 10^{-4}	9,51 10^{-4}
Abiotic depletion [kg Sb eq]	1,33 10^{-2}	1,11 10^{-2}	1,11 10^{-2}	1,11 10^{-2}	1,12 10^{-2}	1,12 10^{-2}	1,12 10^{-2}

The steel superstructure presents higher values per tonkm for all impact categories compared with the sandwich alternatives. Between the sandwich superstructures the one with core of balsawood presents the lowest values per tonkm for all impact categories. This is mainly explained by the decreased fuel consumption per functional unit. Regarding the waste handling no differences can be seen between the alternatives for the sandwich structure. This is also clearly seen in Figure 13-17 where the result is presented in form of staples with the 100% staple illustrating the steel superstructure and the other staples 7-8% lower illustrates the sandwich structures.

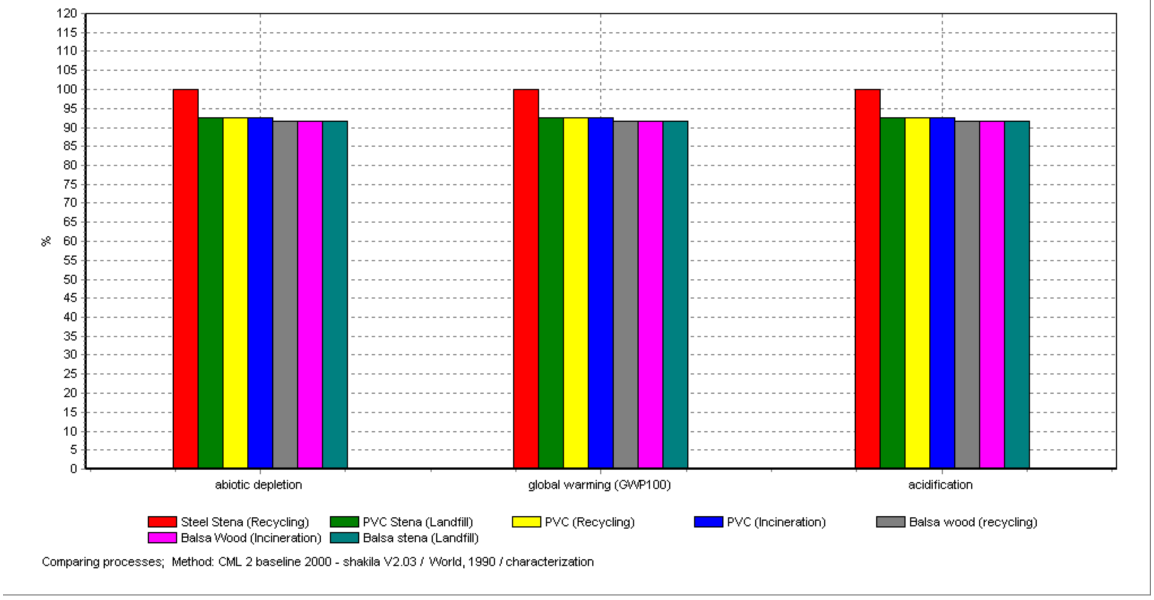


Figure 13-18 Total result of the LCA for the three superstructures.

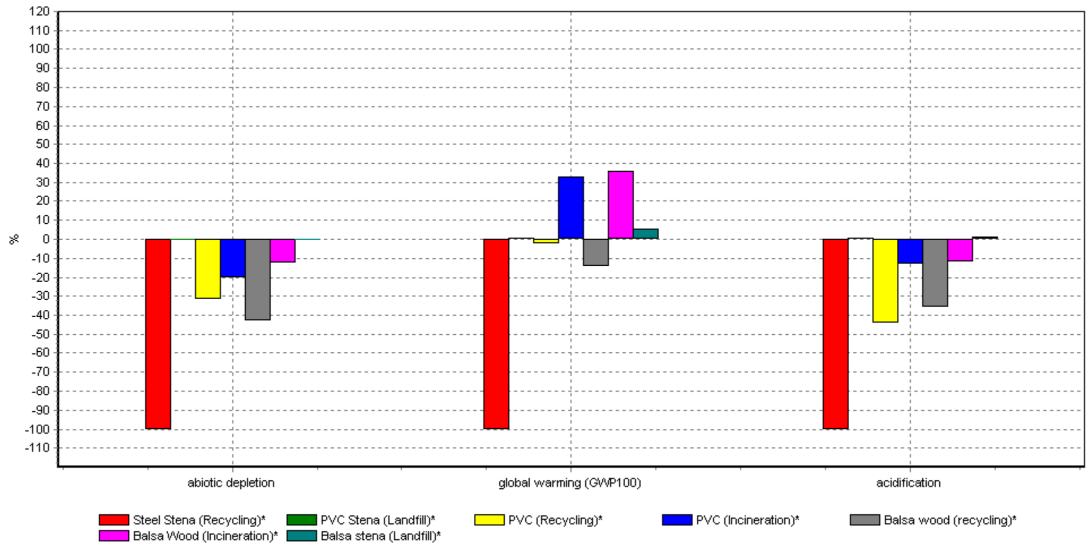
In Table 13-21 the total environmental impact for the manufacturing phase is presented, not per functional unit. Here the results differ between the versions with the highest values for the sandwich structure regarding global warming and acidification. This comes from the use of the cellular plastic material PVC. The low value for the sandwich-balsa version is explained by the use of balsa wood which is a renewable resource, making good for the environment by capturing CO_2 while growing.

Table 13-21 Environmental effects fro the manufacturing phase for the three versions.

Impact categories	Version 0 Steel	Version 1 Sandwich - balsa	Version 2 Sandwich - PVC
Global warming (in kg CO_2 eq)	1 750 000	370 000	2 060 000
Acidification (in kg SO_2 eq)	6 740	7 570	11 700
Abiotic Depletion (kg Sb eq)	16 900	5 900	12 800

The overall best result for the manufacturing phase, with lowest environmental impact, is shown for the sandwich-balsa superstructure.

In Figure 13-18 just the effects from the final phase, the end of life treatment, is presented. The best result is shown for the steel version with a high degree of recycling. For the impact category abiotic depletion and acidification both recycling and incineration for the sandwich versions are positive since recycling saves virgin material and incineration produces heat and saves oil or coal. On the other hand incineration produces CO_2 causing global warming.



Comparing processes; Method: CML 2 baseline 2000 - shakila V2.03 / World, 1990 / characterization

Figure 13-19 Environmental impacts for the scrapping phase.

In Figure 13-19 the environmental impact from manufacturing and scrapping is put together showing the overall best result for the sandwich-balsa version except for the acidification impact, were the steel version presents the lowest impact. The large influence from the fuel consumption in the operation phase makes it impossible to see the differences in Figure 13-19 as it is seen in Figure 13-17. Although the focus is on decreasing fuel consumption in operation phase it is also of importance to keep track of the other life cycle parts and try to minimize environmental effects as much as possible.

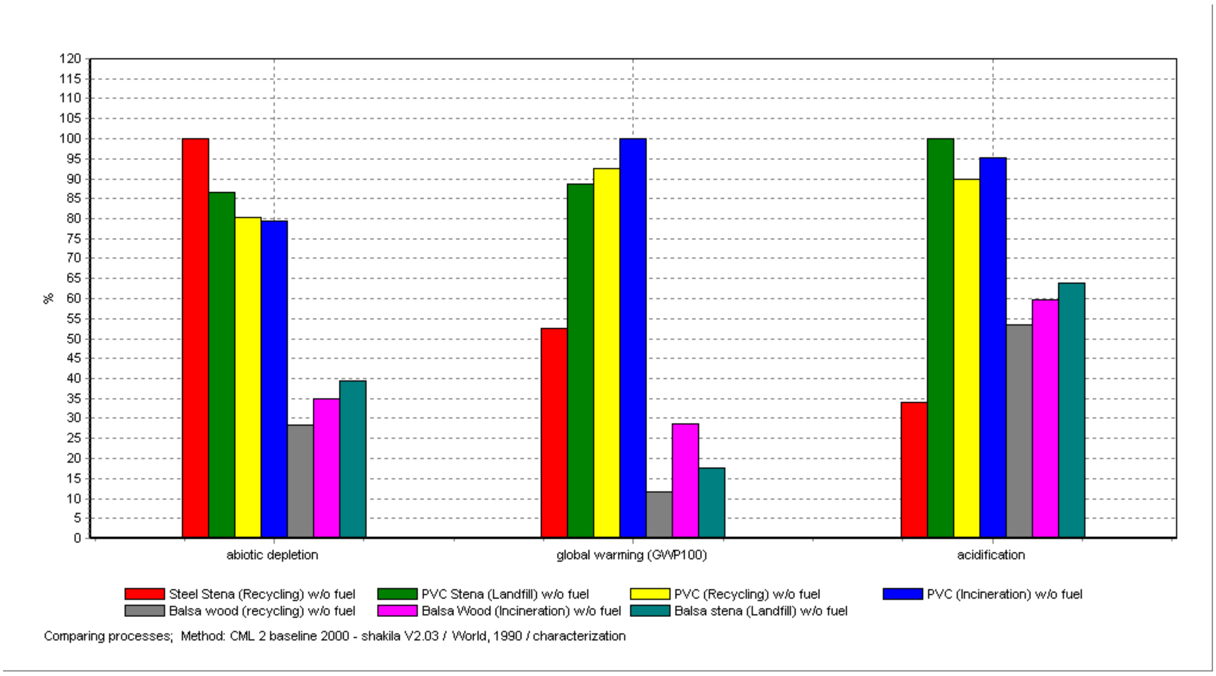


Figure 13-20 Environmental impacts for both manufacturing and scrapping phase.

13.7 Results and discussion

For all structures included in this study, operation is the totally dominating life cycle phase, both environmentally and economically. This is of course explained by the large fuel consumption, which stands for over 90% of the total life cycle cost. Though, for three of the structures in this study, this figure should be slightly lower, since only the production of the superstructure is included. The fuel consumption though, involves the complete structure.

For the high speed vessel the complete structure is included, and here the operation cost covers 96 to 99.7% of the total cost dependent on version. The highest weight reduction is presented for the version 3A in carbon fibre sandwich, with a weight decrease of 40% compared to the origin aluminium version 0. This saved weight is utilized in a reduction of fuel consumption during operation of the vessel, which is 21% for version 3A compared to version 0. One important issue included in this study of the high speed vessel is the optimization of the carbon version, from 3 to 3A, showing how secondary effects can result in a reduction in fuel consumption with 14%.

The production cost 26% lower for version 3A compared to version 0. This means that the cost for version 3A is lower, seen over the complete life cycle, than version 0. Investigating a break-even point between these two versions is then not of interest and not possible.

Considering the connection, production cost and rest value, one can state that the life cycle cost here is actually only the operation cost. Since the rest value is set to 100% for the sandwich structures the life length obviously is longer for these alternatives. Therefore an analysis including the actual life length for the sandwich should be made. To compare with the aluminium structure it would perhaps be necessary to scrap one aluminium ship and build a new one at the same life length for one sandwich vessel. Then eventually, for the sandwich alternatives, also cost for refurbishment should be included.

At the end of life the actual cost for disposal, as recycling for aluminium and incineration for the sandwich alternatives should be considered.

In the study of the high speed ferry two different material alternatives for the superstructure is investigated. This results in a weight reduction of 33%, comparing the origin aluminium version 0 to version 2, the carbon fibre sandwich alternative. This weight reduction is utilized in a decrease in fuel consumption with 22%. The production cost also differs and is increased by 74% for version 2 compared to version 0. However, due to the decrease in fuel consumption the total life cycle cost is 19% lower.

The analysis of present value of future cost gives a break-even point at year 5 of the life cycle. By doubling the fuel price the break-even comes at year 4 instead and an influence of a 100% increase of carbon fibre price gives a break-even after 6,5 years.

For the Ro-Ro and Ro-Pax superstructures the saved weight, around 50%, is utilized in an increased payload. This means that the fuel consumption is the same for all versions. But the cost per payload then differs. The break-even is analysed comparing cost to revenue. Also the influence on the break-even point for increased fuel price and material price is included. For the Ro-Ro structure comparing the break-even comes at year 4. With an assumed decrease in revenue of 25%, due to increased fuel price, the break-even pointy is moved forward to year 5. With an increase of the aluminium price by 25% the break-even appear at year 7. For the Ro-Pax the revenue is not known, therefore an assumption of a break-even point at year 5 is made. Then an income from the extra payload of around 10 000 kSEK/year is necessary to achieve the 5 year point.

For the Ro-Pax superstructure also a LCA has been performed to investigate environmental effects over life time. The analysis focused on the impact categories, global warming, acidification and abiotic depletion. These effects are coupled to the functional unit which is transport of gods, measured in tonkm. Totally dominating is of course the operation phase with its large fuel consumption. Due to increased payload for the two sandwich structures, version 1 and 2, the environmental effect for all impact categories becomes slightly lower compared to the origin version in steel, version 0.

Not discussed very much, is the final life cycle phase. In this type of life cycles for transporting structures were the operation phase is so dominating the last phase, disposal, is not visible in comparison. Disposal alone stands for around 0,1% of the total cost. Due to increased awareness regarding especially environmental issues focus has increased on waste handling, with new regulations and taxes. For conventional building materials as steel and aluminium a well organized end of life treatment with collection, transports, dismantling and material recycling exists. But, dismantling of ship structures by beaching in Asia can of course be discussed from an ethical point of view. What about fibre composite structures? Today no commercial methods exist, but with an increased use of composites the base for organizing collection and treatment increases. Today wasted composite structures ends up at landfill or is incinerated. Of large interest is the Wallenius initiative with reuse, resulting in a life cycle extension of 10 years. This method could also be applied to sandwich structures.

Finally, many different factors will have an influence on the future. An increase in energy costs will influence material price and fuel price. This combination with an increase in both material and fuel price has not been investigated, for example increasing carbon fibre and fuel prices or aluminium and fuel prices. For sure, the last combination will be in favour for composite sandwich structural alternatives. Also an influence of man-hour cost can be of interest depending on were the structure is built.

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Appendix A Data for cost calculation of high speed craft

Appendix B Data for cost calculation for high speed ferry - superstructure

Appendix C Data for cost calculation of Ro-Ro ship - superstructure

Appendix D Data for cost calculation of Ro-Pax ferry - superstructure

Appendix A Data for cost calculation of high speed craft

All cost information about material and production was calculated by the Swedish Shipyard, Swedeship AB in April 2007.

Table A-I Detailed cost information, initial costs

Cost element [kSEK]	Version 0	Version 1	Version 3	Version 3A
Development[1]	3 000	3 000	3 000	3 000
Manuf. Equiment[1]	3 990	2 000	2 000	2 000

1. Valid for 20 ships.

Table A-II Detailed information, materials weight and price, equipment, man-hour and certification cost

Cost element (gross for material)	Price [kr/kg]	Version 0 [kg]	Version 1 [kg]	Version 3 [kg]	Version 3A [kg]
Aluminium	38,4	11 236	-	-	-
Glass fibre	28,3	-	3 148	-	-
Carbon fibre (T700)	350,0	-	-	1 823	1 823
Vinylester	39,2	-	2 680	-	-
Vinylester	43,9			2 011	2 011
Core material (Divinycell)	176.8		1 776	1 376	1 376
Thermal insulation (glasswool)	20	274	-	-	-
Fire insulation (Firemaster 607)	93	476	890	890	890
Fire insulation (Fireliner FPG)	430	-	525	525	525
Noise insulation (Damping compound, damping elements, mineral wool) [kSEK]	-	1 819 (87 kSEK)	928 (31 kSEK)	928 (31 kSEK)	928 (31 kSEK)
Hull mounted equipment [kSEK]	-	290	170	170	170
Total man-hour cost [kSEK]	-	4 265	2 110	2 090	2 090
Equipment [kSEK]	-	11 400	11 000	11 000	8 500
Certification [kSEK]		500	500	500	500

Calculation of fuel consumption was made by Geir Arnestad, Geir Arnestad Design, Norway, see Table A-III.

Table A-III Fuel consumption from ship performance tests

Fuel consumption [litre/hour]	Version 0	Version 1	Version 3	Version 3A
26 knots	264	257	247	212
20 knots	165	148	137	114
10 knots	38	33	30	28

The ship is predicted to run 3000 hours per year as follows:

- 80% running time at 26 knots
- 10% running time at 20 knots
- 10% running time at 10 knots

Table A-IV Total fuel consumption

Fuel consumption [litre x 1000]	Version 0	Version 1	Version 3	Version 3A
80% 26 knots/year	634	619	593	509
10% 20 knots/year	50	44	41	34
10% 10 knots/year	11	10	9	8
Total 1 year	695	673	643	551
Total 20 year	13 890	13 460	12 860	11 020

Table A-V Accumulation of costs for versions 0 and 1 for high speed craft, (fuel price 10 SEK/liter)

Cost element[1]	**Year**	**Version 0**			**Version 1**		
		CP[2]	PV[3]	Total	CP	PV	Total
Initial							
Initial	1	0,35	0,35	0,35	0,25	0,25	0,25
Production							
Production	2	17	16,7	17	14,6	14,3	14,6
Operation and maintenance							
Operation	3	6,95	6,75	23,8	6,73	6,54	21,1
Operation and maintenance	4	7,1	6,83	30,6	6,85	6,59	27,7
Operation and maintenance	5	7,1	6,77	37,4	6,85	6,52	34,2
Operation and maintenance	6	7,1	6,7	44,1	6,85	6,46	40,7
Operation and maintenance	7	7,1	6,64	50,7	6,85	6,4	47,1
Operation and maintenance	8	7,1	6,57	57,3	6,85	6,34	53,4
Operation and maintenance	9	7,1	6,51	63,8	6,85	6,28	59,7
Operation and maintenance	10	7,1	6,45	70,3	6,85	6,22	65,9
Operation and maintenance	11	7,1	6,39	76,7	6,85	6,16	72,1
Operation and maintenance	12	7,1	6,33	83	6,85	6,1	78,2
Operation and maintenance	13	7,1	6,26	89,2	6,85	6,04	84,2
Operation and maintenance	14	7,1	6,2	95,4	6,85	5,98	90,2
Operation and maintenance	15	7,1	6,14	102	6,85	5,92	96,1
Operation and maintenance	16	7,1	6,09	108	6,85	5,87	102
Operation and maintenance	17	7,1	6,03	114	6,85	5,81	108
Operation and maintenance	18	7,1	5,97	120	6,85	5,75	114
Operation and maintenance	19	7,1	5,91	126	6,85	5,7	119
Operation and maintenance	20	7,1	5,85	131	6,85	5,64	125
Operation and maintenance	21	7,1	5,8	137	6,85	5,59	130

Cost element[1]	Year	Version 0			Version 1		
Operation and maintenance	22	7,1	5,74	143	6,85	5,54	136
Rest value							
Rest value	23	-12	-9,7	133	-15	-12	124
Total				**133**			**124**

1. The costs are presented in Million SEK.
2. CP Current Price
3. PV Present Value

Table A-VI Accumulation of costs for versions 3 and 3A for high speed craft, (fuel price 10 SEK/liter)

Cost element[1]	Year	Version 3			Version 3A		
		CP[2]	PV[3]	Total	CP	PV	Total
Initial							
Initial	1	0,25	0,25	0,25	0,25	0,25	0,25
Production							
Production	2	15,2	14,9	15,2	12,6	12,4	12,6
Operation and maintenance							
Operation	3	6,43	6,25	21,4	5,51	5,35	18
Operation and maintenance	4	6,54	6,3	27,7	5,63	5,41	23,4
Operation and maintenance	5	6,54	6,24	33,9	5,63	5,36	28,8
Operation and maintenance	6	6,54	6,18	40,1	5,63	5,31	34,1
Operation and maintenance	7	6,54	6,12	46,2	5,63	5,26	39,3
Operation and maintenance	8	6,54	6,06	52,3	5,63	5,21	44,5
Operation and maintenance	9	6,54	6	58,3	5,63	5,16	49,7
Operation and maintenance	10	6,54	5,94	64,2	5,63	5,11	54,8
Operation and maintenance	11	6,54	5,88	70,1	5,63	5,06	59,9
Operation and maintenance	12	6,54	5,83	75,9	5,63	5,01	64,9
Operation and maintenance	13	6,54	5,77	81,7	5,63	4,96	69,8
Operation and maintenance	14	6,54	5,72	87,4	5,63	4,91	74,7
Operation and maintenance	15	6,54	5,66	93,1	5,63	4,87	79,6
Operation and maintenance	16	6,54	5,61	98,7	5,63	4,82	84,4
Operation and maintenance	17	6,54	5,55	104	5,63	4,77	89,2
Operation and maintenance	18	6,54	5,5	110	5,63	4,73	93,9
Operation and maintenance	19	6,54	5,45	115	5,63	4,68	98,6
Operation and maintenance	20	6,54	5,39	121	5,63	4,64	103
Operation and maintenance	21	6,54	5,34	126	5,63	4,59	108
Operation and maintenance	22	6,54	5,29	131	5,63	4,55	112
Rest value							
Rest value	23	-15	-12	119	-13	-10	102
Total				**119**			**102**

1. The costs are presented in Million SEK.
2. CP Current Price
3. PV Present Value

Table A-VII Accumulation of costs for versions 0 and 1 for high speed craft, (fuel price 20 SEK/liter)

Cost element	Year	Version 0			Version 1		
		CP	PV	Total	CP	PV	Total
Initial							
Initial	1	0,35	0,347	0,347	0,25	0,248	0,248
Production							
Production	2	17,02	16,7	17,04	14,63	14,35	14,59
Operation and maintenance							
Operation	3	13,89	13,49	30,54	13,46	13,08	27,66
Operation and maintenance	4	14,05	13,52	44,05	13,58	13,06	40,72
Operation and maintenance	5	14,05	13,39	57,44	13,58	12,94	53,66
Operation and maintenance	6	14,05	13,26	70,69	13,58	12,81	66,47
Operation and maintenance	7	14,05	13,13	83,82	13,58	12,69	79,16
Operation and maintenance	8	14,05	13	96,83	13,58	12,57	91,73
Operation and maintenance	9	14,05	12,88	109,7	13,58	12,45	104,2
Operation and maintenance	10	14,05	12,75	122,5	13,58	12,33	116,5
Operation and maintenance	11	14,05	12,63	135,1	13,58	12,21	128,7
Operation and maintenance	12	14,05	12,51	147,6	13,58	12,09	140,8
Operation and maintenance	13	14,05	12,39	160	13,58	11,98	152,8
Operation and maintenance	14	14,05	12,27	172,3	13,58	11,86	164,6
Operation and maintenance	15	14,05	12,15	184,4	13,58	11,75	176,4
Operation and maintenance	16	14,05	12,04	196,4	13,58	11,63	188
Operation and maintenance	17	14,05	11,92	208,4	13,58	11,52	199,5
Operation and maintenance	18	14,05	11,81	220,2	13,58	11,41	210,9
Operation and maintenance	19	14,05	11,69	231,9	13,58	11,3	222,2
Operation and maintenance	20	14,05	11,58	243,4	13,58	11,19	233,4
Operation and maintenance	21	14,05	11,47	254,9	13,58	11,08	244,5
Operation and maintenance	22	14,05	11,36	266,3	13,58	10,98	255,5
Rest value							
Rest value	23	-11,9	-9,74	256,5	-14,6	-11,7	243,8
Total				**256,5**			**243,8**

1. The costs are presented in Million SEK.
2. CP Current Price
3. PV Present Value

Table A-VIII Accumulation of costs for versions 3 and 3A for high speed craft, (fuel price 20 SEK/liter)

Cost element	Year	Version 3			Version 3A		
		CP	PV	Total	CP	PV	Total
Initial							
Initial	1	0,25	0,248	0,248	0,25	0,248	0,248
Production							
Production	2	15,2	14,9	15,15	12,63	12,39	12,64
Operation and maintenance							
Operation	3	12,86	12,49	27,64	11,03	10,71	23,35
Operation and maintenance	4	12,97	12,48	40,12	11,14	10,72	34,07
Operation and maintenance	5	12,97	12,36	52,49	11,14	10,62	44,69
Operation and maintenance	6	12,97	12,24	64,73	11,14	10,52	55,2
Operation and maintenance	7	12,97	12,13	76,85	11,14	10,42	65,62
Operation and maintenance	8	12,97	12,01	88,86	11,14	10,31	75,93
Operation and maintenance	9	12,97	11,89	100,8	11,14	10,22	86,15
Operation and maintenance	10	12,97	11,78	112,5	11,14	10,12	96,27
Operation and maintenance	11	12,97	11,67	124,2	11,14	10,02	106,3
Operation and maintenance	12	12,97	11,55	135,8	11,14	9,924	116,2
Operation and maintenance	13	12,97	11,44	147,2	11,14	9,828	126
Operation and maintenance	14	12,97	11,33	158,5	11,14	9,734	135,8
Operation and maintenance	15	12,97	11,22	169,8	11,14	9,64	145,4
Operation and maintenance	16	12,97	11,12	180,9	11,14	9,548	155
Operation and maintenance	17	12,97	11,01	191,9	11,14	9,456	164,4
Operation and maintenance	18	12,97	10,9	202,8	11,14	9,365	173,8
Operation and maintenance	19	12,97	10,8	213,6	11,14	9,275	183,1
Operation and maintenance	20	12,97	10,69	224,3	11,14	9,186	192,2
Operation and maintenance	21	12,97	10,59	234,9	11,14	9,097	201,3
Operation and maintenance	22	12,97	10,49	245,4	11,14	9,01	210,4
Rest value							
Rest value	23	-15,2	-12,2	233,2	-12,6	-10,1	200,2
Total				**233,2**			**200,2**

1. The costs are presented in Million SEK.
2. CP Current Price
3. PV Present Value

Appendix B Data for cost calculation for high speed ferry - superstructure

Table B-I Detailed data for initial costs

Cost element [kSEK]	Version 0	Version 1	Version 2
Development	-	-	-
Manuf. Equiment	560[1]	946[2]	946[2]

1. 10% of material cost according to SSPA Sweden AB.
2. Info. from Kockums AB Kkrv.

Table B-II Detailed information, materials weight and price, equipment, man-hour cost

Cost element (gross for material)	Price [kr/kg]	Version 0 [kg]	Version 1 [kg]	Version 2 [kg]
Aluminium[1]	-	57 000[2]	-	-
Glass fibre	-	-	22 909[3] (664 kSEK)	-
Carbon fibre (T700)	-	-	-	14 278[3] (6 896 kSEK)
Vinylester	-	-	14 416[3] (627 kSEK)	13 480[3] (586 kSEK)
Core material (Divinycell)	-	-	7 575[3] (1 477 kSEK)	6 488[3] (1 331 kSEK)
Insulation	30,13[4]	6000[4]	-	-
Insulation	62,50[5]		23 143[5]	23 142[5]
Man-hour sandwichstructure [kSEK]		-	9 007[3]	8 957[3]
Man-hour insulation [kSEK]	-	-	3009[5]	3009[5]

1. Based on 15$/kg, info from SSPA work with Ro-Ro ship, includes manufacturing.
2. Info from ref. [2], includes 15% manufacturing waste according to SSPA work on Ro-Ro ship, version 1.
3. Info from Kockums AB Kkrv.
4. Info from SSPA work on Ro-Ro ship, cost 4,6$/kg.
5. Info from Kockums AB Kkrv cost analysis on Ro-Pax version 2, 10% waste.

Table B-III Detailed data for fuel consumption and costs

Cost element	Version 0	Version 1	Version 2
Fuel consumption ton/year	10 800[1]	9 612[3]	8 424[3]
Fuel cost 25 year[2]	615 550 kSEK	547 844[2] kSEK	480 128[2] kSEK

1. Info from H. Nordhammar Stena, 1 080 h, 10 ton/hour.
2. Fuel price 350 $/ton, info from H. Nordhammar.
3. Assumption made from fuel consumption based on weight reduction from ref [2].

Table B-IV Recycling and disposal costs

Cost element [kSEK]	Version 0	Version 1	Version 2
Aluminium	-240[1]	-	-
Insulation	6[2]	-	-
Insulation and sandwich	-	113[3]	95[3]

1. www.demolitionscrapmetalnews.com, 500 Euro/ton.
2. Ref [13]
3. 180 Euro/ton, ref [15].

Table B-V Accumulation of costs for the three versions of high speed ferry superstructure (fuel price 350 $/ton)

Cost element[1]	Year	Version 0			Version 1			Version 2		
		CP[2]	PV[3]	Total	CP	PV	Total	CP	PV	Total
Initial										
Initial total	1	0,56	0,555	0,555	0,946	0,937	0,937	0,946	0,937	0,937
Production										
Production total	2	5,781	5,67	6,225	16,23	15,92	16,86	22,23	21,8	22,74
Operation										
Operation	3	24,62	23,92	30,14	21,91	21,29	38,14	19,21	18,66	41,39
Operation	4	24,62	23,69	53,83	21,91	21,08	59,23	19,21	18,48	59,87
Operation	5	24,62	23,46	77,29	21,91	20,88	80,11	19,21	18,3	78,17
Operation	6	24,62	23,24	100,5	21,91	20,68	100,8	19,21	18,12	96,29
Operation	7	24,62	23,01	123,5	21,91	20,48	121,3	19,21	17,95	114,2
Operation	8	24,62	22,79	146,3	21,91	20,28	141,6	19,21	17,78	132
Operation	9	24,62	22,57	168,9	21,91	20,09	161,6	19,21	17,61	149,6
Operation	10	24,62	22,35	191,3	21,91	19,9	181,5	19,21	17,44	167,1
Operation	11	24,62	22,14	213,4	21,91	19,7	201,2	19,21	17,27	184,3
Operation	12	24,62	21,93	235,3	21,91	19,51	220,8	19,21	17,1	201,4
Operation	13	24,62	21,72	257	21,91	19,33	240,1	19,21	16,94	218,4
Operation	14	24,62	21,51	278,5	21,91	19,14	259,2	19,21	16,78	235,1
Operation	15	24,62	21,3	299,8	21,91	18,96	278,2	19,21	16,61	251,8
Operation	16	24,62	21,1	320,9	21,91	18,78	297	19,21	16,45	268,2
Operation	17	24,62	20,89	341,8	21,91	18,59	315,6	19,21	16,3	284,5
Operation	18	24,62	20,69	362,5	21,91	18,42	334	19,21	16,14	300,6
Operation	19	24,62	20,49	383	21,91	18,24	352,2	19,21	15,98	316,6
Operation	20	24,62	20,3	403,3	21,91	18,06	370,3	19,21	15,83	332,5
Operation	21	24,62	20,1	423,4	21,91	17,89	388,2	19,21	15,68	348,1
Operation	22	24,62	19,91	443,3	21,91	17,72	405,9	19,21	15,53	363,7
Operation	23	24,62	19,72	463	21,91	17,55	423,4	19,21	15,38	379
Operation	24	24,62	19,53	482,6	21,91	17,38	440,8	19,21	15,23	394,3
Operation	25	24,62	19,34	501,9	21,91	17,21	458	19,21	15,08	409,4
Operation	26	24,62	19,15	521,1	21,91	17,05	475,1	19,21	14,94	424,3
Operation	27	24,62	18,97	540	21,91	16,88	491,9	19,21	14,8	439,1
Disposal										
Disposal total	28	-0,23	-0,18	539,8	0,113	0,086	492	0,095	0,073	439,2
Total				539,8			492			439,2

1. The costs are presented in Million SEK.
2. CP Current Price
3. PV Present Value

Table B-VI Accumulation of costs for the three versions of high speed ferry superstructure (fuel price 700 $/ton)

Cost element	Year	Version 0			Version 1			Version 2		
		CP	PV	Total	CP	PV	Total	CP	PV	Total
Initial										
Initial total	1	0,56	0,555	0,555	0,946	0,937	0,937	0,946	0,937	0,937
Production										
Production total	2	5,781	5,67	6,225	16,23	15,92	16,86	22,23	21,8	22,74
Operation										
Operation	3	49,24	47,84	54,06	43,83	42,58	59,43	38,41	37,31	60,05
Operation	4	49,24	47,38	101,4	43,83	42,17	101,6	38,41	36,95	97
Operation	5	49,24	46,92	148,4	43,83	41,76	143,4	38,41	36,6	133,6
Operation	6	49,24	46,47	194,8	43,83	41,36	184,7	38,41	36,25	169,8
Operation	7	49,24	46,02	240,9	43,83	40,96	225,7	38,41	35,9	205,7
Operation	8	49,24	45,58	286,4	43,83	40,57	266,2	38,41	35,55	241,3
Operation	9	49,24	45,14	331,6	43,83	40,18	306,4	38,41	35,21	276,5
Operation	10	49,24	44,71	376,3	43,83	39,79	346,2	38,41	34,87	311,4
Operation	11	49,24	44,28	420,6	43,83	39,41	385,6	38,41	34,54	345,9
Operation	12	49,24	43,85	464,4	43,83	39,03	424,7	38,41	34,21	380,1
Operation	13	49,24	43,43	507,9	43,83	38,65	463,3	38,41	33,88	414
Operation	14	49,24	43,01	550,9	43,83	38,28	501,6	38,41	33,55	447,6
Operation	15	49,24	42,6	593,5	43,83	37,91	539,5	38,41	33,23	480,8
Operation	16	49,24	42,19	635,7	43,83	37,55	577,1	38,41	32,91	513,7
Operation	17	49,24	41,78	677,4	43,83	37,19	614,2	38,41	32,59	546,3
Operation	18	49,24	41,38	718,8	43,83	36,83	651,1	38,41	32,28	578,6
Operation	19	49,24	40,99	759,8	43,83	36,48	687,6	38,41	31,97	610,5
Operation	20	49,24	40,59	800,4	43,83	36,13	723,7	38,41	31,66	642,2
Operation	21	49,24	40,2	840,6	43,83	35,78	759,5	38,41	31,36	673,5
Operation	22	49,24	39,81	880,4	43,83	35,44	794,9	38,41	31,06	704,6
Operation	23	49,24	39,43	919,8	43,83	35,09	830	38,41	30,76	735,4
Operation	24	49,24	39,05	958,9	43,83	34,76	864,7	38,41	30,46	765,8
Operation	25	49,24	38,68	997,6	43,83	34,42	899,2	38,41	30,17	796
Operation	26	49,24	38,3	1036	43,83	34,09	933,3	38,41	29,88	825,9
Operation	27	49,24	37,94	1074	43,83	33,76	967	38,41	29,59	855,5
Disposal										
Disposal total	28	-0,23	-0,18	1074	0,113	0,086	967,1	0,095	0,073	855,5
Total				**1074**			**967,1**			**855,5**

1. The costs are presented in Million SEK.
2. CP Current Price
3. PV Present Value

Table B-VII Accumulation of costs for the three versions of high speed ferry superstructure, carbon fibre price increased 100%, fuel price 350 $/ton

Cost element[1]	**Year**	**Version 0**			**Version 2**		
		CP[2]	PV[3]	Total	CP	PV	Total
Initial							
Initial total	1	0,56	0,555	0,555	0,946	0,937	0,937
Production							
Production total	2	5,781	5,67	6,225	29,12	28,56	29,5
Operation							
Operation	3	24,62	23,92	30,14	19,21	18,66	48,16
Operation	4	24,62	23,69	53,83	19,21	18,48	66,63
Operation	5	24,62	23,46	77,29	19,21	18,3	84,93
Operation	6	24,62	23,24	100,5	19,21	18,12	103,1
Operation	7	24,62	23,01	123,5	19,21	17,95	121
Operation	8	24,62	22,79	146,3	19,21	17,78	138,8
Operation	9	24,62	22,57	168,9	19,21	17,61	156,4
Operation	10	24,62	22,35	191,3	19,21	17,44	173,8
Operation	11	24,62	22,14	213,4	19,21	17,27	191,1
Operation	12	24,62	21,93	235,3	19,21	17,1	208,2
Operation	13	24,62	21,72	257	19,21	16,94	225,1
Operation	14	24,62	21,51	278,5	19,21	16,78	241,9
Operation	15	24,62	21,3	299,8	19,21	16,61	258,5
Operation	16	24,62	21,1	320,9	19,21	16,45	275
Operation	17	24,62	20,89	341,8	19,21	16,3	291,3
Operation	18	24,62	20,69	362,5	19,21	16,14	307,4
Operation	19	24,62	20,49	383	19,21	15,98	323,4
Operation	20	24,62	20,3	403,3	19,21	15,83	339,2
Operation	21	24,62	20,1	423,4	19,21	15,68	354,9
Operation	22	24,62	19,91	443,3	19,21	15,53	370,4
Operation	23	24,62	19,72	463	19,21	15,38	385,8
Operation	24	24,62	19,53	482,6	19,21	15,23	401
Operation	25	24,62	19,34	501,9	19,21	15,08	416,1
Operation	26	24,62	19,15	521,1	19,21	14,94	431,1
Operation	27	24,62	18,97	540	19,21	14,8	445,9
Disposal							
Disposal total	28	-0,23	-0,18	539,8	0,095	0,073	445,9
Total				**539,8**			**445,9**

1. The costs are presented in Million SEK.
2. CP Current Price
3. PV Present Value

Appendix C Data for cost calculation of Ro-Ro ship – superstructure

Table C-I Detailed data for initial costs and material weight and price

Cost element	Price [$/kg]	Version 0	Version 1
Initial[1] [kSEK]	-	956	2 505
Steel[2] (gross) [kg]	2,5[3]	637 426	-
Aluminium[2] (gross) [kg]	15[3]	-	278 346
Insulation[4] (gross) [kg]	4,6[3]	11 876	28 422

1. Based on 10% of structural material cost
2. Includes manufacturing cost and 15% waste from manufacture.
3. Info from SSPA Sweden AB.
4. Includes 4% waste from mounting.

Table C-II Detailed data for fuel consumption and costs

Cost element	Version 0	Version 1
Fuel consumption 35 year[1] [ton]	490 875	490 875
Fuel cost 35 year[2] [kSEK]	1 203 383	1 203 383

1. Info from S. Gorton, Wallenius Marine AB.
2. Fuel price 350 $/ton, info from S. Gorton.

Table C-III Accumulation of costs for the two versions of Ro-Ro ship superstructures

Cost element[1]	**Year**	**Version 0**			**Version 1**		
		CP[2]	PV[3]	Total	CP	PV	Total
Initial							
Initial total	1	0,956	0,947	0,947	2,505	2,481	2,481
Production							
Production total	2	9,693	9,508	10,45	25,22	24,74	27,22
Operation							
Operation	3	34,38	33,4	43,85	34,38	33,4	60,62
Operation	4	34,38	33,08	76,93	34,38	33,08	93,7
Operation	5	34,38	32,76	109,7	34,38	32,76	126,5
Operation	6	34,38	32,45	142,1	34,38	32,45	158,9
Operation	7	34,38	32,13	174,3	34,38	32,13	191
Operation	8	34,38	31,82	206,1	34,38	31,82	222,9
Operation	9	34,38	31,52	237,6	34,38	31,52	254,4
Operation	10	34,38	31,22	268,8	34,38	31,22	285,6
Operation	11	34,38	30,92	299,7	34,38	30,92	316,5
Operation	12	34,38	30,62	330,4	34,38	30,62	347,1
Operation	13	34,38	30,32	360,7	34,38	30,32	377,5
Operation	14	34,38	30,03	390,7	34,38	30,03	407,5
Operation	15	34,38	29,74	420,5	34,38	29,74	437,2
Operation	16	34,38	29,46	449,9	34,38	29,46	466,7
Operation	17	34,38	29,17	479,1	34,38	29,17	495,9
Operation	18	34,38	28,89	508	34,38	28,89	524,8
Operation	19	34,38	28,62	536,6	34,38	28,62	553,4
Operation	20	34,38	28,34	565	34,38	28,34	581,7
Operation	21	34,38	28,07	593	34,38	28,07	609,8
Operation	22	34,38	27,8	620,8	34,38	27,8	637,6
Operation	23	34,38	27,53	648,3	34,38	27,53	665,1
Operation	24	34,38	27,27	675,5	34,38	27,27	692,4
Operation	25	34,38	27	702,6	34,38	27	719,4
Operation	26	34,38	26,74	729,4	34,38	26,74	746,1
Operation	27	34,38	26,49	755,9	34,38	26,49	772,6
Operation	28	34,38	26,23	782,1	34,38	26,23	798,9
Operation	29	34,38	25,98	808,1	34,38	25,98	824,8
Operation	30	34,38	25,73	833,8	34,38	25,73	850,6
Operation	31	34,38	25,48	859,3	34,38	25,48	876
Operation	32	34,38	25,24	884,5	34,38	25,24	901,3
Operation	33	34,38	25	909,5	34,38	25	926,3
Operation	34	34,38	24,76	934,3	34,38	24,76	951
Operation	35	34,38	24,52	958,8	34,38	24,52	975,6
Operation	36	34,38	24,28	983,1	34,38	24,28	999,8
Operation	37	34,38	24,05	1007	34,38	24,05	1024
Total				**1007**			**1024**

1. The costs are presented in Million SEK.
2. CP Current Price
3. PV Present Value

13.7.1 Appendix D Data for cost calculation of Ro-Pax ferry – superstructure

Table D-I Detailed data for Initial cost

Cost element [kSEK]	Version 0	Version 1	Version 2
Development[1]	4 400	7 800	9 825
Manuf. Equiment	-	-	-

1. 10% of manufacturing cost according to SSPA Sweden AB.

Table D-II Detailed information, materials weight and price, equipment, man-hour cost

Cost element	Price [kr/kg]	Version 0 [kg]	Version 1 [kg]	Version 2 [kg] (gross)
Steel	-	800 000[1]	-	22 000[8] (800 kSEK)
Glass fibre + polyester	-	-	176 000[4]	-
Glass fibre	-	-	-	125 000[8] (3 400 kSEK)
Polyester	-	-	-	95 000[8] (1 900 kSEK)
Structural glue	-	-	-	15 500[8] (1 000 kSEK)
Core material (Divinycell)	-	-	-	64 000[8] (11 500 kSEK)
Core material (balsa wood)	-	-	138 000[4,5]	-
Insulation	200[2]	50 000[2]	57 000[6]	160 000[8] (10 000 kSEK)
Deck-cover, floating floor	50[3]	100 000[3]	64 000[7]	64 000[7]
Man-hour sandwichstructure [kSEK]	-	-	-	38 000[8]
Man-hour insulation [kSEK]	-	-	-	21 000[8]

1. From ref [18], 4x 10^6 \$, manufacture included (29 x 10^6 SEK, Forex 1/3 2007).
2. From ref [18], cost estimated to 10 x 10^6 SEK (mounting included), based on calculation of insulation cost for sandwich superstructure made by Karlskronavarvet, J. Edvardsson.
3. Deck-cover, info from Stena.
4. Total cost balsa+glass fibre+vinylester from ref [18], 7,1 x 10^6 \$ (50 x 10^6 SEK, Forex 1/3 2007).
5. 920 m^3 from ref [18], (150 kg/m^3, density, info from C.J. Lindholm, DIAB, 28/9 2006).
6. Estimated cost based on calculation of insulation cost for sandwich superstructure made by Kockums AB Kkrv, J. Edvardsson, 23 x 10^6 SEK.
7. Floating floor, info from H. Johansson Karlskonavarvet, 17/8 2007, LOLAMAT Floor, Type "LR14" cost of 5 253 kSEK, (5100 m^2 á 1030 SEK/m^2).
8. Info from Kockums AB Kkrv.

Table D-III Detailed data for fuel consumption and costs

Cost element	Version 0	Version 1	Version 2
Fuel consumption 25 year[1] [ton]	446 250	446 250	446 250
Fuel cost 25 year[2] [kSEK]	1 120 000	1 120 000	1 120 000

1. Info from H. Nordhammar, Stena
2. Fuel price 350 $/ton, info from H. Nordhammar, (2 509 SEK/ton, Forex 1/3 2007).

Table D-IV Detailed data for disposal

Cost element [kSEK]	Version 0	Version 1	Version 2
Steel recycling	-1 280	-	-32
Incineration - Composite + insulation +deck cover	-	792	878
Landfill - Insulation + deck cover	150	-	-
Total disposal	**-1 130**	**792**	**846**

1. www.demolitionscrapmetalnews.com, 250 $/ton.
2. 1000 SEK/ton, ref [13].
3. 180 Euro/ton, ref [15].

Table D-V Accumulation of costs for the three versions of high speed ferry superstructure

Cost element[1]	**Year**	**Version 0**			**Version 1**			**Version 2**		
		CP[2]	PV[3]	Total	CP	PV	Total	CP	PV	Total
Initial										
Initial total	1	4,4	4,358	4,358	7,8	7,725	7,725	9,825	9,731	9,731
Production										
Production total	2	44	43,16	47,52	78,25	76,76	84,48	92,85	91,08	100,8
Operation										
Operation	3	44,8	43,52	91,04	44,8	43,52	128	44,8	43,52	144,3
Operation	4	44,8	43,1	134,1	44,8	43,1	171,1	44,8	43,1	187,4
Operation	5	44,8	42,69	176,8	44,8	42,69	213,8	44,8	42,69	230,1
Operation	6	44,8	42,28	219,1	44,8	42,28	256,1	44,8	42,28	272,4
Operation	7	44,8	41,87	261	44,8	41,87	297,9	44,8	41,87	314,3
Operation	8	44,8	41,47	302,4	44,8	41,47	339,4	44,8	41,47	355,7
Operation	9	44,8	41,07	343,5	44,8	41,07	380,5	44,8	41,07	396,8
Operation	10	44,8	40,67	384,2	44,8	40,67	421,1	44,8	40,67	437,5
Operation	11	44,8	40,28	424,5	44,8	40,28	461,4	44,8	40,28	477,8
Operation	12	44,8	39,9	464,4	44,8	39,9	501,3	44,8	39,9	517,7
Operation	13	44,8	39,51	503,9	44,8	39,51	540,8	44,8	39,51	557,2
Operation	14	44,8	39,13	543	44,8	39,13	580	44,8	39,13	596,3
Operation	15	44,8	38,76	581,8	44,8	38,76	618,7	44,8	38,76	635,1
Operation	16	44,8	38,38	620,1	44,8	38,38	657,1	44,8	38,38	673,4
Operation	17	44,8	38,01	658,2	44,8	38,01	695,1	44,8	38,01	711,4
Operation	18	44,8	37,65	695,8	44,8	37,65	732,8	44,8	37,65	749,1
Operation	19	44,8	37,29	733,1	44,8	37,29	770,1	44,8	37,29	786,4
Operation	20	44,8	36,93	770	44,8	36,93	807	44,8	36,93	823,3
Operation	21	44,8	36,57	806,6	44,8	36,57	843,6	44,8	36,57	859,9
Operation	22	44,8	36,22	842,8	44,8	36,22	879,8	44,8	36,22	896,1
Operation	23	44,8	35,87	878,7	44,8	35,87	915,7	44,8	35,87	932
Operation	24	44,8	35,53	914,2	44,8	35,53	951,2	44,8	35,53	967,5
Operation	25	44,8	35,19	949,4	44,8	35,19	986,4	44,8	35,19	1003
Operation	26	44,8	34,85	984,3	44,8	34,85	1022	44,8	34,85	1038
Operation	27	44,8	34,51	1019	44,8	34,51	1056	44,8	34,51	1072
Disposal										
Disposal total	28	-1,13	-0,86	1018	0,792	0,604	1057	0,846	0,646	1073
Total				**1018**			**1057**			**1073**

1. The costs are presented in Million SEK.

2. CP Current Price

3. PV Present Value

14 Risk Analysis and SOLAS regulation 17

This chapter contains a description of the risk analysis methodology used in order to handle the requirements of SOLAS regulation 17, “Alternative design and arrangement”, when a RoPax vessel, the LASS WP3d case, is designed with a composite superstructure. The LASS group worked in close co-operation with a DNV-led subgroup within the EU-FP6 project SAFEDOR and the text below is copied from a book on risk based ship design with permission from Springer Verlag and DNV.

Lightweight composite sandwich RoPax superstructure

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Section 6.3 in ‘Risk-Based Ship Design – Theory and Applications’, A Papanikolaou (Ed.), Springer Verlag ©. Reproduced with permission.

Abstract Lightweight composite materials have a long and successful track record in demanding and weight-critical applications. The benefits of lightweight composite materials have so far not been available to the merchant ship designer because international regulations require that the structure shall be made of non-combustible materials. However, these regulations allow alternative arrangements that deviate from such prescriptive requirements provided that adequate safety is demonstrated by an engineering analysis. For a RoPax ship this method has shown that a weight saving of about 60% can be achieved for the superstructure if the traditional steel superstructure is replaced by a lightweight composite design. This estimate accounts for structural fire protection and other risk control measures. An acceptable level of safety was documented for the new risk-based composite design. This demonstrates the feasibility of significant weight saving in superstructures of merchant ships by using composite materials and gives promise for more efficient and profitable merchant ship designs in the future.

Nomenclature

The following abbreviations are used:

CAF	Cost of averting a fatality
GRP	Glass fibre reinforced plastics
FRP	Fibre reinforced plastics
PLL	Potential loss of lives
PVC	Polyvinylchloride
RCO	Risk control option
Reg	Regulation
SOLAS	The International Convention for the Safety of Life at Sea

14.1 Introduction

Fibre reinforced plastic (FRP) composite materials offer high strength at low weight. A particularly effective form of construction is obtained by using sandwich panels where two light and strong FRP laminates are separated by a lightweight core as illustrated in Figure **14-1**. Such sandwich structures provide both high stiffness and strength at low weight compared to other common forms of construction. For this reason, FRP sandwich structures have been used extensively in such demanding maritime applications as high speed craft and naval ships.

Although weight is more critical in high speed craft than in other merchant ships and composites offer additional advantages in some types of naval ships, weight saving is attractive also for merchant ships. The application of composite materials to merchant ships has, however, been very limited because the International Convention for the Safety of Life at Sea (SOLAS) (IMO 1974) requires that "*the hull, superstructures, structural bulkheads, decks and deckhouses shall be constructed of steel or other equivalent material*" (Ch II-2 Reg 11), the latter being defined as non-combustible materials (Ch II-2 Reg 3.33). This has till now prevented the use of combustible composite materials in the main load-bearing structure of ships approved according to SOLAS.

SOLAS was recently amended with the new Regulation 17 in Ch II-2 allowing for approval of alternative designs and arrangements provided that the safety of the alternative arrangement is documented by an engineering analysis. A composite design may be regarded such an alternative arrangement and, provided that adequate fire safety can be documented, the SOLAS convention provides an opening for approval of such designs.

In what follows, the benefits of using this opening to introduce light-weight composite structures to shipbuilding are demonstrated.

14.2 Developing the novel risk-based design

The initial design case selected for this work was an existing RoPax passenger vessel with roughly a length of 200 m, a deadweight capacity of about 7,500 tonnes, a tonnage of about 33.000 GT, 3,100 lane meters and 500 passengers. A so-called base design for the superstructure module of this ship was developed according to the current state of the art composite sandwich technology. The major features of that base design are described in the next sub-section. Through a risk based design process described in the subsequent sub-sections the design was further improved by a number of cost effective risk control options (RCOs). The risk assessment supporting the design process is described briefly. The cost effective RCOs that distinguish the final risk based design from the base design are summarized. They proved the feasibility of the concept. In a next step, a new vessel design of *Stena Rederi AB* was considered and a risk assessment adapted was also to this new design. Both designs are shown in
Figure 14-2.

14.2.1 The base design

The sandwich concept illustrated in
Figure 14-1 was used to obtain a light-weight design of the superstructure module. Composite face sheets of vinyl ester thermosetting polymeric material reinforced with glass fibres were used. The core material should be light but stiff in shear. Common core materials include balsa wood and polymeric foams usually made of rigid PVC.

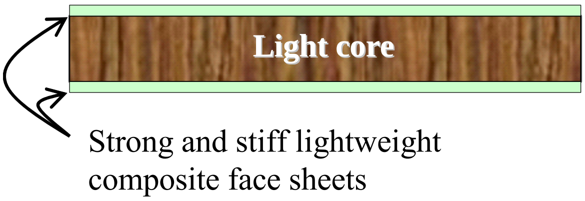

Figure 14-1 The sandwich form of construction

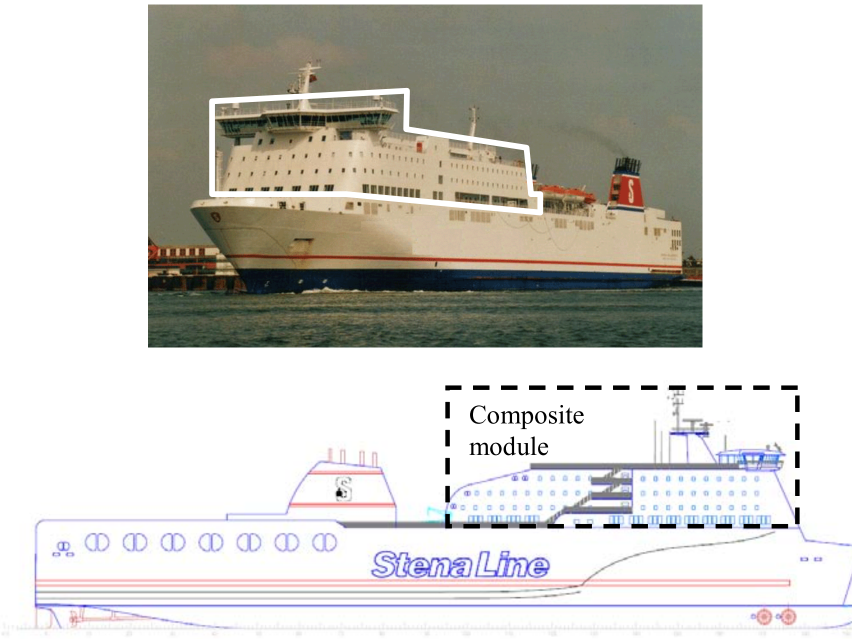

Figure 14-2 The composite superstructure modules considered in the SAFEDOR study

All interiors such as cabin modules, decorative surface panels etc were chosen to be of standard commercial types that fulfil the SOLAS requirements to such items and are in use onboard steel designs and are hence approved for use in ships.

Both the face and core materials are combustible. If directly exposed to a fire, these materials would contribute to the fire and the fire could also spread on the exposed surfaces. That could compromise the ship's fire safety. Therefore all the surfaces inside the super-structure were protected by a suitable fire protection system. Structural panels that are hidden behind standard elements, e.g. decks and bulkheads in accommodation areas, would have standard low cost fire protection systems typically of mineral wool. Other structural panels such as bulkheads facing corridors are protected with dedicated fire protection systems that have a decorative and robust surface. Some systems of this type have been earlier described and characterized by Gutierrez et. al. (2005) and McGeorge and Høyning (2002). All the surfaces satisfy the fire reaction requirements specified in the IMO HSC Code (IMO 2000). These requirements are stricter than those of the SOLAS convention.

This ensures that, as long as the fire protection capacity is not exceeded, the behaviour of the composite superstructure in a fire will be at least as favourable as that of a traditional steel design. The critical question for equivalence with prescriptive steel designs is the risk contributions associated with the rare events of fires that last longer than the fire protection time of the FRP structure such that the combustible structural material is exposed. This is addressed herein by the risk assessment.

The weight of the lightweight module was only about 40% of that of the existing traditional steel design. This weight comparison includes all fire and thermal insulation and represents the real weight difference of the two arrangements as installed onboard. The cost of this weight saving was estimated to about 5 € per kg. Whether this is commercially attractive depends on the intended trade of the vessel, but plausible examples were identified where the cost increase would be expected to pay back in one to two years of service.

14.2.2 The risk based design process

A risk based design process was performed involving the usual steps of a risk assessment: hazard identification, ranking of risks using a qualitative risk assessment, identification of risk control options (RCOs), quantitative risk assessment with focus on the most critical risks and a decision process where the most effective risk control options were adopted. To ensure that the most critical risks and the best RCOs were identified and that the most appropriate methods were used to assess risks; 26 experts were involved in the risk based assessment and design process. These 26 experts covered all relevant areas of expertise and represented all stakeholders.

Several design iterations were performed. In the first iteration, focus was placed on identifying design solutions that were effective in meeting the design objectives. Then focus was gradually shifted towards identifying effective ways of controlling the risks associated with the novel design. To support this process, each expert was involved at the most appropriate stage in the design process.

The estimated risks were compared to the risk acceptance criteria given in Table 14-1. The criteria were derived from a set of recommended risk acceptance criteria suggested by Skjong et al (2005) considering that the total risk will be dominated by the more severe risks due to collision and grounding such that the superstructure fire risk should only represent a small fraction of the total acceptable risk. Hence, the criteria used for superstructure fires are much stricter than the criteria suggested by Skjong et al (2005) and correspond to the difference between those and the historic risks from collisions, grounding and engine room fires as reported by Vanem and Skjong (2004, 2004b). The individual risk acceptance criteria cover individual risks to passengers and crew. If the individual risks exceed any of those criteria, the level of risk is unacceptable and must be reduced. Furthermore a societal risk criterion was specified in terms of the potential loss of lives (PLL). This number represents the statistical expectation of the number of fatalities per year of operation of an average ship. Exceeding the societal risk criterion implies that the risk level is too high and that the risk must be reduced irrespective of costs. Finally, a cost effectiveness criterion is specified in terms of the cost of averting a fatality (CAF). This criterion need not be used if one can show that the societal risks are negligible. However, the historic collision and grounding risks are themselves significant. They were not aimed to be reduced in the present work. Therefore, irrespective of the new design, the total risk could not be regarded negligible and the CAF criterion would have to be used. This criterion does not apply to the design itself, but to identified RCOs. It implies that, after all the other risk criteria are met, RCOs having a CAF less than the given CAF criterion should be implemented to further reduce risk such as to become *As Low As Reasonably Practicable* (ALARP).

Table 14-1 Acceptance criteria for superstructure fires

Limit for intolerable *individual superstructure fire risk* for passengers.	$8.2\ 10^{-5}$ per ship year
Limit for intolerable *individual superstructure fire risk* for crew.	$7.5\ 10^{-4}$ per ship year
Limit for *intolerable societal superstructure fire risk* expressed as PLL	0.0005
Cost of averting a fatality (CAF) used for evaluation of RCOs (to be used as indicator including also serious and less serious injuries).	3 million USD

14.2.3 Major features of the risk based design

The risk assessment showed that, for the base design, the fire risk associated with the superstructure was much less than other risks (e.g. risks associated with grounding and collision), but nevertheless that the risk was indeed significant, above the target level and higher than that associated with a traditional steel design. Furthermore, assessment of RCOs identified through the risk based design process showed that there were a number of cost effective RCOs. The results of the risk assessment are summarized below. The RCOs considered cost effective on the basis of the risk assessment were:

- The use of a drencher system that is able to sprinkle water on the external surfaces of the superstructure. The aim of this RCO is to cool the external surfaces of the superstructure in the event of a fire so as to prevent the propagation of a fire via the external surfaces should external windows or doors fail to contain the fire.
- The use of windows and doors in external bulkheads that are rated to survive for at least 60 minutes in the standard fire. The aim of this RCO is to prevent flames and smoke from a fire inside the superstructure to escape to the outside and potentially cause fire propagation and a threat to the passengers that have escaped from the fire zone.
- The use of an emergency control station away from the bridge allowing controlling the fire-fighting and escape operations as well as navigating towards a safe refuge even if the bridge has had to be abandoned.

These RCOs had only a small impact on the weight and cost of the lightweight composite design and are unlikely to compromise the profitability of the novel design.

14.2.4 Fire risk assessment

A fire onset onboard a ship is not a particularly uncommon occurrence. However, due to effective fire safety measures, almost all fire onsets are safely extinguished before becoming a threat to passengers or crew. In rare cases, however, the fires develop and become a threat. Whether this happens or not depends on factors such as whether detection and active fire fighting systems function as intended, the precise location of the fire onset, the presence of persons nearby, their training and state of mind, whether fuel for the fire exists near the fire onset, the precise nature of the surface of these fuel items, local ventilation condition etc. These factors and their consequences do not lend themselves easily to theoretical predictions from first principles. For this reason, every fire risk assessment faces the challenge that the probabilities and initial development of relevant fire scenarios can currently not be predicted with theoretical models.

A solution to this problem is to *define* a limited set of design fire scenarios that, based on service experience and expert judgment, are *deemed* to contain the major risk contributions and assign probabilities to each scenario based on experience, judgment and available fire statistics. This simplified approach is acceptable according to international standards and guidelines (ISO 1999, SFPE 2000). A more rational approach was chosen in the present case. The design solutions that were considered for the alternative design were restricted to those options that would not change the probability of ignition and the initial development of a fire compared to that implied by the prescriptive fire requirements of SOLAS. How this was done was explained before. This ensures that the occurrence probability of a significant fire would be the same as that of traditional steel designs. This probability can be estimated from available fire accident statistics for ships and therefore need not be predicted from theoretical models or assigned based on judgment.

With this approach, an initial event being the occurrence of a significant fire could be defined with a probability that can be estimated from historic records. Furthermore because the composite superstructure model is located in the fore ship far away from the engine room, one can assume that the novel design would not affect engine room fire scenarios. Hence, only a subset of the fire accident statistics needs to be considered. Statistics for historic fires can be established from *Lloyd's Register – Fairplay* (online). Such statistics were compiled and reported by Vanem and Skjong (2004). According to their results the probability of a significant superstructure fire for this ship type is $5.6\ 10^{-4}$ per ship year. This probability is dominated by accidents that occurred before the latest amendments to the fire safety regulations where e.g. sprinkler systems became mandatory. Taking account of the reliability of sprinkler systems (Hall 2006), an improved estimate of this probability for current ships of $5\ 10^{-5}$ per ship year was established and used for the risk assessment.

From the initial event (occurrence of a significant superstructure fire), a range of 25 distinct fire scenarios were developed and together formed an event tree representing all the fire scenarios considered relevant. In this way, the risk model accounted for all fires from the small ones making little damage to uncontrolled fires that, due to the effectiveness of the adopted RCOs are very rare indeed, but if occurring would lead to severe consequences. Escape simulations were performed to estimate the required safe egress time. Small scale fire tests (
Figure 14-3) were performed to obtain input data for fire simulations.

Fire simulations (
Figure 14-4) predicted the development of significant fires and the propagation of heat and smoke in the specified fire scenarios. This could be compared to the results from the escape simulations to establish the risks associated with escape from the fire zone. Full scale fire test trials established the fire resistance of structural components such as decks and bulkheads (
Figure 14-5) including cable, pipe and duct penetrations (
Figure 14-6) and the effectiveness of fire rated windows and doors and external drencher system (
Figure 14-7) as RCOs. All fire tests were continued beyond the intended survival time thus providing information about the true capacity that was used in the risk modelling.

Furthermore, the effects of human decisions such as the captain's decision to abandon ship were included in the risk model. On that basis also the risks associated with the later stages of escalating fires were estimated. Making use of advice from the group of experts, this produced the conditional probabilities and consequences of all the events in the event tree. This allowed to estimate the consequences in terms of expected number of fatalities both among those nearby the initial fire being exposed to risk on their escape from the fire zone and those safely mustered that would be exposed to risks in the unlikely event of an escalating fire getting out of control. The risk contributions were updated for the RCOs such that the effect of adopting the RCO on risk could be quantified.

Figure 14-3 Small scale tests performed at SP (Sweden)to provide inputs to fire simulations

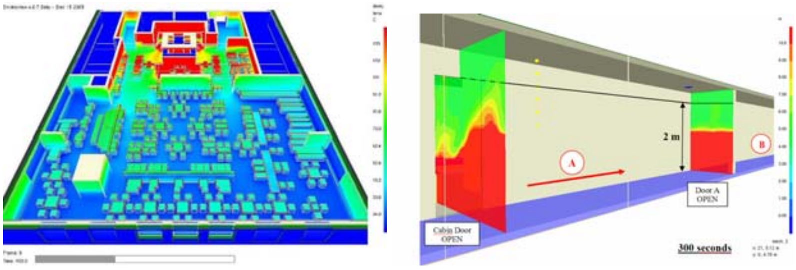

Figure 14-4 Results from unpublished simulations performed by CETENA of fires in the cafeteria and a corridor

Figure 14-5 Fire resistance test performed at Sintef (Norway) of a balsa-cored bulkhead that survived 2 h 20 min

Figure 14-6 Fire resistance test performed at SP (Sweden) of bulkhead with cable, pipe and AC duct penetrations

Figure 14-7 Full scale fire test trial performed at SP (Sweden) demonstrating the efficiency of a drencher system in preventing external fire propagation when an internal fire exits through a broken window

14.2.5 Results of fire risk assessment

Application of the fire risk model to the base design provided an estimate of the superstructure fire risk associated with it. All individual risk criteria were met. A superstructure fire PLL of 0.016 was estimated. This is above the limit specified for societal risk and may be regarded unacceptable. The effects of a range of RCOs were estimated using the risk model.

Figure 14-8 shows the estimated effects of the most promising RCOs. For comparison, the historic PLL from collision and grounding as well as fire are shown. The historic fire PLL includes contributions from all fires, also those that would not be caused by the superstructure fire (e.g. engine room fires) and is dominated by accidents that occurred before the latest amendments to the fire safety regulations. An attempt was made at correcting these two factors producing a lower and an upper bound estimate of the PLL due to superstructure fires in current steel designs. These estimates are also shown in Figure 14-8. The upper bound coincides with the target PLL defined in Table 14-1.

Figure 14-8 shows that the risk of the base design is above the specified acceptable societal risk (PLL) but that implementation of the most effective RCOs brings the PLL below the target such that it compares favourably with that of traditional steel designs.

The main reason why the risk of the composite superstructure is less than that estimated for steel superstructures is that the use of fire rated windows and doors increases the probability that a fire inside the superstructure will be contained inside and thus not be exposed to passengers and crew.

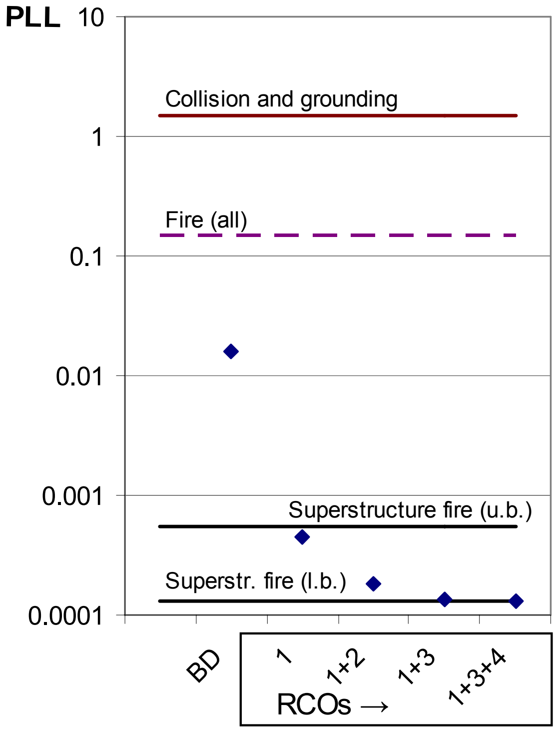

Figure 14-8 Estimated effect of the four most promising RCOs on societal risk of superstructure fires

14.3 Benefits of the risk based design

The composite design offers considerable weight-saving. Table 14-2 shows a comparison of weights and new-build costs of a steel design compared with two alternative composite designs for the case used in the first step of the study. About 60 % weight saving compared to the steel superstructure was estimated for the second composite design. The costs and weights include all the differences between the steel and composite designs such as fire insulation and deck coverings and can thus be compared directly. The estimated weight saving is likely to be attractive at the estimated cost if increased payload can be achieved for the particular project considered.

Table 14-2 Summary of weights and new-build costs of a steel design compared with two alternative composite designs for the case used in the first step of this study

	Weight (tonnes)		New-build cost (mill USD)	
	Superstructure	Saving	Superstructure	Increase
Steel reference design	950	0	4	0
Composite design 1	440	510	7,1	3,1
Composite design 2	360	590	6,9	2,9

14.4 Discussion

Simplifying assumptions were made in the risk assessment. One may replace some of these assumptions with more detailed simulations or test trials to provide more accurate estimates of conditional probabilities or consequences in the various fire scenarios and hence also more accurate risk estimates. However, the risk contributions from the various fire scenarios are all conditional upon the occurrence of a significant superstructure fire. The historic occurrence frequency of significant superstructure fires is indeed quite small. Hence one may conclude that that the sensitivity of the fire risk estimates to uncertainties in the conditional probabilities or consequences of the subsequent events is limited for alternative designs where the deviation from the prescriptive fire safety requirements do not alter the occurrence probability of significant superstructure fires. This implies that it would not be cost effective for such designs to invest a great effort at improving the fire risk estimates. If shipping safety is the concern, it would certainly be more useful to spend those resources on improving the understanding of more significant risks such as those due to collisions and groundings. This suggests that the level of rigor employed in the risk assessment is sufficient for the intended purpose.

The IMO guidelines on alternative design and arrangements for fire safety (IMO 2001) require that the effects of the uncertainties and limitations of the input parameters are determined by a sensitivity analysis. In the present case a probabilistic analysis was used. It explicitly includes uncertainties in the input parameters used to characterise the design fire scenarios and quantifies the effects of these uncertainties. Therefore, the probabilistic approach provides a direct and rational way of satisfying the requirement to perform a sensitivity analysis. However, simplifying assumptions and simplified models were needed to complete the assessment within reasonable budgets and time limits even with the probabilistic approach. Therefore, it is important also to assess the sensitivity of the conclusions to the uncertainties introduced by those simplifications. This was done by changing the best available estimates of probabilities and consequences with values that were considered obviously pessimistic. This did neither raise the individual or societal risk estimates into the intolerable region nor did it make additional RCOs cost effective. Therefore, it is considered that the reported conclusions are robust with regard to uncertainties and limitations of the input parameters.

All the RCOs that were cost effective according to the CAF criterion were adopted. In addition, some RCOs that were somewhat less cost effective were adopted although that would not strictly be required. Those RCOs were cost effective and did not significantly affect the cost of the superstructure module. They were adopted because they were considered to provide the margin necessary to ensure safe use of the new technology also for other slightly different design cases. Hence, the technology described herein is likely to have wider application than the design cases studied and could provide a useful basis for a possible future goal-based standard for composites in passenger ship superstructures should the ongoing work with the regulatory regime allow that in the future. Under the current regulations, however, the fire risks would have to be assessed in each individual case.

14.5 Conclusions

Current state of the art composite sandwich technology was used to develop a base design for a large superstructure module for a RoPax passenger ship. The weight of this light-weight design proved to be only about 40% of that of a traditional steel design. However, a risk assessment showed that, although individual risks were acceptable, the societal risk was not.

A risk based design process was performed leading to the identification of a set of risk control options deemed cost effective. Adopting these risk control options reduced the risk to acceptable levels that compare favourably with steel designs compliant with current prescriptive SOLAS requirements. Such a lightweight design could be regarded an alternative arrangement as defined in SOLAS and could therefore be approved according to SOLAS Ch II-2 Reg. 17. This gives promise for more efficient and profitable merchant ship designs in the future. Furthermore, the present work provides a useful basis for a possible future goal-based standard for composites in passenger ship superstructures should the ongoing work with the regulatory regime allow that in the future.

Acknowledgements

Tommy Hertzberg and Jesper Axelsson of SP, Sweden, provided valuable advice on fire testing and simulations and managed many of the tests trials and simulations from which the results were used to estimate risks. Federica Devoto of CETENA, Italy, performed a large amount of fire simulations used in the risk assessment. Arnulf Aa of Brødrene Aa, Norway, assisted with weight and cost estimates and making of test objects. The success of the risk based design process depended on the contributions also from many experts within all the relevant fields of expertise, too many to be mentioned individually here. The valuable contributions of all these persons are gratefully acknowledged.

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15 Summary and conclusions

The LASS main project targets were to demonstrate how to design lightweight ships using aluminium and FRP composites and to demonstrate practical methodologies for obtaining an approval and general acceptance for a lightweight design from authorities and classification societies. Targets were also a 30 % lower construction weight and a 25 % lower total cost (based on total operation time) compared to a conventional steel design. Participating ship owners did, however, quickly change the latter target for a 5-8 years pay-back time requirement. Both LCCA (life cycle cost analysis) and LCA (life cycle analysis) were used in the project in order to investigate costs and environmental impacts of using lightweight materials.

The LASS project organisation consists of 29 partners, 25 of these are Swedish and 9 are SME's (small or medium sized enterprises).

During the project, co-operation has been developed with several other lightweight projects, both national (DIBS-Swedish, EMC2-French), and EU projects (SAFEDOR IP), "De-Light Transport" (STREP) and SURSHIP (Eranet). The amount of existing and planned research projects in this area is a clear indication of the large interest in lightweight shipbuilding.

Together with SAFEDOR, a risk-based methodology was developed and demonstrated for "equivalent safety-acceptance" according to SOLAS regulation 17 on "Alternative design and arrangement", when combustible composites were used on a RoPax vessel. Together with "De-Light Transport", a lightweight ship conference was organised at the Kockums-Karlskrona ship yard in May 2008 and together with SURSHIP a ~500 k€ project on development of new IMO-regulations for fire protection of RoRo decks was initiated.

Initially was intended to study four different vessels: a high speed composite passenger craft, an aluminium HSC with composite superstructure, a RoRo-vessel with a deckhouse in aluminium and a RoPax vessel with superstructure made of composites. Two more objects for study were later included: a dry cargo vessel used mainly for inland waterway transportation, re-designed with parts in composites, and an offshore living quarter in aluminium.

Two very interesting lightweight materials for shipbuilding have been part of the investigations: extrudeble aluminium and composites consisting of a lightweight core material (PVC-foam or Balsa) surrounded by thin FRP (fibre reinforced polymer) laminates.

Aluminium is more easily acceptable for shipbuilding than composites by authorities and classification societies as it is already in use for HSC and passenger vessels. It is also part of the material group entitled by SOLAS "steel or equivalent materials" (chapter II-2 Reg 11), accepted for ship building. In the project it has been used for the design of a deck-house on a RoRo vessel and off-shore living quarters. In the process, discussions with the classification society Germanische Lloyd regarding class rules for strength requirements on such a deck house, made it possible to optimise the design based on FEM calculations using relevant loads. The extruded profile also made it possible to lower the deck house weight drastically.

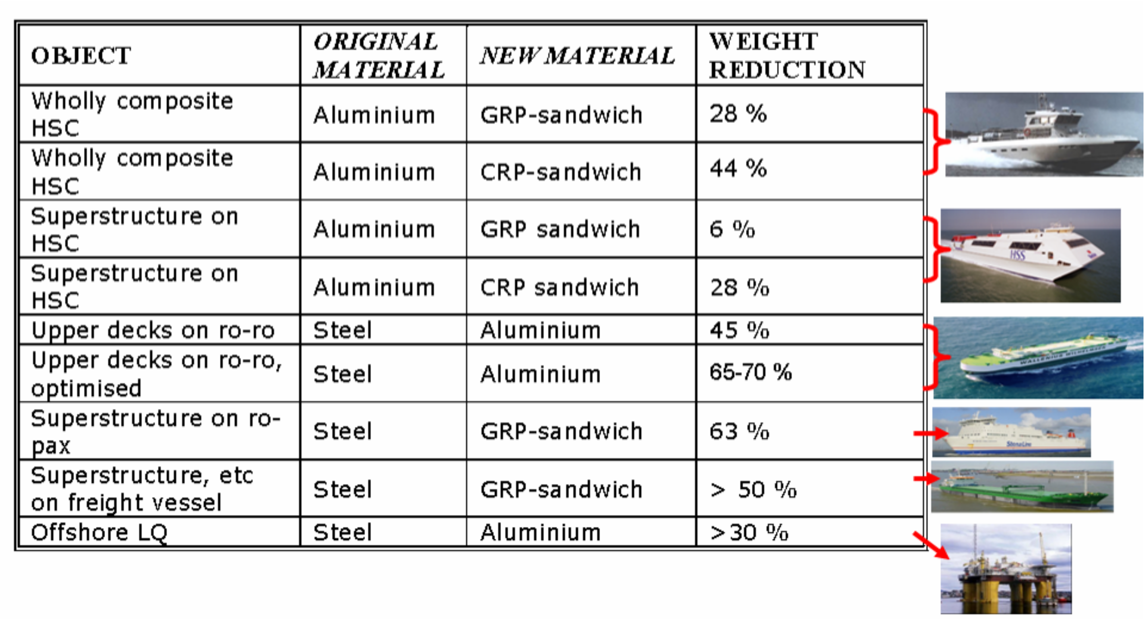
Aluminium was also used when designing a new offshore living quarter's construction that showed very promising results. Unfortunately, the construction was not fully completed, due to a reconstruction of the participating industry and WP-leader Pharmadule-Emtunga.

Much of the work in LASS has involved composites as this material was used in four out of six investigated objects. Composites also introduce the biggest challenges since they are not considered “steel or equivalent material”, i.e. they are not allowed to be used on a SOLAS vessel, at least not when the prescriptive SOLAS code is used as the basis for approval. Using the new regulation 17, however, it is possible provided safety can be demonstrated.

A focal point for the project has therefore been to demonstrate and certify fire safe composite construction elements for ships (deck, bulkhead, door and window in bulkhead, deck and bulkhead penetration constructions). Before the LASS project there were, to our knowledge, no such certified elements based on mineral wool. More than a dozen have been tested and certified as part of the LASS project. Thanks to this, it is now possible to actually build a high speed craft (HSC) in FRP-composites in accordance with the HSC-code. The certified construction elements also provide a basis for the methodology developed for equivalent safety acceptance for SOLAS vessels in accordance with SOLAS regulation 17.

15.1 Target results

All concrete targets for the LASS project have been reached. Typical weight reduction when using aluminium or FRP composites have been over 50 % compared to a conventional steel design[xviii] and cost analysis has demonstrated possible pay-back times of 5 years or less for the lightweight material investment. In the original application sent to VINNOVA, four objects were suggested for the investigation. Two more objects were added to the project at project mid-term and even though the analysis of these was less thorough due to constraints in time and resources, the addition can be said to have lead to the production of more results from the project than promised in the original application.



OBJECT	*ORIGINAL MATERIAL*	*NEW MATERIAL*	WEIGHT REDUCTION
Wholly composite HSC	Aluminium	GRP-sandwich	28 %
Wholly composite HSC	Aluminium	CRP-sandwich	44 %
Superstructure on HSC	Aluminium	GRP sandwich	6 %
Superstructure on HSC	Aluminium	CRP sandwich	28 %
Upper decks on ro-ro	Steel	Aluminium	45 %
Upper decks on ro-ro, optimised	Steel	Aluminium	65-70 %
Superstructure on ro-pax	Steel	GRP-sandwich	63 %
Superstructure, etc on freight vessel	Steel	GRP-sandwich	> 50 %
Offshore LQ	Steel	Aluminium	>30 %

Figure 15-1 Weight reductions obtained within LASS

[xviii] In Figure 15-1 is given weight reductions compared to the original material, which is not necessarily steel.

In Figure 15-1 the weight reductions obtained for all objects is shown. This was accomplished by making the design based on fire certified lightweight construction elements, using lightweight insulation materials. All necessary certificates were generated within the project.

15.2 Other results

As direct results of LASS, several commercial projects have been initiated. One example is the RoPax study and the risk-based safety methodology used in the ongoing discussions between the ship owner STENA and the British national authorities (MCA) regarding a new British-flagged RoPax ship with a composite superstructure.

Another example is the fact that the Swedish Coast Guard as a direct consequence of the LASS WP3a (the study on a composite HSC-vessel) results, decided to include composite materials in their purchase order for new patrol vessels. The more robust construction necessary for the Coast Guard compared to the passenger vessel in WP3a, was developed and designed by the LASS partner FMV, Swedish Defence Materiel Administration, as part of their contribution to the project. This work is reported in appendix-report “Prestudy of new surveillance ship”.

Yet a third example is the launching of a LASS-subgroup (Kockums, DIAB and Thermal Ceramics) commercial initiative on ”Composite Superstructure” (www.composite-superstructure.com).

Worth mentioning is also the two conferences on lightweight constructions held with more than 200 national and international participants. An initiative has also been taken for organising bi-annual, lightweight conferences in co-operation between the LASS group and the University in Glasgow.

The LASS project will further continue until 2009 in the form of another VINNOVA sponsored project ”LASS-c”, where composite constructions for part of the superstructure of a cruise vessel will be studied. The web site www.lass.nu had received almost 9 000 visitors in January 2009 and it will also host the LASS-c project. Therefore, it will be continuously active in spreading information on lightweight constructions.

Finally, a very important result is the Technical Platform created and the network of contacts obtained for the 29 LASS partners and also the numerous contact points generated with different industries and universities outside of the consortium. The ongoing co-operations with several EU and national projects should be mentioned in this context.

The project, “Lightweight construction applications at sea”, will through all of the factors mentioned above, continue for a long time.

Appendix

In addition to this report, a number of appendix-reports have been added as separate documents that are downloadable from the website www.lass.nu.

16 Acknowledgements

The LASS projects main sponsor has been VINNOVA, The Swedish Governmental Agency for Innovation Systems. Support was given to LASS specifically from the VINNOVA programme "Light materials and lightweight design". The importance of this support and the support from the programme manager Anders Marén, is greatly acknowledged.

Further has the project been possible through important contributions given by all LASS participants. We started with a budget of ~22 MSEK and ended having used over 25 MSEK, as more resources were put in to the project from the partners than was originally asked for.

I am indebted to Mr Dag Mcgeorge at DNV, leader of a SAFEDOR subgroup that helped fulfil the LASS target on a methodology for safety assessment in accordance with SOLAS regulation 17. I would in this context also like to thank Mr Björn Höjning from the Norwegian company Fireco AS for the assistance and support in understanding composite ship constructions and the behaviour of such constructions under fire conditions.

Co-ordinating LASS has been a very easy task due to a project group of highly motivated people, all experts in their particular field of knowledge. I am in particular most grateful for the support and ease of communication with the LASS research group: Kurt Olofsson from SICOMP-Swerea, Anders Ulfvarson and Gaurav Ahuja from Chalmers, Peter Gylfe and Robert Hjulbäck from SSPA, Jörgen Sökjer-Petersen and Henrik Johansson from Kockums, Anna-Hedlund Åström from KTH. A special thanks also to ship designer Mats Hjortberg at Coriolis AB for his assistance and help to understand shipbuilding and the IMO regulations.

The project is indebted to the willingness and support to certify fire safe constructions from the insulation companies Thermal Ceramics and Saint-Gobain/Isover. I appreciate the vivid discussions and open exchange of information on ship building and insulation made possible through the frequent project participation of Mr Allan Beeston from Thermal Ceramics and Mr Jan Goor from Saint-Gobain/Isover.

I could finally add a long list of Swedish people in the LASS consortium that have taken active and often decisive roles in the developments made. There is a long tradition of shipbuilding and materials in Sweden and the project has been lucky enough to attract some of this existing expertise. As there have been a lot of people involved and there is a risk of forgetting to mention someone, I prefer to give the link to the LASS web-site where all people are presented, www.lass.nu.

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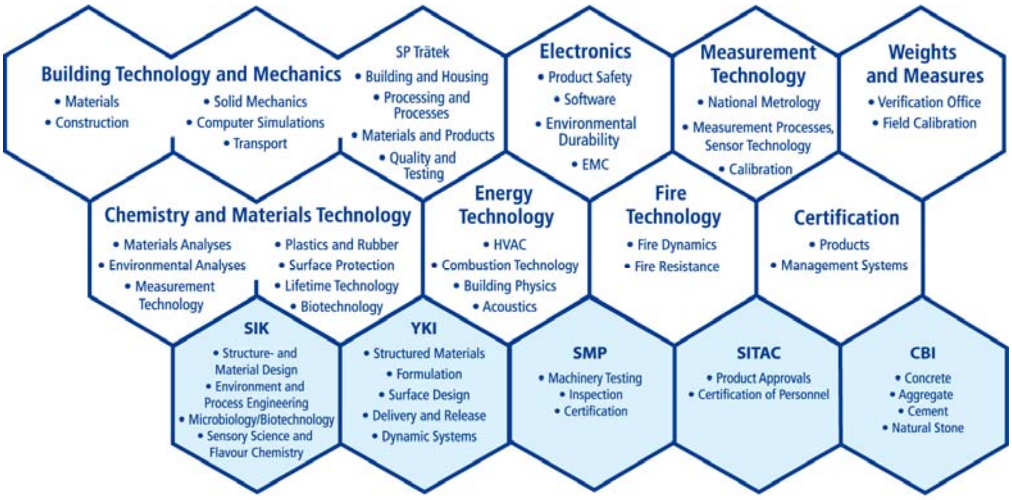

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