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Risk-Based Hybrid Light-Weight Ship Structural Design Accounting for Carbon Footprint

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Abstract: The study aims to develop an integrating risk-based formulation and cost-benefit analysis for identifying an optimal ship hull structural design solution where the steel cargo holds aluminium honeycomb sandwich panels to replace inner side shells. The risk of progressive structural failure includes hazards related to environmental pollution due to accidental fuel and oil spills, possible loss of cargo, crew members and ship during operations, and air pollution during shipyard construction and ship voyages. The structural failure incorporates progressive time-dependent structural degradation coupled with ship hull load-carrying capacity in predicting structural integrity during the service life. The ship hull structural failure and associated risk are estimated over the ship's service life as a function of the design solution. The carbon footprint and cost to mitigate the impact for the entire steel and hybrid ship hull structural solution implemented as a sustainable life cycle solution are analysed where the steel ship hull structure is built through primary construction. The cost of structural measures accounts for redesigning the ship structure and implementing aluminium honeycomb composite panels instead of steel plates, reducing steel weight, environmental pollution and cost and increasing the transported cargo and corrosion degradation resistance. It has been found that design solutions AHS1 and AHS2, in which aluminium honeycomb panels replace the inner steel shell plates, enhance the corrosion degradation resistance, and reduce the ship hull's lightweight, reflecting a better beta-reliability index at the time of the first repair with a lower repair cost and more transported cargo. The cost of the ship associated with the design solutions AHS1 and AHS2 is about 11% lower than the steel solutions.

Keywords: lightweight; ship structures; carbon footprint; risk-based design; reliability

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1. Introduction

Light-weight materials and structures in shipbuilding have gained significant attention recently in reducing fuel consumption and emissions while maintaining structural integrity and load-carrying capacity. The International Maritime Organization (IMO) [1] reported that in 2018 the global shipping energy reached nearly 11 exajoules (EJ), which is about 1 billion tonnes of carbon dioxide (CO_2), resulting in about 3% of the annual global greenhouse gas (GHG) emissions. According to the International Energy Agency [2], the estimated emissions could further increase because of the rapid increment of maritime freight traffic. One possible solution in mitigating the environmental pollution due to the activities in the shipping industry is to reduce ship weight—and consequently the required power and fuel consumption—and to increase the share of more sustainable and recyclable materials in construction maintenance during the ship's life cycle.

Implementing lightweight materials in ship structures presents a promising solution to the abovementioned challenges. The sandwich structures consisting of two thin, stiff outer skins separated by a lightweight core material demonstrate a good advantage. These materials result in a light structure, making it an attractive option for reducing the weight of different ship structural components. Most sandwich types of structures are destined for small boats and generally comprise glass fibre-reinforced plastic (GFRP) skins with a polymeric foam core. However, as reported in [3], the disposal of marine composite sandwich panels at the end of their life are not economical and energetically expensive, leading to very poor recyclability. This further supports the need to address sustainability issues in the design process, promoting more effective integration of lifecycle-based analysis [4] and a green design approach that combines structural requirements, reuse and recycling of materials and weight reduction. Recent analyses, such as in [5], recognised the significance of limiting structural weight by combining fuel consumption reduction with light displacement limitation to achieve effective environmental benefits.

Palomba et al. [6] provided an overview of the relevant lightweight materials that can be used for marine structural applications and compared their potential environmental impact. It was observed that aluminium sandwich structures represent an attractive alternative to composite sandwich materials in maritime structures. Aluminium is recognised as a sustainable and light material due to its high degree of recyclability [7] and low weight density. In this scenario, aluminium honeycomb sandwich (AHS) panels can provide sustainable and lightweight marine structures and excellent impact absorption capabilities. Some applications of AHS for marine structures are reported in [8–11].

A preliminary evaluation of the potential advantages of integrating AHS in shipbuilding was performed in [12], where AHS was suggested as an alternative to the steel inner side shell of the ship hull. A key point to address to support the actual use of AHS in shipbuilding concerns their suitable integration in risk-based design approaches, whose importance is recognised by IMO [13,14] in their guidelines on Formal Safety Assessment (FSA). Risk-based methodologies are driven by the need to address safety issues as part of the design objectives from a cost-effective perspective [15]. The research project SAFEDOR testifies the efforts toward a more comprehensive integration of risk assessment approach in the design of all marine vehicles. Oil tankers are one of the main categories where the relevance of risk-based design is well-recognised, as highlighted in tan [16]. They focused on developing a preliminary design procedure accounting for oil outflow risk after collisions, addressing the consequences of relevant structural details. However, economic impacts and cost-benefit considerations were not included in the process. Autonomous vessel design is another branch of ship design that could benefit from using risk assessment procedures effectively.

An example was provided in [17], which proposed a methodology targeting the initial safety management strategy but suggested the need to develop the strategy further to evolve during vessel design and construction. Bolbot et al. [18] developed a process for the risk assessment of maritime autonomous surface ships, including safety, security, and cybersecurity in the initial design phase considerations. One of the main challenges in a broader application of risk-based approaches is the need to rely on reliable data, which cannot be readily available, especially for low-added value ships or ships subjected to customisation. Núñez-Sánchez and Pérez-Rojas [19] moved a step toward such a direction by suggesting a risk-based design using the combination of Goal-Based Standards and a Safety Level Approach applied to a fishing vessel fleet. As indicated in [20], further risk assessment can be improved by accounting for the Energy Efficiency Design Index (EEDI), which introduces environmental aspects in the conceptual ship design.

The study in [12] was extended concerning the shipbuilding energy efficiency and carbon footprint [11]. The initially designed hybrid lightweight ship hull structure in [12] is analysed here concerning the cost-benefit for identifying the merit of the steel and hybrid designs of the bulk carrier where aluminium honeycomb panels replaced the inner side shell of the cargo holds. The risk of progressive structural failure during ship operations and environmental pollution during shipyard construction and ship voyages is analysed.

The present study develops a risk-based formulation for identifying an optimal ship hull structural design where the aluminium honeycomb sandwich panels replace a part of steel ship hull structures. The reliability estimate is based on the ultimate limit state employing the first-order reliability method. The risk due to the hull structural failure is evaluated over the ship's service life as a function of the design solution. The carbon footprint and cost to mitigate the impact of the complete steel and hybrid ship hull structural design solutions implemented as a sustainable life cycle solution are analysed, accounting for the structural degradation. The proposed formulation can quantify the best time for the first repair, the beta-reliability index's associated level, and the repair cost. Employing the developed risk-based design formulation, the best design solution reduces the weight, cost of the ship, and carbon footprint, better corrosion resistance and increases cargo transport. The developed risk-based formulation can be used as a design tool in defining modern ships' optimal design solutions, accounting for the environmental pollution associated with the manufacturing process and ship operation, which is one of the primary objectives of the international maritime community, where some latest measures have been adopted for example in [21].

2. Sandwich Structures: Light-Weight Solution

Introducing alternative lightweight materials in shipbuilding is one of the paths to promote a reduction of the environmental impact due to weight reduction and attention to the consequences during the ship's life cycle, including dismantling. The structural design addressed weight minimisation would result in several advantages [22,23] in energy efficiency, which include required power and consequent fuel consumption reduction, capital expenditure (CAPEX) and operational expenditure (OPEX) decrease. In addition to weight reduction, practical benefits in terms of environmental impact can be achieved by addressing the environmental consequences of the whole ship's life cycle, from raw materials production to dismantling (see Figure 1).

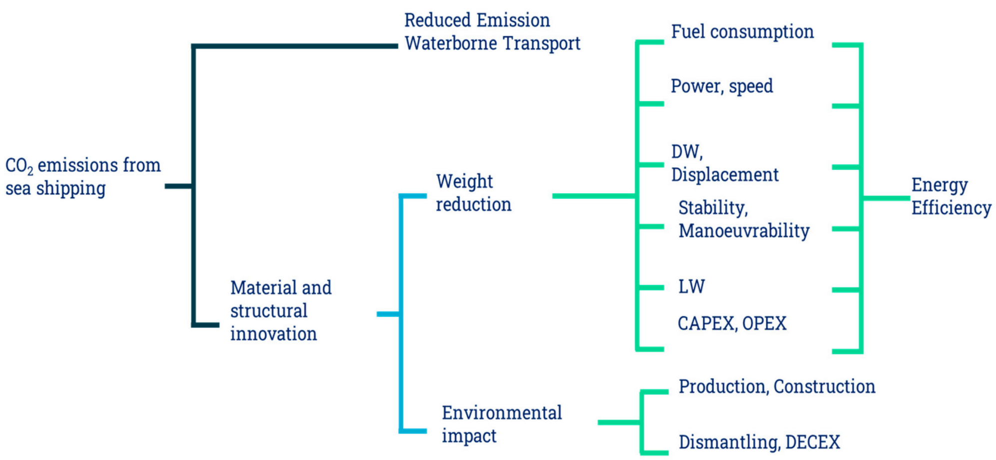

Figure 1. Key points to address to achieve environmental impact reduction in the shipping industry.

Sandwich structures represent one of the most common solutions the marine industry adopts to address weight-saving. In addition to high stiffness-to-weight and strength-to-weight ratios, sandwich structures may benefit marine applications since they can provide excellent crashworthiness, good damping properties, economical assembly, and reduction of secondary stiffening. When applied in the maritime industry, sandwich structures should fulfil different requirements such as manufacturing feasibility for large structures, economic boundaries or resistance to corrosion [24]. The latter is a key feature that makes sandwich structures competitive with traditional materials such as steel.

Viable sandwich structures for shipbuilding include polymer-based solutions and all metal sandwich structures. The selection and comparison among alternatives for a specific application can be based on several approaches and criteria. As reported in [6,10], a preliminary mechanical comparison among several solutions could be based on their bending stiffness, a valuable parameter in ship structural design. According to the results reported in [6]—which compared GFRP (glass-fibre reinforced plastics)-PVC foam sandwich structures, GFRP-balsa wood sandwich structures, web-core steel sandwich structures and AHS—given a specific bending stiffness, AHS is potentially the solution able to provide the highest weigh reduction (−76.7%) in comparison to traditional steel plate structures. The fulfilment of the required bending stiffness may lead to a higher thickness of AHS panels compared to steel plates or other heavier sandwich structures.

The direct environmental benefits deriving from the ship's structural weight reduction could be estimated according to simplified approaches as those reported in [25,26], who respectively suggested that fuel consumption depends on $\Delta^{2/3}$ (where Δ is ship displacement) and that CO_2 emissions are linearly proportional to fuel consumption. It follows that the highest the weight reduction, the lowest the CO_2 emissions. Hence focusing on AHS, which has excellent potential for weight reduction, means investing in an attractive option to mitigate the environmental impact of the operational phase in the ship life-cycle.

In addition to emissions due to operation, the environmental consequences of other activities, such as raw materials extraction, manufacturing, disposal, and reuse, influence ships' environmental impact. Therefore, a crucial aspect to consider in selecting alternative materials and structures is the environmental impact of their production, manufacturing, transport, and disposal. In this scenario, aluminium is recognised as a highly recyclable material [27], and its production from recycled sources (secondary aluminium) is reported to save between 93% and 95% [28,29] of energy than the primary production. It can be concluded that aluminium-based sandwich structures are excellent candidates to address sustainability issues in shipbuilding.

3. Hybrid Light-Weight Structural Design

A novel ship structural design solution has been developed in [12] for a midship section design of a bulk carrier, where a part of the steel plates of the cargo holds was replaced by aluminium honeycomb sandwich panels creating a hybrid structure. The best design solutions for steel and hybrid use of steel and aluminium honeycomb panels were identified through the multiple criteria decision-making approach, demonstrating reduced ship costs and improved energy efficiency.

The ship structural design was defined as a multi-objective optimisation problem with several objective functions, including minimum lightweight, minimum total ship cost as a function of the capital, operational and dismantling expenditures, minimum transportation cost, maximum transported cargo, and ultimate strength of the ship hull structure. The decision variables cover plate thickness, stiffener net-sectional area, shipbuilding yield stress, span and space and the constraints for the steel part of the ship hull structure are related to the plate thickness (local strength), section modulus (longitudinal strength) and critical buckling stress. The constraints for the AHS part of the ship hull are related to deflection, facing skin stress, shear stress in the core, panel buckling, shear crimping, skin wrinkling, intracell buckling and buckling. The descriptors of ship design solutions are given [11]. The ship length of the analysed ship is 224.5 m, the breadth is 40.7 m, the depth is 20 m, the block coefficient is 0.85, and the ship speed is 13 knots. For Steel, AHS1, and AHS2 design solutions, the draft is 14.60, 14.60 and 14.36 m, respectively, where the displacements are 116,227, 116,227, 114,342 tonnes, the cargo deadweights are 84,840, 100,489 and 98,625 tonnes. The lightweights are 16,107, 14,268 and 14,262 tonnes; the annual cargos are 776,604, 834,469 and 828,146 tonnes. The transportation cost for the three design solutions is 8.49, 7.31 and 7.35 €, where the ship cost is 20,717,152€, 18,721,159€ and 18,683,008€ and the attained EEDIs are 2.78, 2.76 and 2.75 g CO_2/t-n m respectively.

The bending-moment curvature relationship and the ultimate strength, defined as the maximum point of the hogging and sagging loading condition of the designed midship section subjected to vertical bending moments, are presented in Figure 2. The ultimate strength in sagging will be used as an input variable in the reliability analysis. The three analysed design solutions are designed to have the same initial ultimate strength.

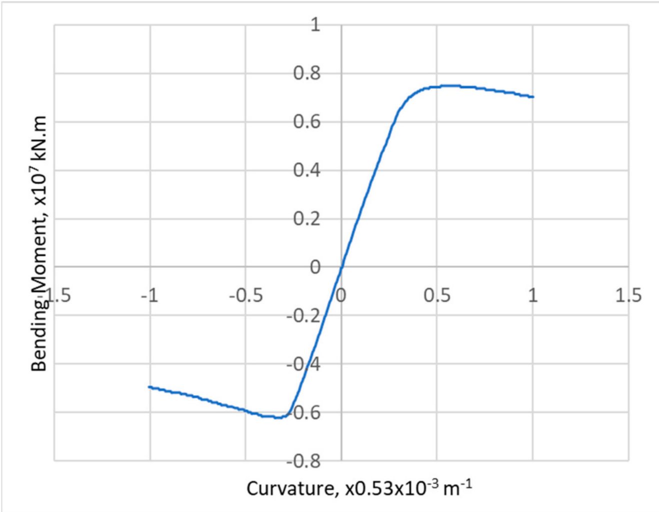

Figure 2. Bending-curvature relationship.

The AHS2 design solution, due to its less lightweight, shows a less draft, less transportation cost, less needed engine power, less attained energy efficiency design index (EEDI) [20,30] and less ship cost than the steel design solution. However, the AHS1 design solution uses the reduced lightweight to increase the deadweight and annual transported cargo for the same draft as steel design solutions and almost the same ship cost as the AHS2 design solution.

Additionally, AHS 1 and AHS2 design solutions, due to the aluminium honeycomb panels, have a better corrosion degradation resistance. The corrosion degradation is accounted for by employing the non-linear time-dependent model developed in [31], where any corrosion-dependent variable is defined as:

$$x_i = \begin{cases} x_{i,0} exp\left[-\frac{(t-\tau_C)}{\tau_t}\right], & t > \tau_C \\ x_0, & t \leq \tau_C \end{cases} \quad (1)$$

where $x_{i,0}$ is the non-corroded status of variable x_i, τ_C is the coating life, and τ_t is the transition life of the corrosion degradation process. The coating life and transition time for the steel design solution are 5 and 4 years, and for AHS 1 and AHS2, they are 5 and 7.12 years and 5 and 6.11 years, respectively. The coating life is assumed to be the same for the three design solutions. The transition time accounts for the honeycomb panels replacing the steel plates and the different wetted surfaces of the ship hull as a function of the draft for different design solutions.

4. Reliability Analysis

The ships are exposed to different hazards during the service life, where the most critical experience includes extreme loading, capsizing, unacceptable seakeeping, structural failure, and others [32].

Different design solutions may initiate different types of structural collapse. The risk-based evaluation may convert this event into a measure where all consequences for the ships are assessed.

The reliability analysis focuses on the progressive ship hull structural collapse and related quantitative consequences associated with the structural failure related to the ultimate compressive strength, progressive corrosion degradation, a possible loss of human life and cargo and environmental pollution, where the last one is seen to be very critical nowadays [32,33].

When a structure or a structural component fails to perform a function for which it was designed, this condition defines its limit state related to serviceability, ultimate, fatigue and accidental limit states [14,34,35].

Three possible design solutions are used as a risk control measure to allow the ship hull structure to be designed and to verify the impact of a hybrid lightweight ship structural design solution and carbon footprint.

The ultimate compressive strength of the ship hull structure is evaluated based on the ship's hull progressive structural collapse approach initially developed in [36] and widely used for ship hull structural analysis as a function of ship hull loading composed of the vertical still water and wave-induced bending moments. The progressive corrosion degradation magnifies structural failure. A non-linear model [31,37,38] is employed for the corrosion degradation assessment of the ship hull as a function of the coating and transition life, as given in Equation (1).

The overall hull girder failure consequences are the possible losses, environmental pollution cleaning and related measures to recover losses. The failure consequences are also time-dependent due to the time value of money.

The collapse failure is defined as stipulated in [39], where reliability is the probability of keeping the service capacity of the ship during the service life. The objective is to evaluate the reliability of the ship's degrading strength against the demanding loading. The limit state function $g(\mathbf{X})$ is related to the ultimate load-carrying capacity of the ship structure, define as [40,41]:

$$g(\mathbf{X}) = \widetilde{x}_u \cdot \widetilde{M}_u - \left(\widetilde{x}_{sw} \cdot \widetilde{M}_{sw} + \Psi_w \widetilde{x}_w \cdot \widetilde{x}_s \cdot \widetilde{M}_w \right) \tag{2}$$

where $\widetilde{M}_u$ is the ultimate bending moment capacity, $\widetilde{x}_u$, is the model uncertainty factor of the ultimate bending moment described by the Normal probability density function, $\widetilde{M}_w$ is the vertical wave-induced bending moment. The combination factor between the still water and wave-induced bending moments, Ψ_w is ranging from 0.8 to 0.95, as described in [42,43]. The model uncertainty factor $\widetilde{x}_w$ accounts for the uncertainties in the linear response calculation and $\widetilde{x}_s$ for the non-linear effects, $\widetilde{M}_{sw}$ is the still water bending moment with a model uncertainty factor $\widetilde{x}_{sw}$. The approach employed to define the statistical descriptors of the still water bending moment is given in [44,45], where the still water bending moment is fitted to a Normal distribution. The regression equations define the mean value and standard deviation as a function of the length of the ship and dead-weight ratio concerning the loading cases as:

$$Mean(M_{sw}) = \frac{Mean(M_{sw,max}) M_{sw,CS}}{100} \tag{3}$$

$$StDev(M_{sw}) = \frac{StDev(M_{sw,max}) M_{sw,CS}}{100} \tag{4}$$

where $M_{sw,CS}$ is given as stipulated by the Classification Societies Rules [46].

The statistical descriptors of the extreme vertical wave-induced bending moment $M_{vw,e}$ are defined as proposed in [40]. It is assumed as a Gumbel distribution, considering that the wave-induced bending moment, $M_{vw,}$ as stipulated by the Classification Societies Rules, is considered as a Weibull distribution and the scale factor and shape parameters as a function of the length of the ship, L of the Weibull distribution are defined as [47]:

$$q = \frac{M_{vw,CS}}{ln(10^8)^{\frac{1}{h}}} \tag{5}$$

$$h = 2.26 - 0.54 log_{10}(L) \tag{6}$$

The extreme values of $M_{vw,e}$ descriptors of the Gumbel distribution α_m and β_m over the reference period T_r are derived based on the statistical descriptors of the Weibull distribution:

$$\alpha_m = q(ln(n))^h \tag{7}$$

$$\beta_m = \frac{q}{h}(ln(n))^{\frac{(1-h)}{h}} \tag{8}$$

where $n = pT_r/T_w$ is the mean number of cycles during the reference period T_r as a function of the mean value wave period T_w assumed here as 1 year and 8 sec, respectively, and p the time the ship spent in seagoing conditions.

The 5% confidence level value of the compressive ultimate bending moment, $M_u^{5\%}$, is defined using the MARS2000, version 2.5i [48] software. It is also assumed that COV is 0.08 and follows the Log-normal probability function.

The statistical descriptors of the limit state functions are given in Table 1.

Table 1. Statistical descriptors of limit state function.

Distribution		Parameter 1	Parameter 2
Gumbel	M_w, MNm	1940	211
Lognormal	$\widetilde{M}_u$, MNm	7298	584
Normal	$\widetilde{M}_{sw}$, MNm	311	395
Normal	$\widetilde{x}_u$	1.05	0.10
Normal	$\widetilde{x}_{sw}$	1.00	0.10
Normal	$\widetilde{x}_w$	1.00	0.10
Normal	$\widetilde{x}_s$	1.00	0.10

Failure will appear when the limit state function $g(\mathbf{X})$ fails, satisfying $P_f = P[g(\mathbf{X}) < 0]$, estimated as $P_f = \Phi(-\beta)$, where β is the reliability index defined based on the First Order Reliability Method (FORM) [49–51]. Using the standard normal probability function Φ, the beta reliability index can also be estimated as:

$$\beta = \Phi^{-1}\left(P_f\right) \tag{9}$$

The reliability index as a function of time $\beta(t)$ is following the generalised corrosion degradation of the ship hull structure, as shown in Figure 3.

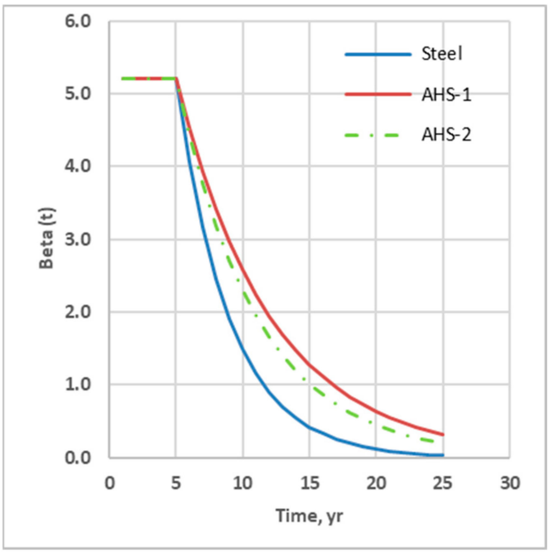

Figure 3. Beta-reliability index as a function of corrosion degradation (without repair and maintenance).

5. Risk-Based Design

The analysis focuses on the progressive ship hull structural collapse and related quantitative risk associated with structural integrity (yielding and buckling), progressive corrosion degradation, structural compressive failure, possible human life and cargo losses and environmental pollution due to ship construction.

The uncertainties related to ship hull collapse are expressed as a probability of failure and are considered in the risk assessment. The probability of failure is numeric, and the consequences are presented in monetary values. The cost-benefit analysis is made based on the expected risk, defined as:

$$Risk(t) = \sum_j P_{f,j}(P[g(\mathbf{X}|t) \leq 0])C_{f,j}(\mathbf{X}|t) \quad (10)$$

where $P_{f,j}(P[g(\mathbf{X}|t) \leq 0])$ is the probability of structural failure, $C_{f,j}(\mathbf{X}|t)$ is the impact or consequence cost, and $\mathbf{X}$ is the vector representing the design parameters.

The ultimate limit state is used to define the probability of failure. The consequence, in monetary value, for the service life include the residual ship cost, measure, loss of cargo, human life and ship, and cleaning the environmental pollution (see Figure 4).

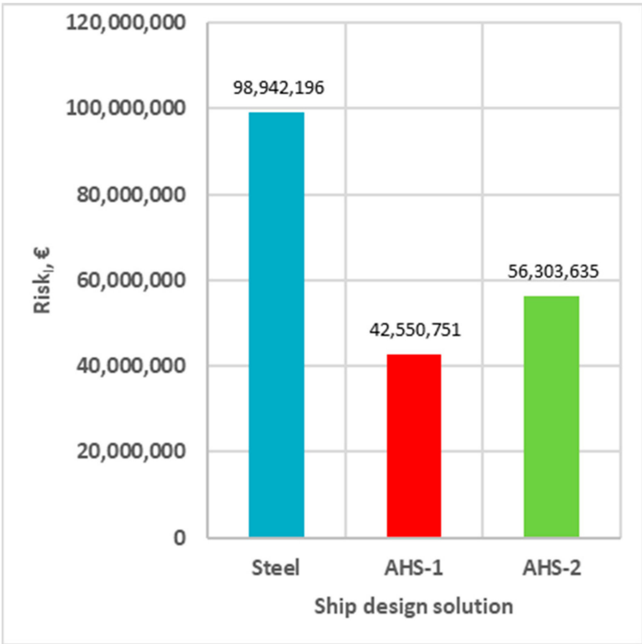

Figure 4. Risk-based design solutions.

The design solutions are defined by employing aluminium honeycomb panels to replace the conventional steel inner shell structures, minimising the total cost and environmental pollution and enhancing the corrosion resistance.

The total expected risk, $Risk_{total}(t_n|\mathbf{X},\ \beta)$, is the sum of the product of the probability of failure and consequence cost and risk of the mitigation measure [33,52]:

$$Risk_{total}(t_n|\mathbf{X},\ \beta) = Risk_{failure}(t_n|\mathbf{X},\ \beta) + Risk_{measure}(t_n|\mathbf{X},\ \beta) \quad (11)$$

where $Risk_{failure}(t_n|\mathbf{X},\ \beta)$ is the risk as a result of ship failure, and its consequence costs and $Risk_{measure}(t_n|\mathbf{X},\ \beta)$ is the ship safety measure in implementing different design solutions.

The risk concerning the ship collapse is estimated for the ship service life, accounting for the probability of failure, consequence cost and the discount rate γ, as a function of $\mathbf{X},\ \beta$:

$$\begin{aligned} Risk_{collapse}(t_n|\mathbf{X},\ \beta) \\ &= \sum_{j=1}^{n} P_f(t_j|\mathbf{X},\ \beta)[C_{residual}(t_j|\mathbf{X},\ \beta) + C_c(\mathbf{X},\ \beta) + C_{spill} \\ &+ C_{human} + C_{air\ pollution}]exp(-\gamma t_j) \end{aligned} \quad (12)$$

where $C_{residual}(t_j|\mathbf{X},\ \beta)$ is the residual cost during the service life $t_j \in [t_0, t_n]$, C_{cargo} is the cost associated with the loss of cargo, C_{spill} is the cost of the accidental spill, C_{human} is the cost associated with the loss of human life, $C_{air\ pollution}$ is the cost due to air pollution, and γ is the discount rate.

The discounted cash flow approach estimates the ship's residual cost. The required net profitability rate is taken as $r = 2\%$, the ship operation is $o = 25$ years, and the depreciation time is 15 years. The annual inflation is assumed as $i_{nfl} = 3\%$, income tax rate $t_x = 15\%$ resulting in a capital recovery factor [20] calculated as:

$$C_{rf} = \frac{r}{1-(1+r)^{o}} \tag{13}$$

and the capital cost, C_{rft}, is defined as:

$$C_{rft} = \frac{r + i_{nfl} + r\, i_{nfl}}{1-\left(r + i_{nfl} + r\, i_{nfl}\right)^{-o}(1-t_x)} \tag{14}$$

The discounted annual average cost of the investment, C_{aaci}, is defined as [20]:

$$C_{aaci} = CAPEX\ C_{rft} \tag{15}$$

The residual cost of the ship, $C_{residual}\left(t_j \middle| \mathbf{X},\ \beta\right)$ is associated with the depth balance plus the interest rate and depreciation accounting for the bank investment, own investment, required net profitability rate, the average annual inflation rate ship operation life, capital recovery and depreciation time, as seen in Figure 5.

Figure 5. Ship cost.

Additionally, what is defined as the cost of the ship, $C_{ship}(t_0|\mathbf{X},\ \beta)$. The cost of environmental pollution due to ship construction needs to be accounted for as follows:

$$C_{air\ pollution} = W_{CO2} C_{cleaning} \tag{16}$$

where W_{CO2} is the carbon footprint in tonnes of CO_2 due to the construction of ship hull structures and $C_{cleaning}$ is the cost of cleaning 1 tonne of CO_2.

The air pollution due to ship hull construction [11] and the cost to mitigate the impact for the complete steel and hybrid ship hull structural solution implemented as a sustainable life cycle solution is estimated for the ship hull structure, built by steel and in for hybrid ship hull structure can be seen in Table 2.

Table 2. Carbon footprint of ship construction.

Description	Energy Consumption, MJ	Carbon Footprint, Tonnes of CO_2	Cost of CO_2 Cleaning, €
Ship hull structure built of steel	242,057,415	21,774	370,158
Hybrid ship hull structure	192,383,835	23,017	391,289

During the progressive ship hull structural collapse, a part of the cargo, P_{cargo} may be lost, and the associated cost, C_c, may be estimated as:

$$C_c(\mathbf{X},\ \beta) = C_{cargo} W_c P_{cargo}(\mathbf{X},\ \beta) \tag{17}$$

where C_{cargo} is the cost of a tonne of cargo and P_{cargo} is the probability of cargo loss in the case of structural collapse and W_c is the cargo weight (see Figure 6).

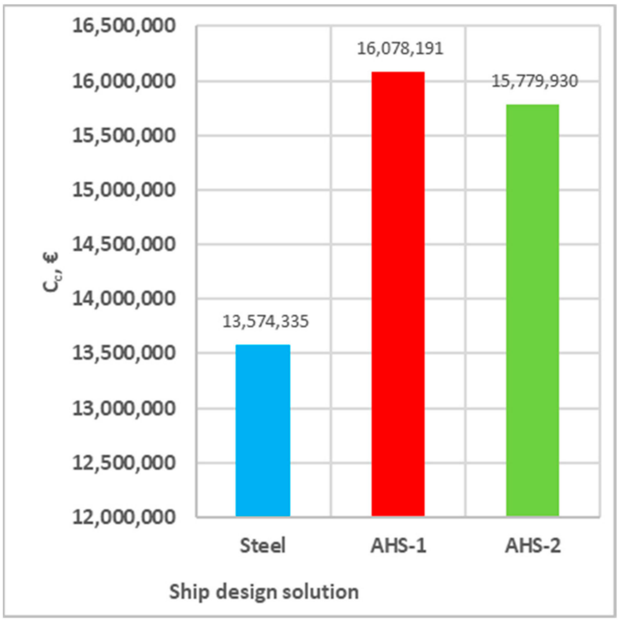

Figure 6. Cost of loss of cargo.

The accidental fuel and oil need to be cleaned up, leading to the following cost [53]:

$$C_{spill}(\mathbf{X},\ \beta) = P_{spill} P_{sl} CATS W_{oil\ and\ fuel} \tag{18}$$

where $CATS$ is the cost of one tonne of accidentally spilt oil and fuel that needs to be cleaned, P_{spill} is the probability of split and P_{sl} is the chance of the oil reaching the shoreline (see Figure 7).

Estimating the cost of loss of human life is based on the Implied Cost of an Averting Fatality ($ICAF$) defined from the average of the $OCDE$ countries [54].

$ICAF$ uses the Life Quality Index (LQI), defined as a function of the GDP per capita. The cost of loss of human life, C_{human} considering the probability, P_{crew} of loss of the crew, n_{crew} is defined by:

$$C_{human} = n_{crew} P_{crew} ICAF \tag{19}$$

where n_{crew} is the number of crew members, P_{crew} is the probability of loss of human life. In the present study C_{human} is estimated as 42,496,568 €.

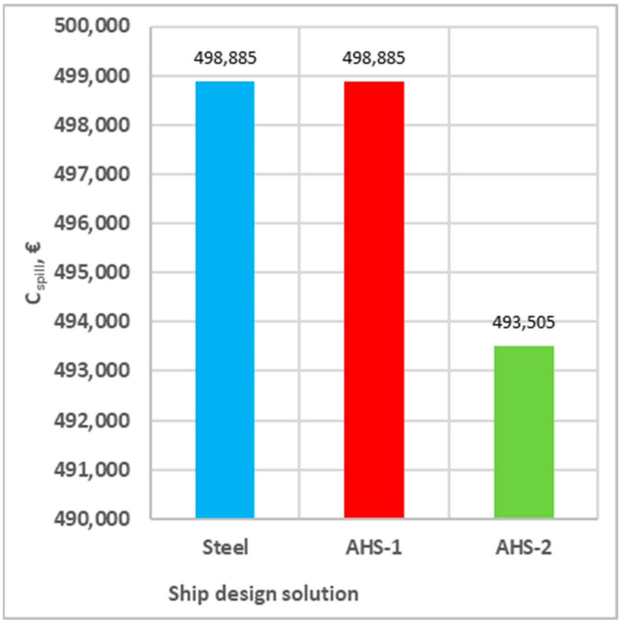

Figure 7. Accidental spill cost.

The cost of structural measures accounts for redesigning the ship structure and implementing aluminium honeycomb composite panels instead of steel plates, reducing steel weight, environmental pollution, and cost and increasing cargo capacity. Depending on the design solution, the associated cost of the measure, $C_{me,i}$, may be defined as (see Figure 8):

$$C_{me,i} = C_i(Design) - C_{steel}(Design) \tag{20}$$

where i = 1 for steel, i = 2 for AHS1 and i = 3 for AHS2.

Figure 8. Cost of structural measure.

6. Cost-Benefit Analysis

The risk-benefit analysis requires an optimisation of design solutions in supporting the ship's functionality subjected to progressive corrosion degradation and ship hull structural collapse, conditional to environmental pollution and energy efficiency.

To balance the repair cost against the benefits and the repair time needs to minimise the risk accounting for the probability of failure and expected consequences accounting for the total expected cost for recovering the structures as a result of the repair calculated as per unit time. Two periods of ship operations can be distinguished. The first one is when the ship arrives at its planned repair time, t_r. The second one is when the ship terminates the operation.

The repair cost per unit of time is estimated as $C_r(t_r)$ [55,56] calculated as a sum of the cost of the ship repair before failure, C_{bf} multiplied by the probability of non-failure, $P_{nf}(t_r)$ and the cost of failure, C_{af} multiplied by the probability of failure, $[1 - P_{nf}(t_r)]$ normalized to the ship service duration, t_r leading to the following:

$$C_r(t_r) = \frac{C_{bf}P_{nf}(t_r) + C_{af}[1 - P_{nf}(t_r)]}{t_r P_{nf}(t_r) + \int_0^{t_r} t f(t)dt} \tag{21}$$

where $P_{nf}(t_r) = 1 - P_f(t_r)$ is the probability of non-failure. The target beta index, β_t, of the ship hull structures' may vary between 1.25 and 5 [57,58] during the service life. The repair costs per unit of time are shown in Figures 9 and 10.

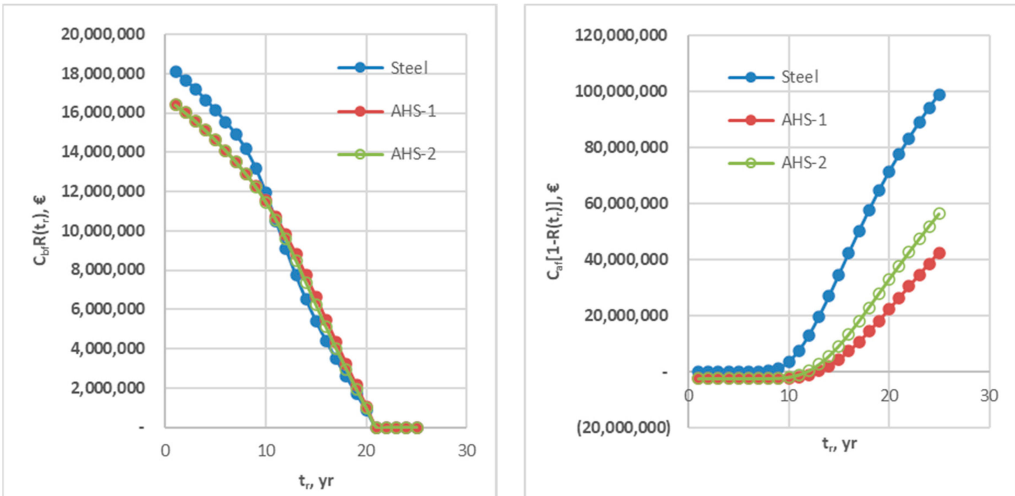

Figure 9. Cost of repair before failure (**left**) and after failure (**right**).

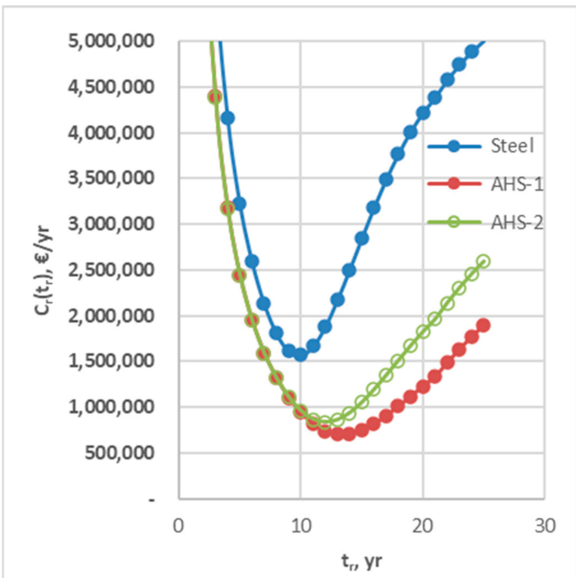

Figure 10. Total cost of repair per unit of time.

The target reliability index for repair and repair time minimises the total cost per year as a function of progressive structural degradation and collapse, conditional to the consequence cost involving environmental pollution cleaning. The optimum/target reliability index at the first repair for the different ship structural designs can be seen in Table 3.

Table 3. Target beta reliability index at the first repair time and associated cost.

Design Solution	β_t	Repair Time, yr.	Repair Cost, €/yr.
Steel	1.49	10.00	1,569,745
AHS-1	1.70	13.00	703,890
AHS-2	1.66	12.00	836,555

Table 3 identify that the best design solution from the three ones analysed here, accounting for all event that may occur during the service life, is AHS1, in which the inner steel shell plates of a bulk carrier ship are replaced by aluminium honeycomb panels enhancing the corrosion degradation resistance. The gained less lightweight is used to transport more cargo by keeping the same needed engine power and fuel with a shipping cost similar to AHS2 and lower than 11% of the steel solution. However, the use of aluminium honeycomb panels is limited in the present study to replace the steel inner side shell, which may be extended for other structures of the ship hull with an expectation of more benefit in weight reduction and the consequent impact on the reduction of the environmental pollution and more transported cargo. Such kind of extended use will require more profound studies of the use of the honeycomb panels subjected to multiaxial and dynamic loading.

7. Conclusions

The study identified the best ship structural design solution concerning the ship service life, accounting for the impact of using AHS panels in a combination of the steel structure and developing a hybrid design solution. The ship structure starts the service life in intact, non-corroded conditions and progressively degrades and collapses if no repair occurs during service life. It has been found that the design solution AHS1 and AHs2, in which aluminium honeycomb panels replace the inner steel shell plates of a bulk carrier ship, enhances the corrosion degradation resistance, and reduce the lightweight. The achieved less lightweight is used to transport more cargo by keeping the same engine power and fuel with a cost of the ship like AHS1 and AHS2 and lover 11% that one of the steel solutions. However, the AHS1 design solution is the best among the other two analysed design solutions. The design solution AHS1 demonstrates a higher beta-reliability index of 1.7 at the time of the first repair in the 13th year of the service life with a lower repair cost of 703 890 €/yr. The second identified design solution is one of AH2, which has very similar characteristics of a beta-reliability index of 1.66 at the first repair time in the 12th year of the service life with a repair cost of 836,555 €/yr. The complete steel design solution showed the worst characteristics, where the beta-reliability index of 1.49 at the first repair time of the 10th year with a repair cost of 1,569,745 €/yr. The application of the aluminium honeycomb panels for different types of structural components of different topologies and loading remains to be further studied.

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