Abstract

The use of light weight materials is increasing at a rapid pace in the marine industry. Stena Line, a Swedish shipping company has a number of passenger ferries running in the European region. They are the proud owners of the HSS series of ships, which are unique as they are catamarans made of aluminium with a maximum length of 124 m. In this report the possibility of having a sandwich superstructure for HSS 900 is evaluated. The preliminary design of the structure under DNV regulations is looked into. Possibilities of using different types of cores and laminates for making the superstructure have been studied. Calculations reveal that about 2.9 kg/m^2 could be saved if sandwich construction is implemented. As it is a weight critical approach, an optimization in terms of weight of the structure has also been performed. ESAComp 3.4 is a software for analysis of composite laminates. It has been extensively utilised in doing the calculations for this project.

Nomenclature

b – Shortest side of the Sandwich panel
C_w – Wave coefficient
C_l, C_s, C_N, C_6, C_7 *and* $C8$ – Constants defined in the DNV HSLC rules, Pt.3 Ch. 4 Sec 5, Pg 18, 19
d – Distance between centre lines of the laminates of a sandwich
Ec – Modulus of the core
Ef – Modulus of the laminate or the face
Gc – Shear Modulus of the core
h_0 – Vertical distance in m from the waterline at draught T to the load point
L – Length of the vessel between perpendiculars
p – Design sea pressure
t – Thickness of the laminate
T – Fully loaded draught in m with the craft floating at rest in calm water.
W_0 – From Table A2, DNV HSLC rules, Pt.3 Ch. 4 Sec 5, Pg 17
W – Mass of reinforcement per unit area (g/m^2)
σ_n – Normal Stress
τ_c – Shear Stress taken by the core
ω – Deflection of the sandwich panel
ρ – Density of the laminate
v – Poisson's Ration
σ_{cr} – Wrinkling Stress

1. INTRODUCTION AND PROBLEM DEFINITION

1.1 A Systems Approach[1]

The problem in question here is to consider the potential of a composite superstructure for the 88 m long aluminium catamaran, Stena Carisma [7]. It is a passenger ferry running between Fredrikshavn in Denmark and Gothenburg in Sweden. The present structure is made in the same material as the rest of the hull which is aluminium. A composite superstructure might help in reducing the light weight of the ship and thus enhance its load carrying capacity. The shaded region in Figure 1 represents the part intended to be studied for sandwich construction. Splitting the problem into parts and dealing with one part at a time was considered the best way to conduct this study. Composites in the marine industry have so far been dominant in the small boat segment [4], in recent times though their implementation in bigger boats and ships is gaining a serious angle.

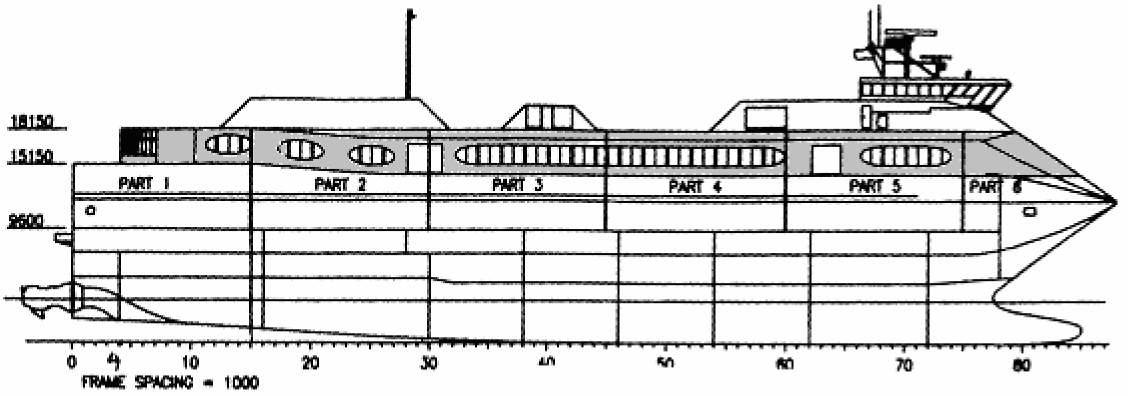

Figure 1 The shaded portion is the superstructure

A systematic approach has been formulated here to counter the problem, which has several parts-

- Selection of material for laminates and core
- Calculations according to DNV HSLC regulations
- FEM calculations
- Joining of the Aluminium Hull with the Sandwich superstructure
- Requirements on Fire Safety because of the composites used
- Method of Manufacture

Although the numbers of issues involved in the project are numerous, in the confines of this paper, only the selection of the materials, structural hand calculations and a basic optimisation are looked upon.

1.2 Division Of The Structure

The superstructure of Stena Carisma is 83 m long and divided into six parts. Each section or part varies from 10 to 20 m in length. This division into parts ensures that it does not contribute to the global hull strength. Each part is small enough not to bend significantly with the hogging or sagging hull. For ease of understanding an 18 m stretch of the superstructure is studied, which would be 30 m wide. There are transverse frames supporting the panels at every 2 m.

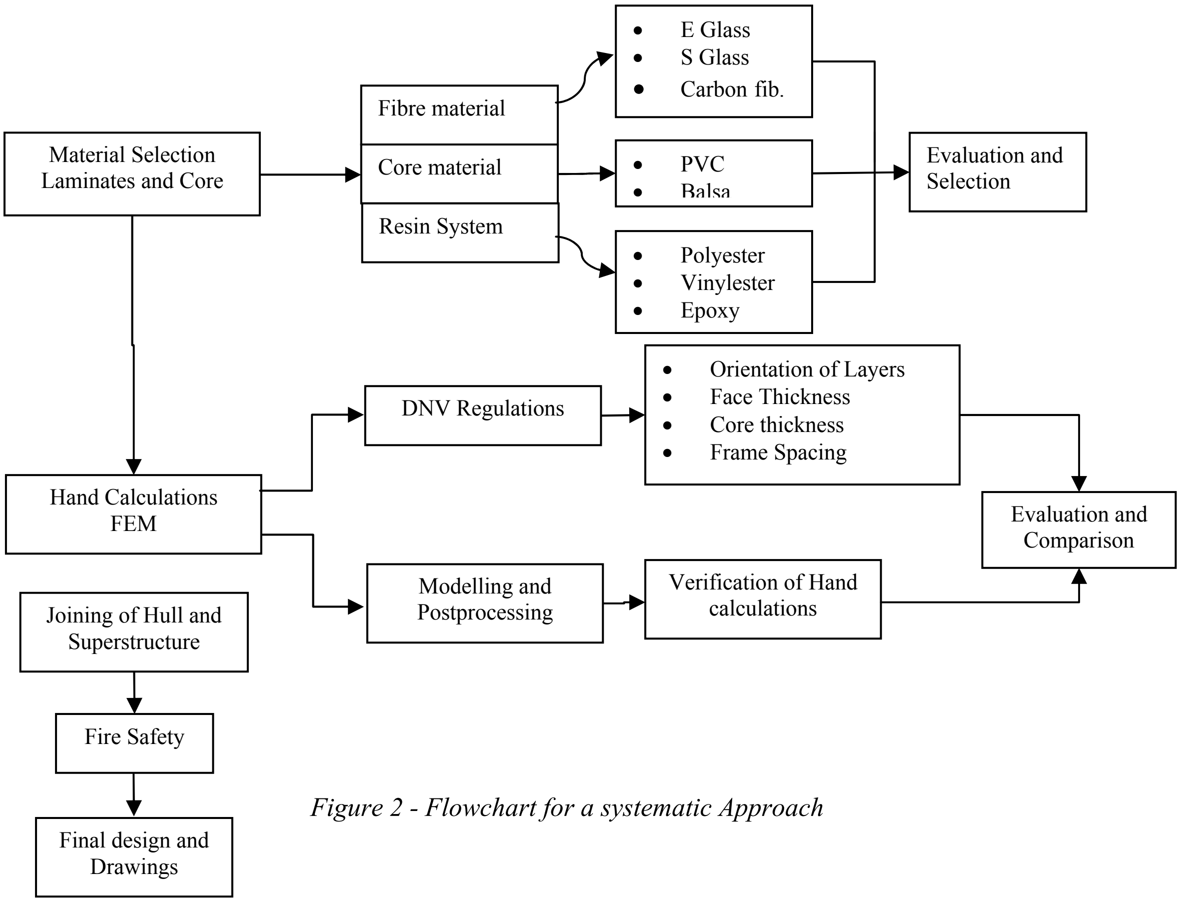

Figure 2 - Flowchart for a systematic Approach

1.3 The Panel On The Weather Deck

The aluminium plate on the superstructure which at many places acts as the weather deck is 2.5 mm thick and has extruded longitudinal stiffeners at a spacing of 140 mm. These stiffeners are welded to the transverse frames. As the transverses are not welded to the plate, there is no contribution to the frames in the form of effective flange from the plate. Hence some weight saving would be achieved by the contribution of the lower plate of the sandwich as an effective flange. At every 4.6 m there are bigger longitudinal frames supporting the transverses.

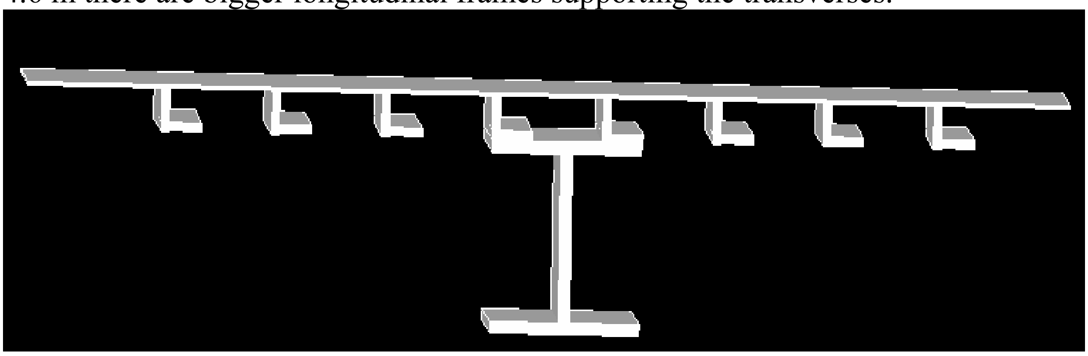

Figure 3 Present Arrangement of the plate and the longitudinal stiffener

1.4 Loading Condition

The design sea pressure according to DNV is given by –

$$p = a.K_s(Cw - 0.67.h_0/T).C_w$$

The value of p on calculation is less than 3 kN/m^2. The rules also state that the minimum design pressure is not to be less than 3 kN/m^2, which in this case becomes the design load.

2 MATERIALS AND MECHANICS

A sandwich can be correlated to a system where different subsystems interact to form a stiff structure [5]. Unlike a plate of steel or aluminium where there is only one isotropic layer, here the layers of materials interact with each other at different levels depending on their orientation and individual properties. The various parts of a sandwich are to be looked into, the requirements of each part and their selection on the basis of fulfilment of those requirements. A basic methodology according to Myer Kutz for material selection has been followed [3]. This preliminary selection of materials would then be followed by the calculations. It should be noted that at this stage of the project, fire has not been taken into account. Work related to fire is under way and talks are being held with some fire insulation companies.

2.1 Cores

The requirements on the core of a sandwich say that it should have low density, high compressive and shear strength, and high shear modulus and be thermally stable. It should also posses a good resistance to water penetration and have good fatigue strength. A number of materials have been developed as cores that have been successfully used in the marine industry. For this superstructure a PVC core or Balsa wood seem to be appropriate.

DIAB is a popular choice for cores and fortunately they are also partners in this project hence calculations etc have been carried out using information from their product catalogues [8]. The *Divinycell* structural foam cores offer good mechanical properties; they are classified as H, HT, HP, HCP and HD grade. The HD core [8] is mainly intended for use below the water line, hence it has not been considered. The HCP core is strong and heavy and unsuitable for this purpose. Further the H, HP and HT grade of cores are split into cores of different densities and strengths. As the loading on the superstructure is the lateral 3 kN/m^2, high densities and very high shear strengths are ignored.

End grain Balsa (i.e. grains oriented in the through thickness direction) is an efficient core, providing good strength with low density. The major problem with Balsa is susceptibility to water penetration, leading to swelling, debonding and rotting. DIAB also has DNV approval on the Balsa cores. They have mainly three kinds of Balsa cores, but all three of them are heavy when compared to the available PVC cores. Hence only the H series cores have been taken into consideration. All calculations have been performed with the H45 core.

Property	Unit	H 45	H 60	Balsa LD7 Lightweight
Nominal Density	kg/m^3	48	60	90
Shear Strength	MPa	0.56	0.8	1.6
Shear Modulus	MPa	18	22	96

Table 1 Properties of different cores

2.2 Laminates

A face or a laminate consists of a resin system and the fibres that are embedded into it. A laminate comprises of plies or laminas that are built up of a fibres and resins. The fibre that could be used for making the faces of structure should be light and strong.

2.2.1 Fibres

The fibres are responsible for taking a majority of tensile and compressive loads [4]. An initial investigation into the kind of fibres that can be used for this project resulted in E-glass, S-glass, Carbon fibre and Aramid Kevlar. The poor compressive strength of Aramid acted as a catalyst in disregarding it. The major advantage of E-glass is that it is a high strength and low cost material. The high strength S glass has slightly better mechanical properties than E-glass and is also more expensive. Carbon fibres are premium when compared to glass fibres, due to the complexity of production. But their high cost can be justified in weight critical structures or after a life cycle analysis [9]. Some properties of the fibre materials in consideration are as follows –

Property	Unit	E – Glass	Carbon Fibre
Young's modulus	GPa	72	230 / 40
Density of fibre	kg/m^3	2600	1710
Poisson's Ratio	-	0.2	0.25

Table 2 Properties of different fibres [1, 4]

2.2.2 Resin System

The most commonly used resin in marine applications is polyester. It is moderately priced and is easy to handle. Vinyl ester, Phenolics and Epoxies are also used depending on the application. As fire safety is very important for marine applications, phenolics offer an edge over other resins. In case of a fire, a phenolic based laminate would burn on the outside forming a char. This char prevents the burning of the inner material. Their initial physical strength is slightly lower than the polyesters however, in the case of a fire; they are capable of maintaining their strength for a longer time period and to a higher temperature. But being very viscous, phenolics also exhibit issues when it comes to infusion. The various physical properties of the resins studied are –

Property	Unit	Polyester (isopthalpic)	Epoxy	Phenolics
Density	Kg/m^3	1210	1200	1150
Young's Modulus	GPa	3.6	3.0	3.0
Poisson's Ratio	-	0.36	0.37	-

Table 3 Properties of different resins

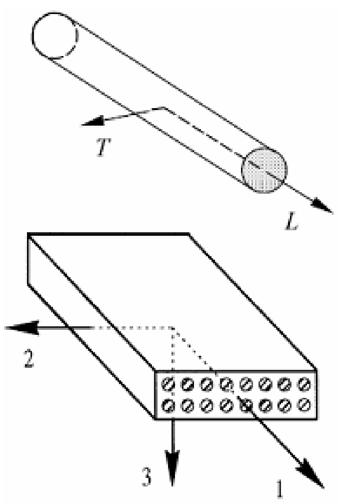

Figure 4 Fibres and a ply [9]

2.2.3 Micro Mechanics of a Glass Fibre and Polyester resin

Fibres are transversely isotropic, the plane of isotropy lying perpendicular to the longitudinal axis of the fibre. Figure 4 illustrates L as the longitudinal while T as the transverse axis of the fibre. A cluster of fibres in a matrix system, results in different physical properties of the lamina in different directions. The properties of a ply are dependent on the properties, quantities and directionality of matrix and fibre in the lamina. A ply having all its fibres aligned in one direction is apt for this application. Assortment of unidirectional (UD) plies in different directions would construct a laminate with different properties in different directions. The reinforcement as defined by DNV, to be present in the laminate of a superstructure is–

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

This gives 2260 g/m^2 of glass fibre and 1508 g/m^2 for carbon.

This reinforcement is distributed into the number of plies that will make a laminate or the face of the sandwich. To have a fair balance, eight plies have been chosen, which gives 283 g/m^2 in each ply. The ply is filled with 50 percent of fibre and matrix and rest of the composition is as follows –

Thickness	Density	Mass per unit area	Directionality
0.25 mm	1905 kg/m^3	476.25 g/m^2	100 % (UD)

Various in plane and out of plane engineering constants of the ply are calculated using the Mechanics of Materials approach as defined in [1] and [5]. The strength of such a glass fibre ply is determined from experiments etc, for more detailed information on first failure stresses and ultimate failure stresses and strains refer to [5]. These physical properties are calculated with the help of ESAComp 3.4

Young's modulus		
	E1	37.8 GPa
	E2	6.85 GPa
	E3	6.85 GPa
Shear Modulus		
	G12	2.53 GPa
	G31	2.53 GPa
	G23	3.26 GPa
Poisson's Ratio		
	ν12	0,28
	ν13	0,28
	ν23	0,05

Direction 1		Stress (MPa)
	Tensile Strength	500
	Comp. Strength	360
Direction 2		
	Tensile Strength	25
	Comp. Strength	80
Shear Strength Plane 12		35

Table 4 Physical properties of the ply in different directions

2.2.4 Sandwich

Combination of plies makes a laminate and two laminates on either side of a core material would make a sandwich. The eight plies that have been chosen shall be laid out in different directions to ensure reasonable properties in all the directions. According to DNV, the modulus of elasticity should not be more than 20% different for the two major directions; hence the layout has been chosen to as to meet this requirement. The layout of the plies in the laminate is [0/0/30/60/-60/-30/90/90]. In the first model of the sandwich a light core (H45) has been used. From the laminate and the core, the sandwich was modelled and the properties of the sandwich were calculated [6].
The core is isotropic in nature hence its directionality does not make a difference. The core represented by the criss cross lines in the centre (0°) is not scaled. Classical Laminate theory (CLT) is used for doing the stiffness analyses of the laminate. Young's modulus and Shear Modulus for the laminate have been calculated to be –

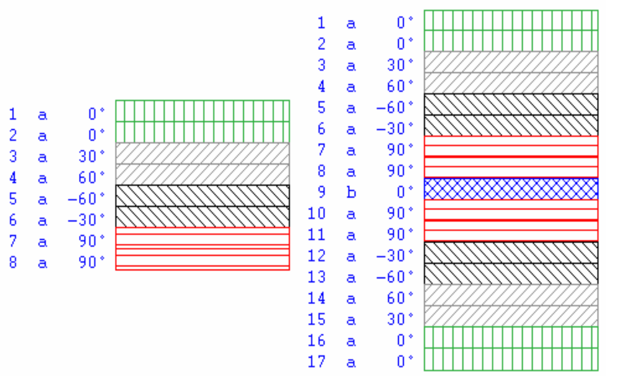

Figure 5 The configuration of the face and the Sandwich

Ex = 12.94 GPa
Ey = 13.33 GPa
Gxy = 5.21 GPa

2.2.5 Boundary Condition

Three types of boundary conditions are specified in the regulations, simple, fixed and partially fixed. For this case, the boundary condition chosen for the sandwich panels is partially fixed, as a simple support seemed too conservative while fixed too open minded. As expected the results obtained with partially fixed BC is almost halfway between the other two.

For the beams as well, it has been assumed that they are partially fixed at the ends, for both longitudinal and transverses as well.

2.3 Macro mechanics of the Sandwich

In the DNV regulations, there are four major requirements other than the amount of reinforcement in the laminate that need to be fulfilled, these are –

i. Maximum normal stress
ii. Maximum shear stress
iii. Maximum allowed deflection
iv. Wrinkling of the face

The faces are assumed to be thin when compared to the thickness of the sandwich (i.e. d/t > 5.77). Hence the thick face affect is ignored. As per the rules the above mentioned four requirements are given by the following formulas –

$$\text{Normal Stress } \sigma_n = \frac{160pb^2}{d.t} C_N C_1 \ (N/mm^2) \qquad \text{Shear Stress } \tau_c = \frac{0.52\, pb}{d} C_s \ (N/mm^2)$$

$$\text{Deflection } \omega = \frac{10^6 pb^4}{D_2} (C_6 C_8 + \rho C_7) \qquad \text{where } D_2 = \frac{Etd^2}{2(1-v^2)}$$

Wrinkling $\sigma_{cr} = 0.5\ (E\ Ec\ Gc)\ ^\wedge\ (1/3)$

The formulas for maximum allowed values of these four criteria are also mentioned in the rules, from which the following is obtained –

$w_{max} = 40\ mm$
$\sigma_{max} = 0.3\ \sigma_{nu}$ *where* $\sigma_{nu} = 72\ MPa$, $\sigma_{max} = 21.6\ MPa$
$\tau_{max} = 0.4\ \tau_u$, *where* $\tau_u = 0.55\ MPa$, $\tau_{max} = 0.22\ MPa$

The maximum normal stress allowed is also used for the allowed stress for wrinkling. The calculations are first performed for a weather deck of dimension 18 by 18.4 m. These are then extended to get a weight estimate of the total section.

3. OPTIMIZATION

As the main idea behind the project is to reduce the light weight of the structure, a procedure of finding the optimum point of various variables affecting the weight is followed. The variables that directly affect the weight are –

- Face thickness
- Core thickness
- Frame spacing

The amount of reinforcement in the laminate determined the minimum thickness requirement of the face thickness. From this it was calculated that to get 2260 g/m^2 of fibre in the laminate, eight faces of 0.25 mm thickness were required. Hence a minimum constraint on the laminate is defined.

3.1 Sandwich Panel optimization

The sandwich panel between the frames, is optimized by finding the point where the face and core thickness meet all the requirements laid out by DNV. As earlier suggested, the frame spacing for this case has been kept at 2 m. Figure 6 outlines the procedure. The slanted lines represent the objective function of weight of the panel. The vertical dashed line represents the minimum amount of thickness required, however in the initial design the face thickness has been fixed at 2 mm, hence this constraint is already fulfilled. The dotted line is the amount of deflection of the panel, which also happens to be the design driver in this case. The cross represents the point where the weight is a minimum. The circle is the initial point from where the search for the optimum point started. At the cross, all the requirements are fulfilled

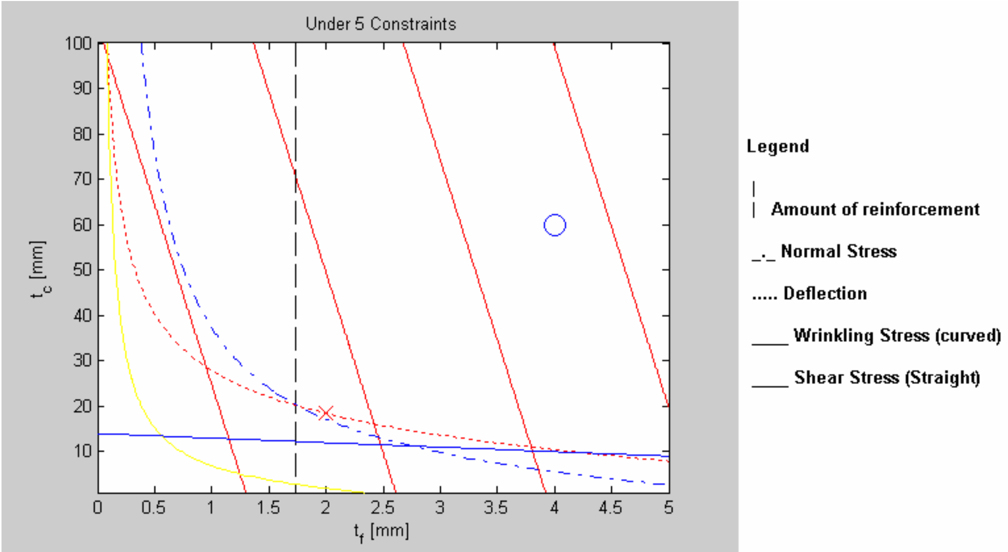

Figure 6 Optimization of a Sandwich Panel

3.2 Optimized Spacing of Frames

The longitudinal frame spacing in the present aluminium superstructure is 4.6 m. As the weight of the transverse frames is directly dependent on the square of the length of the beams, the distance between the longitudinal is kept fixed at 4.6 m. If this spacing is increased, the weight of the transverse beams increases significantly. Hence the optimum point is to keep the length of the transverse or the spacing between the longitudinal uniform at 4.6 m.

The present spacing between the transverses is 2 m, as the distance between these frames is reduced the strength requirements on the sandwich panel reduce and so does the weight of the panel. The weight of the panel is also dependent on the thicknesses of the core and the laminate, which have to meet the various requirements laid out by the classification society. The section modulus requirement of the transverse beams reduces linearly with the spacing and so does the weight; the number of beams thus increases, consequentially increasing the weight as well. Total weight thus changes with variables and in this change somewhere there is an optimum point where weight is a minimum. The aim is to find that point.

Various frame spacing ranging from 100 mm to 4 m, in steps of 100 mm were plotted to find the point of lowest weight. For all the frame spacing, the sandwich panel was optimised for weight. Core and face thicknesses were checked to ensure that they meet all the requirements and also do not contribute excessively to the weight. The weight of the frame was optimised by distributing the material in the web and the flange to obtain the right section modulus and keeping a low weight. However as the frame spacing exceeded 3 m, the deflections became too high for the Mindlin plate theory to hold, the results on that side are thus not reliable, but are presented for a comparison. It can be seen from Figure 7 that the total weight of the transverse and longitudinal frames and the panel remains on a fairly constant level between 1 and 2 m spacing. The weight is lowest at about 1 m, and increases slightly at 2 m. After 2 m and before 1 m, the weight increases sharply because of the minimum constraints on the thicknesses of the plates, web and flange, to avoid buckling. Thus labour cost would be the determining factor in choosing adequate spacing. It can be suggested that the present Aluminium frame spacing of 2 m would serve the purpose well. A graph like Figure 6 cannot be drawn for the frame spacing vs. weight variation curve as the number of variables involved are more than two, hence the graph would become multidimensional.

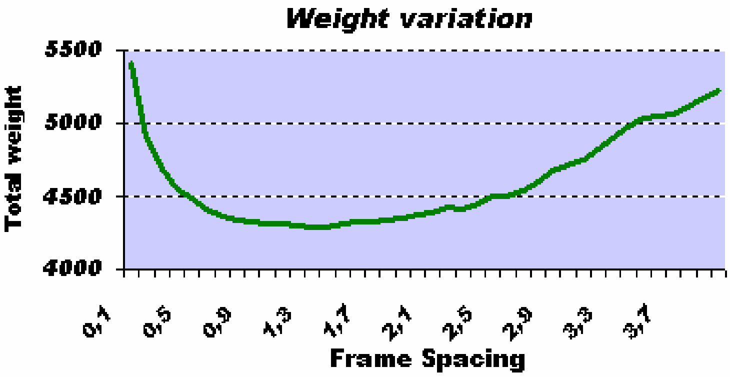

Figure 7 Weight variation with change in frame spacing

The unit weight with an aluminium structure comprising of longitudinal, transverses, plate and stiffeners is 16.17 kg/m^2. The weight per meter square of the sandwich glass fibre laminate with a PVC core and glass fibre transverse and longitudinal is found out to be about 13.2 kg/m^2. This is the weight without taking into account the additional requirements of fire insulation. Including those, the weight would be higher.

Of particular interest here is that the weight of the glass fibre and aluminium panel is not very different. The sandwich weighs 8.6 kg/m^2 and the aluminium panel with the extruded stiffeners weighs 9.5 kg/m^2. The inclusion of the weight of the fire insulation would probably balance this difference. The major saving in weight comes from the transverse and longitudinal beams. As in the case of aluminium, there is no utilisation of the effective flange, where as in the glass fibre beams, the lower sheet of the sandwich contributes to the section modulus of the beam. This results in a significant amount of saving for the glass fibre. The contribution from the lower skin of the sandwich to the section modulus of the beam is about 36%. If the aluminium plate were made utilised as an effective flange then the weight of the aluminium structure would be lesser, but it would have caused an increases amount of welding and also would have resulted in loss of strength of the plate.

Similar calculations for carbon fibre revealed a weight of 10.2 Kg/m^2. From aluminium to carbon fibre, there is a weight saving of almost 37%. However handling and manufacture with carbon fibre would be expensive both in terms of material and labour cost. A thorough life cycle analysis needs to be performed to check the profitability and pay back time with lighter materials.

4. CONCLUSIONS

Two different materials have been used for doing the calculations. Both the materials indicate a weight saving. It seems from the results that it would be a worthwhile investment to build up a composite superstructure for this vessel.

However, there are various issues that need to be addressed, both pre and post manufacturing. Fire insulation should be given special consideration as the design is for a passenger ferry. If excessive insulation is required then there may not be enough weight saving to make this a profitable venture.

Massive usage of composite and Sandwich construction is possibly the next step in the world of construction. Light weight constructions give the shipping industry an advantage of carrying more cargo and earn more revenues. Composite also provide the flexibility of shape and form and thus can be an excellent from the viewpoint of aesthetics.

5. ACKNOWLEDGEMENTS

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