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The Effects on the Operating Condition of a Passenger Ship Retrofitted with a Composite Superstructure

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Abstract

As sustainability and climate change have come on the political agenda, the shipping industry will have to be operating energy efficient ships. An appealing way to achieve this is by designing superstructures made out of Fiber Reinforced Plastics (FRP) aiming at the reduction of the ship's lightship weight. The benefits of a light superstructure become more prominent in large passenger ships, as the superstructures constitute a significant percentage of the lightship; additionally, depending on the size of the ship, the superstructure may tower several decks above the weather deck, affecting the stability of the ship. In this work, the superstructure of a RoPax ferry has been redesigned using composite materials emphasizing on the effects on the ship from an operational perspective. To this end, the weight reduction has been calculated for a realistic average operating condition has been considered to quantify the effects on the stability and the fuel consumption of the retrofitted ship compared to the original design.

Keywords

Superstructure, Composites, Passenger Ship

Introduction

Composites exhibit several appealing characteristics being lightweight, corrosion resistant and exhibiting good performance under fatigue loading. These characteristics constitute them an excellent choice for marine applications. Until now composites have been predominantly used in the maritime applications in small crafts and military vessels given that their implementation onboard SOLAS vessels was restricted. In 2002 the Regulation 17 (SOLAS 2002) was introduced in the SOLAS convention enabling the use of combustible materials provided that the achieved level of safety is equivalent of a steel structure. This regulation has allowed for alternative designs allow to surpass several limitations that were imposed by the use of traditional metallic materials. Despite the potential benefits from the implementation of lightweight materials, 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. In the project, an existing RoPax ferry selected as a case study part of its superstructure has been redesigned using composite materials. While, previous works from the same authors (Karatzas et al 2015a, 2015b) on this topic were focused on the structural response of the superstructure, this work presents the effects the conversion has on the overall performance of the vessel. In detail the effects on the lightship weight, the stability, resistance and propulsion power requirements have been estimated. Finally a simplified estimation of the fuel oil consumption reduction is performed.

Case study description

The vessel which comprised the study case is named PRINSESSE BENEDIKTE and is operated by Scandlines between Rødby and Puttgarden. The upper part of the ship's superstructure has been redesigned out of composites materials according to the DNV Rules for Classification of Ships (2014) and DNV's Rules for Classification of High Speed, Light Craft and Naval Surface Craft (2014) [M. D. Jacobsen, personal communication]. In detail, the upper passenger deck, the wheelhouse deck along with the masts, funnels and the wheelhouses have been considered for conversion (Fig. 1).

Fig. 1: PRINSESSE BENEDIKTE and the part of the superstructure considered for conversion

Since the original design requirements and constraints were unknown, it was decided to keep the exact same general arrangement for the new design. Bearing this in mind, it is evident that the resulted design is not optimsed with respect to the ships' life cycle. Glass fibers impregnated in epoxy resin were selected for the sandwich panels faces along with a PET core (P100) provided by DIAB. The core was selected based on its desirable performance in terms of fire, smoke and toxicity. The ply sequence for the structural elements for the conversion are presented in figure 2

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

Fig. 2: Ply sequence of the structural elements of the superstructure

Weight reduction

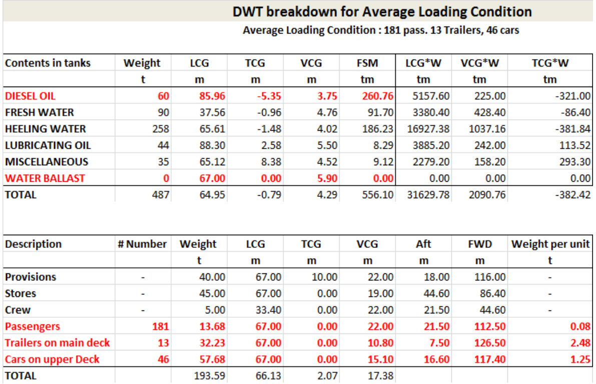
Following the design of the new superstructure, weight calculations have been performed for the aforementioned cases and compared to the calculated existing steel weight. The calculation of the steel weight has been performed based on available data from the ROPAX ferry PRINS RICHARD which is the sister ship of PRINSESS BENEDIKTE. At this point it is underlined that the calculated weight corresponds to the steel weight of the original superstructure excluding outfitting weights. Similarly the presented calculations for the composite cases solely consider the weight of the composite parts. Special considerations have been given to address structural and manufacturing details in the composite such as pillar support areas, local reinforcement at openings/edges and the resin intake based on available date for the selected core type. Comparing the composite superstructure to the original steel one, it can be seen that the structural weight reduction is drastic being approximately 70%. Based on the weight calculations the new Lightship weight for each case was calculated (Table 1). Results indicate that replacing part of the superstructure with sandwich materials leads to a reduction of the lightship of circa 5% which is considerable.

Table 1: Weight Calculations

Superstructure	Weight of converted part	Lightship
Steel	475400 kg	6346000 kg
Composite	142500 kg	6013000 kg

Loading condition

To investigate how this weight reduction affects the performance of the ship the average loading condition the vessel sails has been considered. This loading case was provided by Scandlines [C. Nicolajsen, personal communication]. Details about the deadweight in that loading condition are provided in figure 3. The duration of each trip is equal to 45 minutes out of which 17 minutes are needed for the acceleration and deceleration to (and from) a service speed of 15 kn. Approximately 15 minutes are needed for the embarkation and disembarkation of passengers and vehicles. The ship makes 8300 trips per year.



DWT breakdown for Average Loading Condition

Average Loading Condition : 181 pass. 13 Trailers, 46 cars

Contents in tanks	Weight	LCG	TCG	VCG	FSM	LCG*W	VCG*W	TCG*W
	t	m	m	m	tm	tm	tm	tm
DIESEL OIL	60	85.96	-5.35	3.75	260.76	5157.60	225.00	-321.00
FRESH WATER	90	37.56	-0.96	4.76	91.70	3380.40	428.40	-86.40
HEELING WATER	258	65.61	-1.48	4.02	186.23	16927.38	1037.16	-381.84
LUBRICATING OIL	44	88.30	2.58	5.50	8.29	3885.20	242.00	113.52
MISCELLANEOUS	35	65.12	8.38	4.52	9.12	2279.20	158.20	293.30
WATER BALLAST	0	67.00	0.00	5.90	0.00	0.00	0.00	0.00
TOTAL	487	64.95	-0.79	4.29	556.10	31629.78	2090.76	-382.42

Description	# Number	Weight	LCG	TCG	VCG	Aft	FWD	Weight per unit
		t	m	m	m	m	m	t
Provisions	-	40.00	67.00	10.00	22.00	18.00	116.00	-
Stores	-	45.00	67.00	0.00	19.00	44.60	86.40	-
Crew	-	5.00	33.40	0.00	22.00	21.50	44.60	-
Passengers	181	13.68	67.00	0.00	22.00	21.50	112.50	0.08
Trailers on main deck	13	32.23	67.00	0.00	10.80	7.50	126.50	2.48
Cars on upper Deck	46	57.68	67.00	0.00	15.10	16.60	117.40	1.25
TOTAL		193.59	66.13	2.07	17.38			

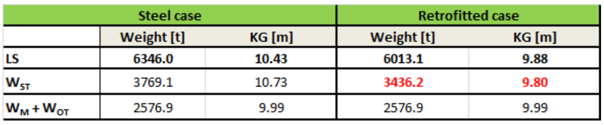
Fig. 3: Deadweight detail for the selected loading condition

Stability calculations

To calculate the stability for the retrofitted cases the calculation of the new center of gravity of the Lightship was necessary. This was achieved by considering that the outfitting weight (W_{OT}), the machinery weight (W_M) and the position of their center of gravity are unaffected by the conversion. This allows the decomposition of the Lightship in two groups namely the structural weight W_{ST} and the sum of $W_M + W_{OT}$ (Eq. 1).

$$Lightship = W_{ST} + W_{OT} + W_M \tag{1}$$

Knowing from the existing data for PRINS RICHARD the center of gravity of the structural weight, the weight and center of gravity for the sum $W_M + W_{OT}$ was calculated (Fig. 4). Additionally from the structural weight data for PRINS RICHARD the position and weight of the retrofitted parts were known. Replacing these weights with the ones estimated for the composite case allowed the calculation of the new Lightship weight and the new center of gravity. In all cases the center of gravity was measured from the Baseline of the vessel.



	Steel case		Retrofitted case	
	Weight [t]	KG [m]	Weight [t]	KG [m]
LS	6346.0	10.43	6013.1	9.88
W_{ST}	3769.1	10.73	3436.2	9.80
$W_M + W_{OT}$	2576.9	9.99	2576.9	9.99

Fig. 4: Weight groups and center of gravity

The new value of the displacement was calculated by adding the deadweight of the loading condition to the new Lightship. The draught and the other relevant hydrostatic data were taken from the ship's hydrostatic tables which enabled the calculation of the metacentric height (GM) and of the righting arm (GZ) (Fig. 5). The dashed lines correspond to the existing steel case while the solid ones to the converted one.

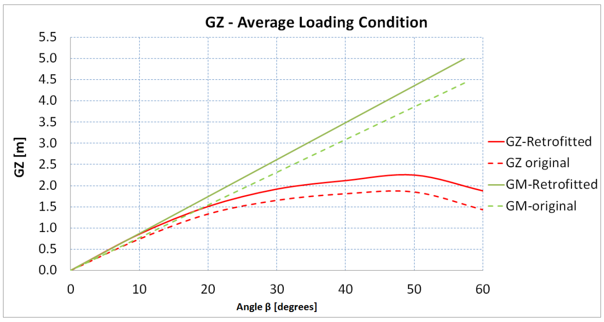


Fig. 5: GZ and GM values for the original and converted cases

Results indicate that by replacing part of the superstructure with composite materials leads to an increase of the GM values of about 12.9%. Additionally, the GZ values are increased as expected. The maximum value of GZ is increased by 24%. In general the new design results in a bigger range of stability and in increased static and dynamic stability. Additionally, knowing the GM values for each case a simplified comparison between the periods of roll can be performed. The period of roll is given by equation (2)

$$T = \frac{2\pi k}{\sqrt{gGM}} \qquad (2)$$

where k is the radius of gyration, g is the acceleration of gravity and GM is the metacentric height. Assuming that the radius of gyration is kept constant, as the waterline area is not significantly affected in the studied cases, the change between in the period of roll can be given by equation (3)

$$\frac{T_{steel}}{T_{composite}} = \sqrt{\frac{GM_{composite}}{GM_{steel}}} \qquad (3)$$

For the examined case the period of roll is reduced around 6% meaning that if the original period of roll was 12 seconds, which is a typical value for passenger ships, the new one is decreased to 11.3 seconds. The fact that the decrease of the roll period is not that pronounced is desirable as shorter periods of roll are uncomfortable for passengers.

Resistance and propulsion power calculations

The resistance estimation for PRINSESSE BENEDIKTE at a mean draught of 5.30 m was available. Before calculating the resistance for the steel and the retrofitted case at the average loading condition it was decided to recreate the available resistance data using Harvald's method (Guldhammer and Harvald, 1974). As expected some deviation was noted between the method's prediction and the available results for the ship. To minimize this it was decided to calibrate to match exactly the measured resistance from the model tests. The calibration was performed by changing the value of the appendages resistance coefficient at each speed. In reality this coefficient is to be kept constant as it is related to the vessel's appendages which are independent of the vessel's speed. The calibrated resistance estimation method was subsequently used to calculate the resistance of the vessel at the examined loading case. The draught for the original steel case is equal to 5.035m while for the converted case the draught is reduced to 4.87m. In addition, corrections for the added wind resistance and the effect of shallow water were taken into account considering a headwind speed of 6m/s and water depth of 18m. These values correspond to the average values for the area of operations of the vessel. As the draught decreases, the friction resistance is reduced. At the same time the area above the waterline increases which lead to an increase on the added resistance due to the wind. Typically for commercial ships air resistance represents about 2% of the total resistance (MAN). Nevertheless in ship types such as containerships, RORO and ferries the added wind resistance can be significant. The propulsion power at shallow waters as a function of the vessel's speed is illustrated in figure 6 for the original case and after the conversion. Additionally the effect of the wind resistance to the propulsion power is illustrated by performing the calculations for both when the wind resistance is added and when it is ignored. Once again, the dashed lines correspond to the existing steel case while the solid ones to the converted one. For the derivation of the propulsion power, apart from the total propulsion coefficient an additional electrical/mechanical transmission efficiency factor was implemented to account for the efficiency of the electric motors. This factor's value was taken equal to 0.9. Evaluating the results it appears that the reduction in resistance is practically negligible, ranging from 1.2% for low speeds to 0.8% for high speeds. This is caused by the fact that the draught change is not significant, resulting in a reduction of the wetted area by merely 67 m^2 (2.5%) and an increase of 5m^2 (<1%) of the projected area above the waterline needed for the calculation of the wind resistance.

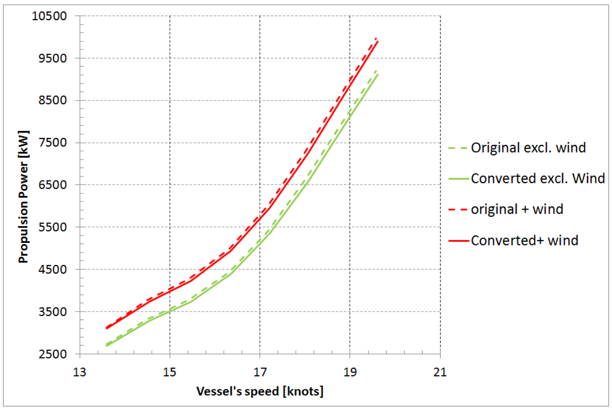


Fig. 5: **GZ and GM values for the original and converted cases**

Fuel Consumption

Having calculated the propulsion power, the fuel consumption can be estimated based on the ship's route. The specific fuel consumption is considered equal to 220 gr/kWh (Papanikolaou, 2014). At the port, power is not needed for the propulsion. Instead, the power consumption corresponds to other purposes such as lighting, communication, refrigiration, climate control and others. The estimated hotel load for PRINSESSE BENEDIKTE is 1000kWh. The estimated consumption can be calculated by multiplying the power consumption by the time and the specific fuel consumption for both the sailing time and port time. The estimated fuel consumption per trip and per year are listed in table 2. It should be emphasized that the followed approach does not account for the fuel consumption of the acceleration and deceleration times which make up for a significant part of the vessels service time (17 minutes per trip). In addition, in the areas close to the ports the water depth is less than 10m which further increases the ship resistance during acceleration. Nonetheless, the followed approach can provide a simple estimation of how the fuel consumption can be affected.

Table 2: **Estimated fuel oil consumption**

Case	Per trip	Annual
Steel	667.4 kg	5540000 kg
Composite	657.4kg	5456400 kg

Comparing the fuel consumption for the original and retrofitted case the fuel savings are about 1.5 % (84 tons) of the initial annual estimation which reflects the reduction of the ship's resistance due to the reduced draught. In reality this percentage would be higher as higher fuel savings are expected during the acceleration and deceleration of the vessel.

Conclusions

Evaluating the effects that the implementation of composite materials has had on the ship the following conclusions can be drawn. The design procedure can be performed by combining existing rules and regulations. The partial conversion of the vessel's superstructure results to a reduction of the Lightship of about 5% for the selected materials. The Lightship reduction in combination with the decrease of the height of the center of gravity from the conversion led to a significant increase of the vessel's overall stability, improving static, dynamic and the range of stability. This is of significant importance for large passenger ships where stability limitations might impose constraints to the number of decks these vessels are allowed to have. Regarding the resistance and propulsion power requirements, the draught change in the average loading condition does not significantly affect the resistance of the ship as the propulsion power reduction was around 1% for the service speed of 15 knots. This in turn led to a small fuel consumption decrease of about 1.5% per year which does not signify a potential source of cost saving for the ship-owner. This observation does not come as a surprise given that it was decided to keep the same general arrangement of the superstructure. Overall it is the authors' view that it would be more profitable to increase the payload to displacement ratio by decreasing the lightship mass than to try to save on fuel by reducing the draught. In addition, the ship that was selected as the demonstration case does not encounter any challenges in reality that would necessitate such a conversion. Last but not least, it should be emphasized that the material acquisition and fuel consumption costs do not account for the total of the vessel's life cycle cost and should not be regarded as the sole criteria for such options. On the contrary these tend to be misleading if all the associated costs are not well estimated and taken into consideration.

Acknowledgements

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