IMPLEMENTING COMPOSITE SUPERSTRUCTURES IN LARGE PASSENGER SHIPS

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ABSTRACT

This study focuses on the structural response of the part of the superstructure of a RoPax ferry that has been redesigned using composite materials. The composite superstructure is presented and subsequently compared to the existing steel design considering different loading conditions by the use of FE modelling. Results indicate that it is not the structural response of the superstructure that inhibits the implementation of composites in the superstructures of large passenger ships but the complicated design procedure and the acceptance of such solutions by the regulatory bodies.

1. INTRODUCTION

Composite materials are increasingly being implemented in a wide variety of industrial applications where metallic materials were predominantly considered as the only viable option. This is due to the attributes they exhibit such as the high specific strength/stiffness ratio, their durability and their resistance to corrosion to name but a few. Moreover, recent technological advancements have led to the industrialisation of composite materials reducing their cost.

In the marine industry composite materials have been mainly used for small crafts and military vessels as the use of composite materials on SOLAS ships had been restricted until 2002 when the so-called Rule 17 [1] was introduced in the SOLAS convention. This regulation enabled the use of combustible composite materials provided that the same level of safety as for the metallic design could be demonstrated.

This regulation has allowed for alternative designs which can increase the efficiency of the ship. One way to achieve this is by designing composite superstructures. A light superstructure results in reduced lightship and in improved stability for the vessel. These benefits are more prominent in the case of passenger ships as superstructures comprise a larger percentage of the lightship and they may tower well above the weather deck.

Despite the benefits that the implementation of composite materials represent, to this day this regulation has been rarely used in practice as both the technical aspects and the appropriate regulatory approval related to the implementation of composites have proven to be complex, time-consuming and therefore not appealing to the ship stakeholders.

The work presented in this paper has been performed within the context of the COMPASS project and is an expansion of a previous work [2] carried out by the same authors. The main aim of COMPASS is to provide guidance to designers and regulatory bodies by suggesting a standardized approach for the implementation of composite superstructures on large passenger ships. To achieve this, an existing RoPax ferry operating between Denmark and Germany has been selected as a case study and its superstructure has been redesigned using composite materials. This work focuses on the structural response of the superstructure for both the steel and the composite case under different loading scenarios.

2. STRUCTURAL DESIGN

2.1 CASE STUDY

The ship selected is a double-ended RoPax ferry named PRINSESSE BENEDIKTE and is operated by Scandlines. The main characteristics of the vessel are listed in Table 1. The upper decks of the superstructure, i.e. the wheelhouse and passenger decks, were selected for retrofitting. Given that the original requirements and constraints on the steel design were unknown, the governing parameter for the new design was to keep the general arrangement unchanged. Bearing this in mind, it is evident that this design might not be the most efficient one. To achieve an optimised design, a life cycle cost analysis is necessary.

Table 1: Ship Characteristics

Length oa	142	[m]
Breadth	24.8	[m]
Depth	8.5	[m]
Draught	5.8	[m]
Service speed	18.5	[kn]
Displacement tonnage	9600	[t]
Lightship	7000	[t]
Gross tonnage	14822	

Fig. 1: PRINSESSE BENEDIKTE

2.2 MATERIALS

GBX450L-1250 E-glass Stitched fabric and Prime 20LV epoxy resin were selected for the sandwich faces. The core was Divinycell P100 provided by DIAB which exhibits good fire, toxicity and smoke properties and high temperature performance. Typical marine grade steel was used in the case of the steel superstructure. The material properties are listed in Table 2.

Table 2: Material properties

Lamina	E_1	21.2	[GPa]
	E_2	21.2	[GPa]
	v_{12}	0.14	–
	G_{12}	3.05	[GPa]
Core	Ec	0.10	[GPa]
	Gc	0.028	[GPa]
Steel	E	203	[GPa]
	v	0.3	–

2.3 DESIGN LOADS AND SCANTLING REQUIREMENTS

DNV's rules were used for the design of the composite superstructure. In particular, the scantling calculations were performed following DNV's Rules for Classification of High Speed, Light Craft and Naval Surface Craft [3,5] while the design loads were calculated according to DNV's Rules for Classifications of Ships [4,5]. The sandwich panel ply sequences are listed in Table 3

Table 3: Composite superstructure lay up

Superstructure	Structural Bulkheads	Accommodation deck	Wheelhouse deck	Wheelhouse
1x $600g/m^2$, Woven Roving $0^o/90^o$	*2x $450g/m^2$, Stitched fabric $0^o/90^o$*	*1x $600g/m^2$, Woven Roving $0^o/90^o$*	*1x $600g/m^2$, Woven Roving $0^o/90^o$*	*1x $600g/m^2$, Woven Roving $0^o/90^o$*
2x $450g/m^2$, Stitched fabric $0^o/90^o$	*2x $450g/m^2$, Stitched fabric +/-45^o*	*2x $450g/m^2$, Stitched fabric $0^o/90^o$*	*2x $450g/m^2$, Stitched fabric $0^o/90^o$*	*2x $450g/m^2$, Stitched fabric $0^o/90^o$*
1x $450g/m^2$, Stitched fabric +/-45^o	*+ local reinforcement*	*2x $450g/m^2$, Stitched fabric +/-45^o*	*1x $450g/m^2$, Stitched fabric +/-45^o*	*2x $450g/m^2$, Stitched fabric +/-45^o*
2x $450g/m^2$, Stitched fabric $0^o/90^o$		*2x $450g/m^2$, Stitched fabric $0^o/90^o$*	*2x $450g/m^2$, Stitched fabric $0^o/90^o$*	*2x $450g/m^2$, Stitched fabric $0^o/90^o$*
Core 40mm	*Core 40mm*	*Core 50mm*	*Core 50mm*	*Core 40mm*
2x $450g/m^2$, Stitched fabric $0^o/90^o$	*2x $450g/m^2$, Stitched fabric +/-45^o*	*2x $450g/m^2$, Stitched fabric $0^o/90^o$*	*2x $450g/m^2$, Stitched fabric $0^o/90^o$*	*2x $450g/m^2$, Stitched fabric $0^o/90^o$*
1x $450g/m^2$, Stitched fabric +/-45^o	*2x $450g/m^2$, Stitched fabric $0^o/90^o$*	*2x $450g/m^2$, Stitched fabric +/-45^o*	*1x $450g/m^2$, Stitched fabric +/-45^o*	*2x $450g/m^2$, Stitched fabric +/-45^o*
2x $450g/m^2$ Stitched fabric $0^o/90^o$	*+ local reinforcement*	*2x $450g/m^2$, Stitched fabric $0^o/90^o$*	*2x $450g/m^2$, Stitched fabric $0^o/90^o$*	

2.4 LOADING CASES

The interaction of the superstructure with the hull of the ship is quite complex. In ships with long continuous superstructures and many decks high, the superstructures unavoidably carry stresses transmitted from the hull girder. Therefore these structures are made effective with adequate scantlings. In smaller ships however it is common to design the superstructure in such a way so as not to contribute to the longitudinal strength of the ship. This can be achieved by different means. One of them, which can be found in older ships, is by fitting expansion joints in suitable positions rendering in this way the structure ineffective from a load carrying perspective. Other methods include the use of lower modulus materials, such as aluminum, as the lower modulus of elasticity results in lower stresses in the structure compared to the steel case, or geometrically designing the superstructure in such a way so that the stress transmission from the hull is minimized. As one might suspect, the hull-superstructure-interaction has long been of concern to naval architects which had to rely on basic understanding of how topological features affect this interaction and on experience for the design. It wasn't until the development of the finite element method that such an adequate analysis became possible. With the use of 3D finite element modelling the analyst is able to model the whole ship and study the interaction between the hull and the rest of the structure. However this task can prove to be tedious and overly time consuming. In addition detailed structural drawings along with the necessary documentation are needed for the whole ship and the analyst has to find a middle ground between the detailed design and ease of modelling which requires experience and good understanding of the ship structure.

In [2] it was shown through the calculation of the midship moment of inertia and its comparison to the minimum value required by the regulations that that the superstructure of PRINSESSE BENEDIKTE is not considered as a contributing element to the longitudinal strength of the vessel. Nevertheless, the case where the superstructure is effectively connected to the hull presents also significant interest. For the latter case the midship moment of inertia up to the car deck, that is the last continuous deck, was calculated, using the available steel drawings presented in Figure 2.

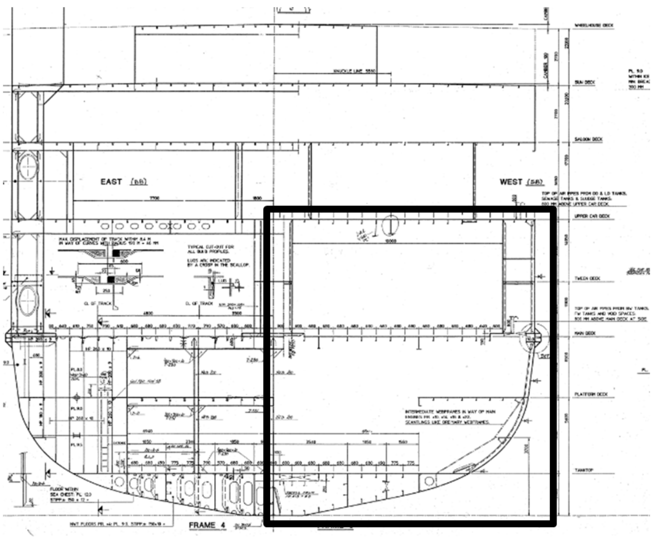


Figure 2: Midship section and elements considered for the moment of inertia

Table 3: Calculated midhsip moment of inertia

Midship moment of Inertia		
Iy	4.15 E9	[cm^4]

Using the aforementioned moment of inertia in the regulations' formulas, the design still water bending moment and wave load bending moment were calculated for both sagging and hogging conditions. It should be pointed out that these values are the maximum design moments according to the regulations and not the ones that the ship is expected to encounter during its service. However it is common practice to use the design values for analyses when other data are not available.

Table 4: Design Bending Moments

Still water moment		
Ms		
Sagging	-295003.8	kNm
Hogging	402008.2	kNm
Wave load bending moment		
Mw		
Sagging	-474275.4	kNm
Hogging	378093.7	kNm
Total bending moment		
Ms + Mw		
Sagging	-769279.2	kNm
Hogging	780101.9	kNm

A simple estimate of the vertical deflection amidhips (δ) can be obtained assuming a prismatic hull with a constant bending moment which is the sum of the still water bending moment and the wave load moment for hogging and sagging respectively [6] (Figure 3). With these assumptions we can employ the following formula:

$$\delta = R\left(1 - cos\frac{L}{2R}\right) \cong \frac{L^2}{8R} = \frac{L^2}{8}\kappa$$

Where L is the length of the ship, R is the radius of curvature and κ the curvature. Alternatively, using the $M_s+M_w=EI_y\kappa$, the formula can be written as :

$$\delta = \frac{(M_s + M_w)L^2}{8EI_y}$$

Assuming that the curvature is constant for the ship we can easily calculate the maximum deflection of the vessel for both hogging and sagging conditions.

In this scenario it has been assumed that these deflections are directly acting on the bottom of the superstructure at the parts where structural continuity exists with the part below. In other words, the variation of deflection along the superstructure length has been introduced as boundary conditions in the superstructure. This scenario represents the most conservative one as the superstructure is considered to be fully cooperative with the hull structure, in reality the degree of interaction between the hull and the superstructure varies depending on the topological features of the latter.

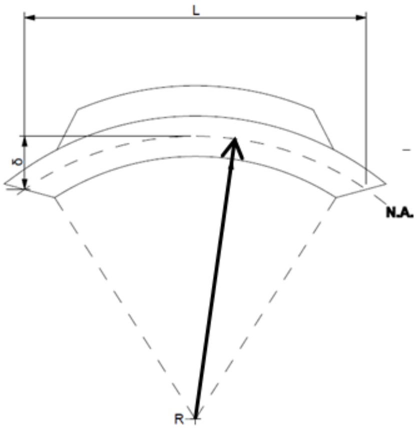


Fig. 3: Deflection of the hull and superstructure

3. FINITE ELEMENT MODELING

3.1 FINITE ELEMENT MODELING

Simplifications to the real geometry were made to facilitate the creation of the finite element models. The FE models were created using the commercial finite element program ABAQUS CAE. Conventional 4 node linear shell elements where used for the plating. Standard 2-node linear beam elements were used to model the supporting pillars between decks and the stiffeners in the transverse and longitudinal direction. For the composite case the ply lay-up and orientation were implemented using the composite layup feature and the composite stiffeners using the general meshed cross section feature [7]. The global element size was approximately 500mm.

As mentioned earlier it has been assumed that the deflections are directly acting on the bottom of the superstructure at the parts where structural continuity exists with the part below. In other words, the variation of deflection along the superstructure length has been introduced as boundary conditions in the superstructure. In addition the local loads according to the regulations were applied on the accommodation decks as uniformly distributed pressure with a magnitude of 0.35 t/m^2.

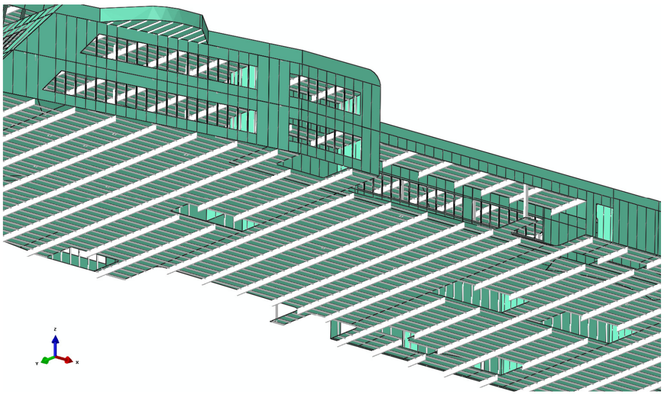


Figure 4: Longitudinal and transverse stiffeners for the steel superstructure case

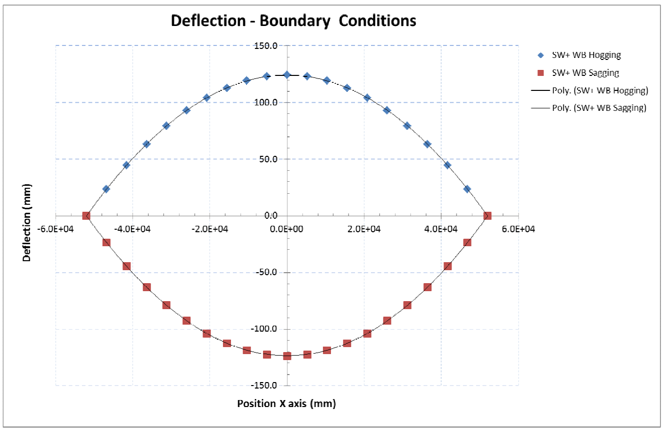


Figure 5: Applied boundary conditions

The stresses did not exceed 150 MPa for both hogging and sagging conditions for the steel case. For the composite case the stresses were significantly lower due to the structures increased compliance. Apart from a few stress concentration points which were introduced to the analysis during the geometry simplification process. Submodelling introducing the precise geometry in combination with finer meshing is needed for the correct interpretation of stresses at these points. However this was out of the scope of the present study. To quantify the deflections caused solely by the local loading of 0.35t/m^2 an additional scenario was selected constraining the degrees of freedom at the same areas where the deflections caused by the design bending moments were applied. For both designs the deflections were below 30 mm (Figure 6).

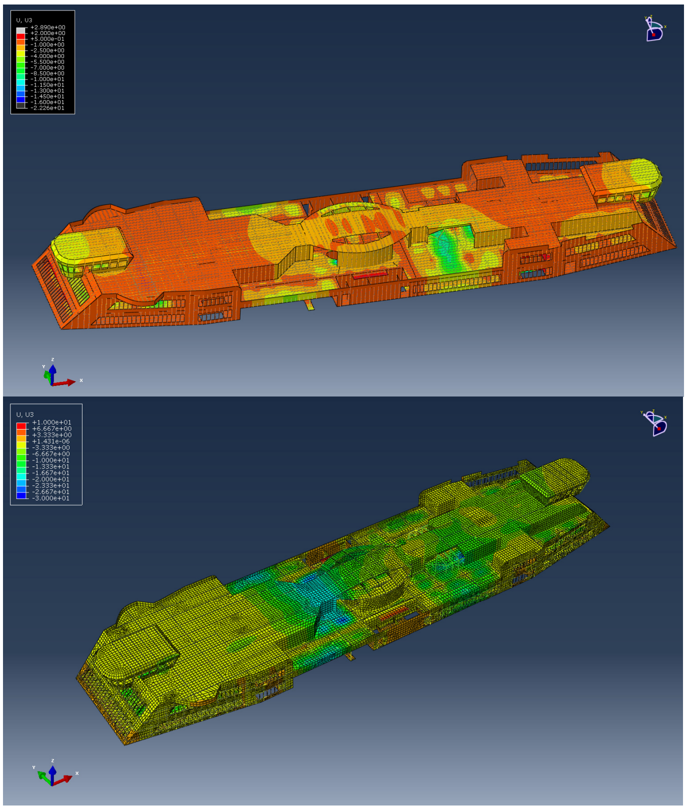
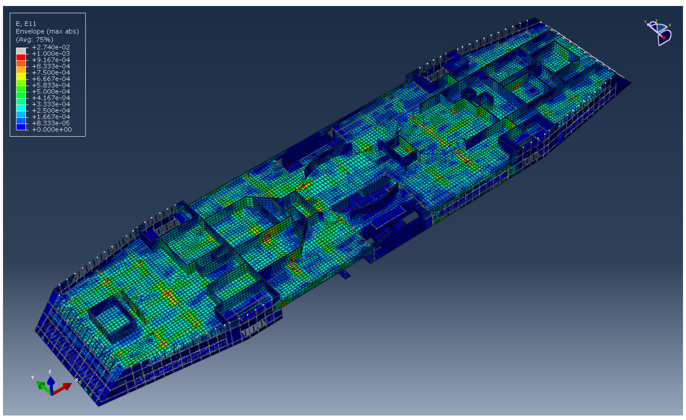


Figure 6: Deflections of the steel (up) and composite (down) case due to local loading

An interesting observation for the case of the composite superstructure can be made comparing the structural response between the hogging, sagging cases and the one where the deflection applied is zero. Due to the increased compliance compared to the steel case, the superstructure is locally loaded to the lower parts of its sides from the imposed deflections, while in the upper decks of the superstructure there is not a significant increase of the loading (Figure 7).



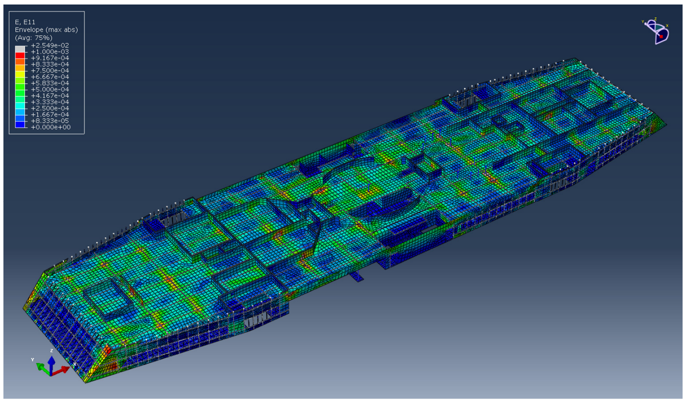


Figure 7: Indicative plots of the longitudinal strains for constrained DOF (up) and for hogging condition (down)

5. CONCLUSIONS

Results indicate that implementing composite superstructures in passenger ships is feasible from a structural point of view. The main obstacles lie in the complexity associated with the regulatory approval and the lack of data from real applications on ships. However, there is an increasing interest for introducing composites on large commercial vessels. This has led to the development of new material systems that exhibit good properties under fire and elevated temperatures. Additionally, classification societies are taking steps to gradually encompass composite materials in their regulations and to adopt a more standardized procedure for the evaluation and approval of composite designs. It is the authors' view that these developments, facilitating the design, acceptance and implementation of composites on SOLAS ships, will constitute composites an increasingly attractive alternative to metallic materials for secondary parts of ships.

ACKNOWLEDGEMENTS

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REFERENCES

[1] International Maritime Organization. SOLAS, Consolidated Edition 2009. International Convention for the Safety of Life at Sea.

[2] V. Karatzas, N. Hjørnet, C. Berggreen, J.J. Jensen, 2015, 'Retrofitting the superstructure of a large passenger ship using composites – a demonstration', *20th International Conference on Composite Materials, Copenhagen 19-24 July 2015*

[3] Det Norske Veritas, January 2014, 'DNV Rules for Classification of High Speed Light Craft and Naval Surface Craft'

[4] Det Norske Veritas, January 2014, 'DNV Rules for Classification of Ships'

[5] M. D. Jacobsen, N. Hjørnet, 2014, Private communication

[6] J.J. Jensen, 2001, 'Load and global response of ships', *Elsevier Ocean Engineering Series Volume 4, Pages 1-337*

[7] 'ABAQUS Analysis User's Manual', Version 6.14-2, 2014 Dassault Systèmes Simulia Corp. Providence: RI, USA