Aluminium Honeycomb Sandwich as a design alternative for lightweight marine structures

Palomba G.[a1], Epasto G. [a], Sutherland L. [b], Crupi V. [a]

[a] Department of Engineering, University of Messina, Italy

[b] CENTEC, Instituto Superior Técnico, Universidade de Lisboa, Portugal

Abstract

Weight reduction and materials sustainability are becoming of primary importance for marine structures. However, the simultaneous application of both constraints is seldom considered. A solution to both issues could lie in the application of all-metal sandwich structures, and in particular of aluminium ones.

The study suggests the substitution of common marine structures with aluminium honeycomb sandwich structures (AHS), as a green and lightweight alternative, through a new methodology for structure comparison and design. Comparisons were based on bending stiffness equivalence and its relation to other design parameters, which were used to produce materials charts. A graphical approach based on plots of stiffness requirements, weight reduction goal and failure modes was applied for the identification of the main design variables.

The feasibility and effectiveness of the developed approach was illustrated by outlining an example regarding the possible substitution of a GFRP-based ship balcony overhang with an equivalent AHS. The results showed the possibility to simultaneously significantly reduce the weight, leave the geometry almost unchanged, and improve the mechanical response.

Keywords: honeycomb structures, lightweight, material charts, failure maps, marine structures, green design

Nomenclature

Symbol	*Description*	*u.m.*
b	Sandwich beam width	mm
c	Core thickness	mm
d	Distance between the centroid axis of the skins	mm
D	Sandwich beam bending stiffness	N mm^2
D_p	Sandwich plate bending stiffness	N mm
E^*_c	Young's modulus of the cellular core	MPa
E_f	Young's modulus of the facings	MPa
E_s	Young's modulus of the core solid material	MPa
G^*	Shear modulus of the cellular core	MPa
H	Overhang length on one side of the sandwich beam	mm
L	Support span	mm
L_{tot}	Overall length of the sandwich beam	mm
m	Sandwich structure mass	kg
P	Load	N
q	Linearly distributed load	N/mm
S	Sandwich plate shear stiffness	N/mm
t	Skin thickness	mm
w	Deflection	mm
w_b	Deflection due to bending	mm
w_s	Deflection due to shear	mm
ν_f	Poisson's ratio of the facing	

[1] Corresponding author: Giulia Palomba, Department of Engineering, University of Messina, Contrada di Dio, Vill. Sant'Agata, 98166 Messina, Italy. *Tel.*: +390906765504. *E-mail address*: gpalomba@unime.it

ρ	Density of the sandwich structure	kg/m^3
ρ_A	Areal density	kg/m^2
ρ_c	Density of the cellular core	kg/m^3
ρ_f	Density of the facing	kg/m^3
ρ_s	Density of the core solid material	kg/m^3
σ_{yc}	Compressive strength of the core material	MPa
σ_{yf}	Yield stress of the facings	MPa
τ_{yc}	Shear strength of the core	MPa
Abbreviations		
AHS	Aluminium honeycomb sandwich structures	
BCC	Body-centred cubic	
FRP	Fibre reinforced plastic	
GFRP	Glass fibre reinforced plastic	
PVC	Polyvinyl chloride	

1 Introduction

Marine structures design is subject to numerous constraints, dependent on structure type, builder and owner requirements, and national and international rules and regulations. A common feature of many marine applications is that they are weight sensitive, i.e. that they are required to fulfil the structural requirements whilst ensuring the lowest possible weight. Applying the lightweight concept to marine structures is beneficial for several reasons (Noury, Hayman, McGeorge, & Weitzenböck, 2002; Stenius, Rosén, & Kuttenkeuler, 2011) such as:

- displacement decrease;
- resistance reduction;
- fuel saving and emissions reduction;
- payload capacity increment;
- speed increase at a given power;
- construction materials reduction;
- stability and manoeuvrability improvements.

One of the most effective approaches to weight reduction in marine applications is to use sandwich structures instead of traditional monolithic materials and structures. The application of this sandwich concept is not only successful in terms of weight savings, but it also offers additional benefits (Kujala & Klanac, 2005; SANDCORe Co-ordination Action, 2013), which include:

- high specific stiffness and strengths;
- excellent energy absorption properties;
- good damping and sound and heat insulation properties;
- the possibility to combine different properties within a single construction element, via pertinent selection of the different core and skin materials used;
- reduction of the number of parts by integrating different functions into the sandwich design;
- improved part quality due to pre-manufacturing;
- time and cost savings during assembly;
- secondary stiffening and reduction of required supporting elements, simplifying the architecture of components and increasing the available useable volume within the structure.

These advantages explain why sandwich structures are now widely used, in applications ranging from pleasure boats to military ships (Di Bella, Galtieri, & Borsellino, 2018; Gaiotti, Ravina, Rizzo, & Ungaro, 2018; Grabovac & Turley, 1993; Kortenoeven, Boon, & de Bruijn, 2008; Maroun, Cao, & Grenestedt, 2007; Mouritz, Gellert, Burchill, & Challis, 2001; Vinson, 2005). Almost exclusively, marine applications use fibre reinforced plastic (FRP) polymeric foam-cored sandwich structures, with some use of honeycomb cores in the very small

high-performance / racing vessel sector of the industry. Further, a very high percentage of the FRP used in marine sandwich skins is glass reinforced polyester resin, commonly referred to as GFRP (Glass fibre reinforced plastic). One of the main reasons for the success of marine composite structures is the ease with which complex geometries (which are required for many parts of a vessel) can be manufactured. Further, numerous cost-effective composite manufacturing techniques are available, from hand lay-up, through vacuum infusion, to pre-preg (pre-impregnated) laminate consolidation (SANDCORe Co-ordination Action, 2013), making their fabrication tailorable to different scales and product values, from small cheap leisure boats to large expensive military or racing vessels. The possibility to integrate sandwich GFRP sandwich structures with traditional structural elements was also explored, for instance by (Andric, Kitarovic, Radolovic, & Prebeg, 2019), proving that an extensive implementation of sandwich concept with traditional solutions is a feasible and profitable path toward weight reduction and energy efficiency.

In addition to lightweight properties, concerns about the sustainability or the materials used are attracting the attention of customers and hence institutions and shipbuilders. Despite the numerous benefits enumerated above, the major drawback of composite sandwich panels is the difficulty of disposing of them at end of life (and of the waste disposable products of the production process, e.g. vacuum bags, breathers, peel-plies etc). A thorough analysis of this problem was presented by Summerscales et al. (Summerscales, Singh, & Wittamore, 2016), who highlighted that the processes involved in marine composite sandwich panels disposal are economically and energetically expensive, and that their recyclability level is poor.

Therefore, sustainability issues should be addressed right from the start of the design phase with an intelligent selection of materials, but which must also comply with the structural and weight constraints.

An attractive alternative to composites materials in marine applications is that of all-metal sandwich structures, and in particular that of aluminium sandwich structures with cellular cores. Aluminium is recognised as a sustainable and versatile material (Mahfoud & Emadi, 2010) due to its recyclability. In addition, aluminium recycling offers promising perspectives considering that the direct energy use in the production of recycled (secondary) aluminium is decreased by 93% in comparison to that required to produce primary aluminium (Schlesinger, 2014).

Despite their excellent lightweight properties and mechanical response to different loading conditions (such as impact (Hazizan & Cantwell, 2003; Zhang, Li, Guo, & Zhu, 2021), bending or compression (Crupi, Epasto, & Guglielmino, 2012; Jen & Lin, 2013; Sun, Huo, Chen, & Li, 2017; Z. Wang, Lu, Tian, Yao, & Zhou, 2016)), currently aluminium sandwich structures are only used in applications for large ships, such as cruise ships or navy ships, where the most common applications are in superstructure roofs, stairs, furniture, decks, overheads or partition walls (Bitzer, 1994; Plascore, n.d.), or in some parts offshore structures such as helidecks (Seo, Park, Jo, Kim, & Park, 2018) However, their potential advantages for some critical loading conditions such as impact due to collisions - which is a topic of high interest for marine industry (Conti et al., 2021; Fernandez, Vaz, & Cyrino, 2021; H. Wang, Pei, Zhang, & Gan, 2020) are still not sufficiently explored. Alternatively, some hybrid sandwich concepts, including aluminium core and composite skins are also of interest for researchers (C. Wang et al., 2021), but the separation of different materials before disposal and recycling is still an open question (Mattsson, André, Juntikka, Tränkle, & Sott, 2020). In addition, hybrid sandwich structures combining composite and metal parts, need to be carefully investigated, both experimentally and analytically, with the aim of assessing their performance under complex loading conditions, such as combinations of impact and bending (He, Liu, Wang, & Xie, 2018; He, Lu, et al., 2019; He, Yao, et al., 2019).

Other issues concerning marine applications of all-metal sandwich structures - which are also applicable to composite sandwich structures – are fire safety, cost and production feasibility. As reported in Palomba et al. (Palomba, Epasto, & Crupi, 2021), the application of sandwich structures to large civil marine vessels requires appropriate design and procedures which satisfy fire safety requirements of the classification

society rules and Naval or shipping registries. In general, fire safety must be guaranteed according to SOLAS standards, therefore every marine structure, including all-metal or composite sandwich, must be tested under particular conditions to assess the fulfilment of safety requirements. Commercially available aluminium honeycomb sandwich panels have already been tested accordingly to international rules on fire resistance (Compocel®, 2021) for shipbuilding. Typical, anecdotal misunderstandings about the fire behaviour of aluminium originated after the loss of nine British ships during the Falklands War, despite the fact that the subsequent official enquiry established that there was no evidence that the use of aluminium was at all to blame for the catastrophe (Almet-marine, 2018). On the contrary, it is well established that aluminium simply melts and does not burn and hence does not support combustion nor flame spread, does not emit smoke when exposed to fire, and it also does not produce sparks on impact (except when struck by rusty ferrous metals) (Almet-marine, 2018; Kaufman, 2016). Of course, any specific applications involving high-temperature exposure should be carefully considered because of the relatively low melting point of aluminium (655 °C) (Kaufman, 2016). Comparisons between steel, aluminium and GFP structures for ship bulkheads were also made in (Hulin et al., 2019), where the of aluminium-based structures were observed to perform excellently, especially when compared to GRP sandwich which can give critical problems such as emission of toxic fumes and flammability (Mouritz & Gibson, 2006).

With regards to cost issues, the same study (Palomba et al., 2021) reports that all-metal sandwich structures guarantee a high accuracy level since they are pre-manufactured in controlled environments, leading to improved quality, and reduced shipyard production times and costs. In general, aluminium sandwich structures have advantageous lightweight properties and are resistant to corrosion, but can be relatively expensive. However, a broader integration of such structures into marine construction should lead to cost reductions as a consequence of the increase in market size. In addition, the full-life costs of a marine structure should be considered - “from the cradle to the grave” - taking into account all relevant aspects: not only raw materials extraction and manufacturing, but also disposal and reuse. The disposal and recycling of marine structures has a high impact on their environmental consequences and costs. “Traditional” marine composite sandwich structures require demanding processes for disposal, both from energetic and economic perspectives. For instance, Nasso et al. (Nasso, Monaca, Marinò, Bertagna, & Bucci, 2018), reports that the pyrolysis of a 15 meter boat requires high temperatures (about 700 °C) and therefore high energy demand and high associated costs (about 16000 €), without mentioning the associated health risks. Therefore, the disposal of composite sandwich panels is still an open problem, and all-metal lightweight structures could provide a beneficial alternative in terms of disposal and recyclability.

The main production issues concerns constrained bending for the production of complex curved components. However, the constrained bending behaviour of Nomex honeycomb has already been experimentally and numerically evaluated in order to give guidelines for designing curved honeycomb sandwich panels (Zhao et al., 2021).

A broader integration of aluminium sandwich components in marine structures requires a deeper knowledge of their mechanical response under complex loading conditions, reliable guidelines to support their design and effective procedures for their selection, and comparisons with better-known “traditional” alternatives. In this scenario, research plays a primary role both in improving the experimental and theoretical knowledge, and in organising the available data into practical tools for design purposes.

The current paper aims to substantiate the advantages of sustainable and lightweight solutions, such as aluminium sandwich structures, for marine applications by providing guidelines to their selection based on comparisons with other materials and on analytical predictions of their mechanical properties.

The present work may be outlined as follows:

- A mechanical parameter, dependant on the design case, is chosen to provide a valid equivalence with other material structural solutions already commonly used in the marine industry;
- Analytical formulations are used to evaluate this mechanical parameter for different sandwich structure options (core configurations, geometrical characteristics, core and skin materials, etc.);
- Material charts reporting the relationships between several mechanical and physical properties of these sandwich structures are provided, to assist in the optimal selection of the main sandwich structure design variables;
- An example case study regarding a specific marine structural design, based on the previous comparisons, is presented.

The main novelty of the present work lies in the application of a comparative and design methodology for lightweight and green marine structures. The identification of bending stiffness as a common baseline criteria on which establishing valid comparisons between different structures was a crucial step for the developed procedure. Materials charts reporting the bending stiffness of several sandwich structures against other design parameters provided a useful tool to aid the selection of a convenient structure to improve the lightweight, environmental and volume properties of a marine structure. The potential of aluminium honeycomb sandwich structures as lightweight competitors for the "traditional" GFRP sandwich structures - especially given their much improved recyclability - were highlighted by the use of such charts. The design methodology was further developed by combining failure maps with equivalence parameter and other constraints (e.g. weight). The application of a graphical approach to each of the steps in the design methodology facilitates the identification of the pertinent optimised main design variables to achieve various goals, providing valuable support in the early design phase.

Although the main tools of the developed procedure, such as material charts and failure mode maps, are well-known in material science and mechanical engineering, their use specifically for marine engineering is not reported in the scientific literature. Hence the current study aims to promote, by providing practical examples of the advantages, the application of a similar approach to marine structures design.

The effectiveness of the developed approach together with the potential advantages of the use of unconventional structures for marine engineering (e.g. aluminium honeycomb sandwich structures) was clarified with an illustrative example concerning a ship balcony overhang. The obtained results emphasised the benefits, in terms of mechanical and lightweight performance, of aluminium honeycomb sandwich structures used as a sustainable alternative to more common, "traditional" solutions and also demonstrated the effectiveness of the described methodology.

2 Development of a novel approach for marine sandwich structures design

2.1 Mechanical properties equivalence and evaluation

In order to verify the effectiveness of aluminium sandwich structures or other "green" solutions for marine applications, a preliminary equivalence with more "traditional" structural solutions is required. The substitution of an existing composites sandwich structure design approach with one using all-metal sandwich panels needs to be carried out whilst ensuring that there is a common "baseline" criteria to which each approach conforms to – i.e. there must be some form of "equivalence" between the two designs. Only by providing a common baseline for the different structural design approaches may valid conclusions as to the advantages and disadvantages of each be drawn. This represents the first step of the design methodology developed in the current work.

In addition, such an equivalence is useful to assess and decide upon the practical geometrical configuration of all-metal sandwich panels, which must also take into account which specific plate thicknesses, core configurations, alloys etc. are readily available in the commercial market.

The current work focuses on the possible replacement of "traditional" GRP sandwich in marine structures with metallic sandwich, specifically AHS. Since bending stiffness is most often the critical design criteria in such cases, it makes sense here to select this bending stiffness as the parameter on which the equivalence of all-metal and composite sandwich structures is to be based. In addition, reliable analytical formulations for the bending stiffness of sandwich panels are well developed and accepted (Allen, 1969; Dan Zenkert, 2005), and their experimental evaluation is relatively straightforward. The specific bending stiffness to be used will depend on the specific design case being studied, but for illustrative purposes, in this section, the beam bending stiffness is used (later, in section 3 plate bending stiffness is used).

In order to provide a realistic evaluation, the reference bending stiffness for the current work was established on data for marine structures reported in the literature. In particular, the study of Muscat-Fenech et al. (De Marco Muscat-Fenech, Cortis, & Cassar, 2014) of impact damage testing on composite marine sandwich panels was identified as the reference work for the current bending stiffness benchmark. In their work the authors designed various candidate composite panels for a specific local boat builder according to the BS EN ISO 12215-5 standard for small craft. The selected materials were PVC foam for the core and glass-fibre reinforced plastics for the skins. They arrived at seven different candidate designs for the same small motor craft, with core thicknesses (*c*) varying from 10 to 30 mm and skin thicknesses (*t*) ranging from 0.81 to 1.76 mm. Panels were manufactured according to each design which were then tested to characterised their structural responses. ASTM D7250M-06 was used as the reference standard for flexural stiffness (*D*) evaluation with testing of 75 mm wide specimens. The stiffness values thus obtained by Muscat-Fenech et al., which are used as benchmark values "typical" of marine structure in the current study, are shown in Table 1.

Table 1: Candidate marine composite sandwich geometrical parameters and flexural stiffnesses (De Marco Muscat-Fenech et al., 2014).

Panel	Core thickness *c* [mm]	Skin thickness *t* [mm]	Bending stiffness *D* [N mm^2]
A	10	0.81	$49.6 \cdot 10^6$
B	10	0.67	$45.3 \cdot 10^6$
C	15	1.35	$248 \cdot 10^6$
D	15	2.03	$374 \cdot 10^6$
E	20	1.22	$393 \cdot 10^6$
F	25	2.03	$945 \cdot 10^6$
G	30	1.76	$1160 \cdot 10^6$

From the values in Table 1 it is clear that relatively small variations in skin thickness and, most importantly, core thickness have a significant effect on bending stiffness. Therefore, these parameters need to be selected carefully in order to fulfil structural requirements, but also to satisfy other constraints such as weight or space requirements.

The bending stiffness of a sandwich beam under three-point bending is reported in Eq.(1) (Allen, 1969):

$$D = E_f \frac{bt^3}{6} + E_f \frac{btd^2}{2} + E_c^* \frac{bc^3}{12} \tag{1}$$

Where E_f is the Young's modulus of the facings, E^*_c is the Young's modulus of the cellular core, *b* is the beam width, *t* is the skins thickness, *c* is the core thickness and *d* is the distance between the centroid axis of the skins (which for sandwich structure having skins with the same thickness is equal to *c + t*).

The first two terms in Eq.(1) represent the bending stiffness of the skins and the third term is the bending stiffness of the core, calculated about the neutral axis. Eq.(1) provides a reliable analytical evaluation of the bending stiffness which can be easily applied, provided that the core and facing materials properties are known, to estimate the effect of geometrical parameters on the resulting bending stiffness. In typical sandwich panels, the second term is dominant, both since the cores are much thicker than the skins, and because the skins are far stiffer than the core.

In the current work, Eq.(1) was applied to assess the bending stiffness of several candidate commercially available all-metal sandwich panels in order to compare their bending stiffness with the target range (Table 1). Despite the fact that the second term of Eq.(1) is dominant, in order to give highly accurate comparisons, initially all three terms were considered. However, later only the second term will be considered so as to develop a practical and convenient graphical design procedure. Some hybrid (metal-composite) sandwich structures were also included in the comparison in order to provide a more general overview on lightweight sandwich structures properties. The Young's modulus of the facings E_f for each sandwich structure was provided by the suppliers or taken from the literature; the Young's modulus of the cellular core E^*_c was evaluated from formulations established in the literature; in particular, for honeycomb core the Young's modulus was evaluated according to the equation suggested by Gibson and Ashby (Gibson & Ashby, 1999):

$$E_c^* = 2.3\, E_s \left(\frac{\sqrt{3}}{2}\right)^3 \left(\frac{\rho_c}{\rho_s}\right)^3 \tag{2}$$

where E_s is the Young's modulus of the solid material, ρ_c is the density of the core and ρ_s is the density of the solid material.

For foam core, the following formulations by Gibson and Ashby for the Young's modulus E^*_c was applied:

$$E_c^* = C_1 \left(\frac{\rho_c}{\rho_s}\right)^2 E_s \tag{3}$$

where $C_1 \approx 1$ for open cell foams.

For the GFRP titanium lattice with a body centred cubic (BCC) unit cell, the experimental results from (Abrate et al., 2018) were adopted.

Once the all-metal and hybrid sandwich panels with a similar beam bending stiffness to the target range of marine composite panels were identified, other panel parameters and properties relevant to the selection and design of sandwich panels were compared.

The sandwich structures included in this comparison and their properties are summarised in Table 2. Some of these values were analysed in previous studies by some of the present authors, as indicated in the table.

Flexural stiffness was calculated according to Eq.(1) for each sandwich structure and for each available combination of facing-core thickness. The panel width was set at 75 mm for all calculations to ensure equivalence with the values given in (De Marco Muscat-Fenech et al., 2014). From the obtained results, the combinations which provided bending stiffness values similar to the range of those of (De Marco Muscat-Fenech et al., 2014) were selected as relevant. Panels A and B from (De Marco Muscat-Fenech et al., 2014) (see Table 1), which have the lowest values of *D*, were excluded from this comparison since very few of the all-metal and hybrid panels considered gave beam bending stiffness similar to those of panel A and B and these were the panels with very thin cores (3-4 mm), making them hardly dissimilar to a solid plate.

Table 2: Summary of the main properties for the sandwich structures included in the comparison.

Sandwich structure type	Skin material	Core material	Considered core thickness c [mm]	Considered skin thickness t [mm]	Considered cell diameter d_c [mm]	Core density ρ_c [kg/m^3]	Ref.
All-Aluminium honeycomb	Al series 3000	Al series 3000	3 ÷ 21	0.5 – 0.8 - 1	6	56	-
	Al series 1000	Al series 3000	3 ÷ 21	1	6	56	-
	AA 5754	AA 5052	9	1	3 - 6	130- 80	(Palomba, Epasto, Crupi, & Guglielmino, 2018)(Palomba, Crupi, & Epasto, 2019)
Steel-Aluminium-honeycomb	AISI 304	Al series 3000	5 ÷ 12	0.5 - 1	6	56	-
Aluminium foam	Al3103	Al series 4000 (AlSi7)	3 ÷ 19	1	-	450	(Crupi, Epasto, & Guglielmino, 2013): c=9 mm
	Al 99.5%	Al series 4000 (AlSi10)	3 ÷ 19	1	-	530	
GFRP-titanium lattice BCC	GFRP	Ti6Al4V8Si	7 ÷ 23	1	-	529	(Abrate et al., 2018): c=7.5 mm
Aluminium-aramid honeycomb	Al series 3000	HRH	3 ÷ 20	1	3.2	80	-
GFRP-PVC	GFRP	PVC foam	15 ÷ 30	15 ÷ 30	1.35 ÷ 1.76	100	(De Marco Muscat-Fenech et al., 2014)

The all-metal and hybrid sandwich structures with a bending stiffness comparable to panels C-G from (De Marco Muscat-Fenech et al., 2014) were considered for further comparisons in order to evaluate the relationship of bending stiffness with other sandwich structures properties which can be crucial during the design process, such as the core thickness, overall panel density and areal density (the product of density and thickness). The bending stiffness was plotted against each of these parameters in Figure 1-Figure 3, giving charts useful for sandwich selection in stiffness-constrained design. The density and the areal density of the panels from (De Marco Muscat-Fenech et al., 2014) were estimated analytically from the data reported in the reference. The development of materials charts is the second step of the design procedure which are useful in making critical comparisons among different candidate structural solutions.

Table 3 shows three examples of how a sandwich bending stiffness of approximately $2.5 \cdot 10^8$ N mm^2 can be obtained using different combinations of core and skin thicknesses for an all-Al series 3000 honeycomb sandwich (AHS) structure.

Table 3: Examples of AHS panels with different core and skin thickness combinations giving approximately equal bending stiffness *D* (Al series 3000 core and skin).

Core thickness *c* [mm]	Skin thickness *t* [mm]	Resulting stiffness *D* [N mm²]	Resulting density *ρ* [kg/m³]	Resulting areal density ρ_A [kg/m²]
9	1	$2.6 \cdot 10^8$	542.8	6.0
13	0.5	$2.5 \cdot 10^8$	248.4	3.5
10	0.8	$2.4 \cdot 10^8$	427.6	4.9

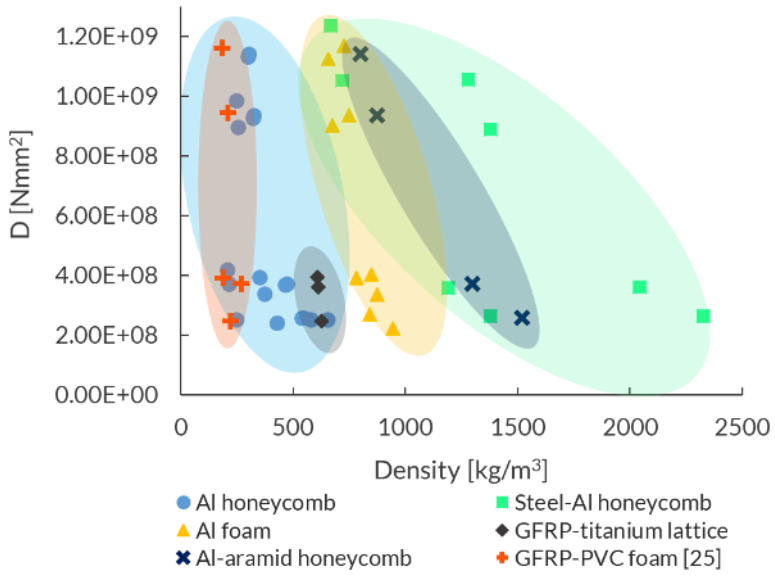

Figure 1: Bending stiffness vs sandwich panel density.

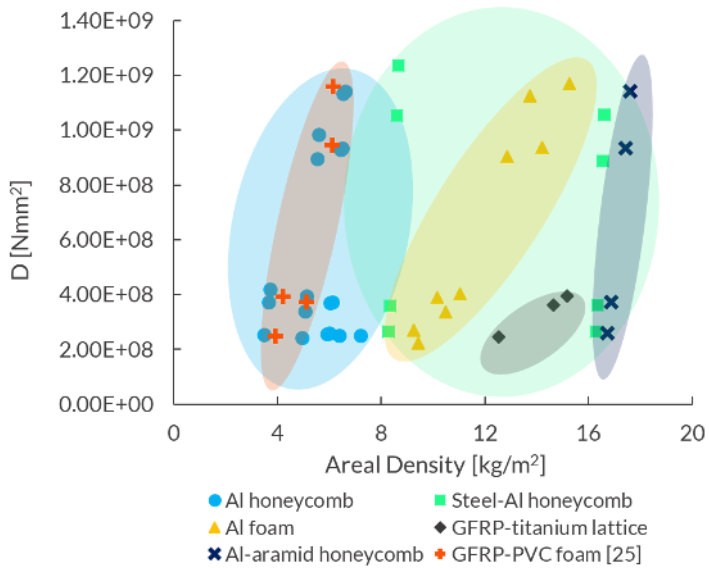

Figure 2: Bending stiffness vs sandwich panel areal density.

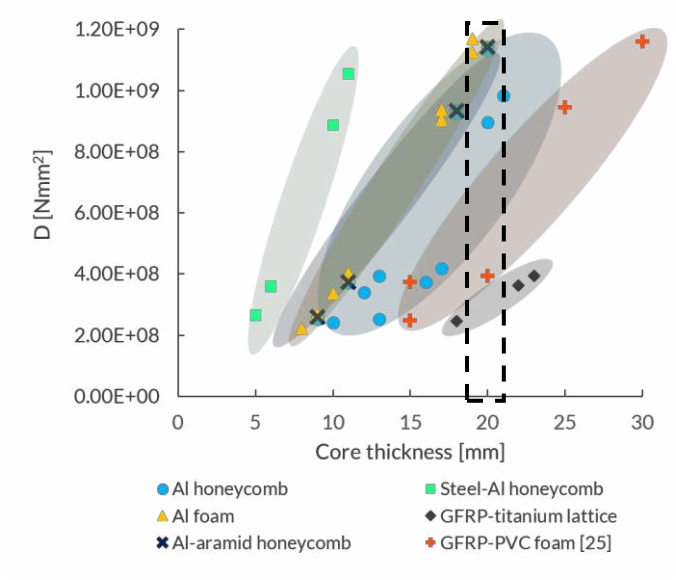

Figure 3: Bending stiffness vs core thickness.

Figure 1 and Figure 2 show that among all-metal or hybrid sandwich panels, all-aluminium honeycomb sandwich structures provide the lowest density and areal density for a given bending stiffness. In addition, they have very similar properties to the sandwich panels from (De Marco Muscat-Fenech et al., 2014) and this suggest that they are attractive competitors for the GFRP sandwich structures, especially given their much improved recyclability. All-aluminium foam sandwich structures could also provide an alternative solution, whereas steel-aluminium honeycomb sandwich panels are not very particularly "lightweight" due to their heavy steel skins, especially with the thicker 1 mm skins. Alternative solutions with thinner steel skins would be difficult to manufacture and would be susceptible to impact and concentrated local damages. In addition, exposing two dissimilar metals to the aggressive marine environment is usually to be avoided for corrosion issues. GFRP-titanium lattice sandwich panels provide intermediate properties, but their elevated cost and their technological feasibility for large structures do not make them suitable for marine applications. Aluminium-aramid honeycomb sandwich panels do not offer any particular advantage in terms of density savings for a given stiffness, but their wide availability and the fact that they can be manufactured into complex shapes could be advantageous for some applications.

As shown in Figure 3, for a given flexural stiffness value, the composite sandwich panels (considered here as stiffness "benchmarks") require the highest core thickness, whereas steel-aluminium honeycomb sandwich structures require the lowest core thickness, followed by aluminium foam and then aluminium honeycomb panels. In other words, for a given core thickness, GFRP-PVC foam panels produce a lower bending stiffness in comparison to the rigidity achievable with other sandwich panel solutions such as AHS or aluminium foam sandwich. An example of this is highlighted in Figure 3 by the dashed lines for a core thickness of approximately 20 mm: the Al honeycomb, Al foam and Al-aramid honeycomb sandwich panels have a bending stiffness an order of magnitude higher than that of the PCV-GFRP panels. The advantages attainable by replacing polymer-based sandwich panels with all-metal ones, and in particular with aluminium honeycomb sandwich structures, are clearly deducible from the material charts presented in Figure 1-Figure 3. When considering environmental issues, the choice of aluminium honeycomb sandwich structures becomes an even more attractive option due to the advantages in terms of the sustainability and recyclability of aluminium (Mahfoud & Emadi, 2010) highlighted in section 1. In addition, if compared to other alternatives such as aramid-based sandwich structures, AHS is less expensive and therefore more suitable for wider applications in the often highly cost-driven marine industry.

Consequently, wider applications of similar structures, supported by extensive experimental and analytical evidences, could lead to improvements in marine structures both from mechanical and environmental points of view. Indeed, one of the objectives of the current work is to emphasise the importance of combining the

search for higher-performance materials and structures with environmental requisites, such as recyclability and ease of disposal. These aspects of environmental impact must be addressed at the initial design stages – they cannot be left until after production, or for the end user to deal with at the end-of life stage.

Plotting materials maps similar to those reported in Figure 1-Figure 3 could support the preliminary selection of lightweight green structures aimed at optimising some crucial aspect, such as weight, and at guaranteeing the structural equivalence with existent solutions.

2.2 Failure map-driven design of honeycomb sandwich structures

The materials charts developed in the previous section could aid in the selection of a convenient structure to improve the lightweight, environmental and volume properties of a marine structure, for instance when compared to "traditional" GFRP-based panel manufacture. Once an alternative structure is selected, the designer then needs to specify the main geometric variables of that structure in order to proceed with the design calculations and other analysis of aspects such as mechanical and/or physical constraints. To enable this specification, the present design procedure was further developed by incorporating the main defining criteria for the alternative structural solution (e.g. all-metal sandwich) which is being considered as a candidate to replace an existing one (e.g. polymer-based sandwich). For example, an analytical description of the main failure modes, if known, can be used to draw failure maps as a function of the main design variables. The previously defined equivalence parameter (e.g. bending stiffness) can also then be plotted along with other constraints (e.g. weight) on these failure maps. Finally, the intersections of the desired characteristics can then be used to define, via a graphical procedure, the main design variables.

The main steps of this method are summarised in Figure 4.

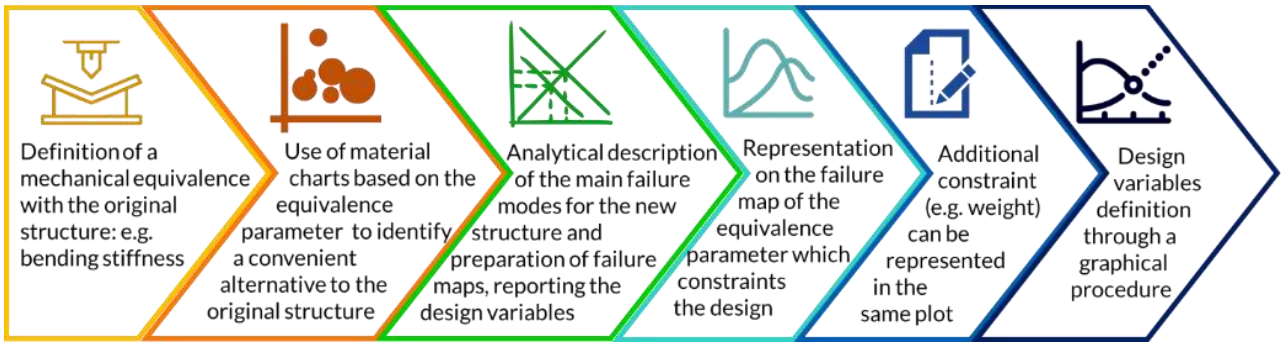

Figure 4: Material comparisons and mechanical equivalence based design procedure sequence

In the present work the preliminary comparison among different structural solutions (see section 2.1) in terms of panel density and volume criteria led to the selection of aluminium honeycomb sandwich structures as potential competitors for "traditional" GFRP sandwich structures.

In order to perform further illustrative comparisons, a specific example of an aluminium honeycomb sandwich panel was selected, whose main properties are given in Table 4.

Table 4: Properties of the selected aluminium honeycomb sandwich structure.

Skin material	Core material	Skin thickness [mm]	Cell diameter [mm]	Skin Young's modulus E_f [MPa]	Core Young's modulus E^*_c [MPa]	Yield stress skin material σ_{yf} [MPa]	Compressive strength core material σ_{yc} [MPa]	Shear strength of the core τ_{yc} [MPa]
AA 5754	AA 5052	1	3	67000	11.8	155	3.3	0.9

Since flexural stiffness was used as the equivalence parameter with "traditional" marine composite sandwich structural panels, the bending behaviour of the selected honeycomb sandwich structure was focused upon for further considerations.

A previous experimental study performed on this aluminium sandwich structure in Table 4 (Crupi et al., 2012), highlighted that under three-point bending conditions, two collapse modes occur:

- Mode I, which involves indentation under the load actuator, combined with the rotation of the two halves of the sample around the mid-plane and with the formation of 4 plastic hinges (see Figure 5a);
- Mode II, which is similar to core shear AB, reported by Kesler and Gibson for metallic foam core sandwich structures (Kesler & Gibson, 2002). This mode consists of the formation of one plastic hinge in each skin at the load point, with one half of the beam entirely deforming in shear, but the other half deforming by shear only between the load application point and the support, where two other plastic hinges form (see Figure 5b). Core compression is also seen in the load application area.

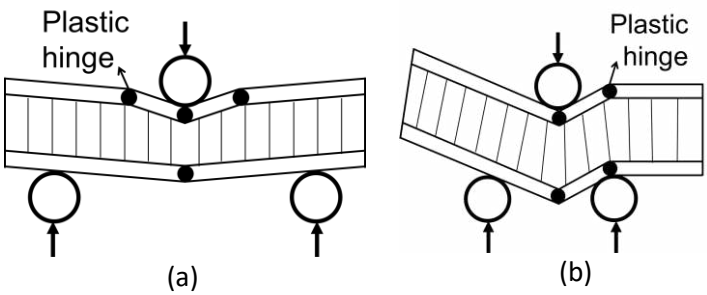

Figure 5: Scheme of collapse Mode (a) I and (b) II.

The manifestation of the two different collapse modes depends upon the boundary condition, and in particular on the support span: smaller support spans trigger the Mode II core shear failure, whilst for larger support spans Mode I indentation prevails. For a given sandwich design and loading conditions the dominant failure mechanism is that which produces the lowest failure load.

In (Crupi et al., 2012) the analytical formulations to predict the failure load for both collapse modes were introduced and their reliability verified against experimental results. The expressions for the failure load of Mode I and Mode II are:

$$F_I = bt\sqrt{3\sigma_{yc}\sigma_{yf}} + \sigma_{yf}\frac{bt^2}{L} + 2bc\tau_{yc}\left(1+\frac{2H}{L}\right) \tag{4}$$

$$F_{II} = 2\sigma_{yf}\frac{bt^2}{L} + 2bc\tau_{yc}\left(1+\frac{H}{L}\right) + \sigma_{yc}\frac{bL}{4} \tag{5}$$

In Eq. (4) and (5), σ_{yc} is the compressive strength of the core material, σ_{yf} is the yield stress of the skin material, τ_{yc} is the shear strength of the core, L is the support span and H is the overhang length on one side. Hence, if L_{tot} is the overall length of the sandwich beam, H is equal to:

$$H = \frac{L_{tot} - L}{2} \tag{6}$$

In the current study, these same expressions were used to draw a failure map for the considered AHS structural panel, with the aim of evaluating the effect of various design parameters on the mechanical response of the sandwich structure.

A failure map displays the transition conditions between two different mechanisms, which occur when both mechanisms may produce the same failure load. For the aluminium honeycomb sandwich panels considered here, under three point bending only two failure mechanisms were observed. Hence the failure map will display only one transition line, which is obtained by equating the failure load for Mode I (Eq. (4)) with that of Mode II (Eq. (5)):

$$bt\sqrt{3\sigma_{yc}\sigma_{yf}} + 2bc\tau_{yc}\frac{H}{L} = \sigma_{yf}\frac{bt^2}{L} + \sigma_{yc}\frac{bL}{4} \tag{7}$$

In order to provide data in a convenient form for design purposes, the failure map is presented here in plots of core against facing thickness (*c* and *t*, respectively), both normalised with respect to the support span, *L* (i.e. plots of *c/L* against *t/L*). The equation of the transition line between Mode I and Mode II in terms of the parameters *c/L* and *t/L* is:

$$\frac{c}{L} = \frac{1}{2b\tau_{yc}H}\left[\sigma_{yf}bt\left(\frac{t}{L}\right) + \sigma_{yc}\frac{bL}{4} - bt\sqrt{3\sigma_{yc}\sigma_{yf}}\right] \tag{8}$$

As observed above, the geometrical parameters such as *c* and *t* also affect flexural stiffness, and therefore reporting this information in the failure map should provide valuable data for selection of the sandwich panel structure during the design phase.

It is clear that some of the design variables need to be set in order to plot the failure map and the trend of bending stiffness in terms of *c/L* against *t/L* .In addition, in order to represent the bending stiffness in terms of a *c/L* against *t/L* plot it is necessary to introduce a simplification into its formulation. It is well-known that the first and third term in Eq. (1) are negligible in common sandwich structures (Allen, 1969), and that if the facings are thin enough in comparison to the core then the distance *d* is approximately equal to that of *c* and thus the flexural rigidity expression reduces to:

$$D \cong E_f\frac{btc^2}{2} \tag{9}$$

Expressing *D* in terms of the variables *c/L* and *t/L,* and rearranging the equation in a convenient form, yields:

$$\frac{c}{L} = \sqrt{\frac{D}{L^3}\frac{2}{E_f b}\left(\frac{t}{L}\right)^{-1}} \tag{10}$$

Figure 6 presents a failure map for the currently considered aluminium honeycomb sandwich structural panel, for which facing thickness, *t* and overall panel length, L_{tot} were set to 1 and 200 mm, respectively. Three different stiffness curves are plotted; one each for D = $2.52\cdot10^8$, $3.93\cdot10^8$ and $9.45\cdot10^8$ Nmm^2.

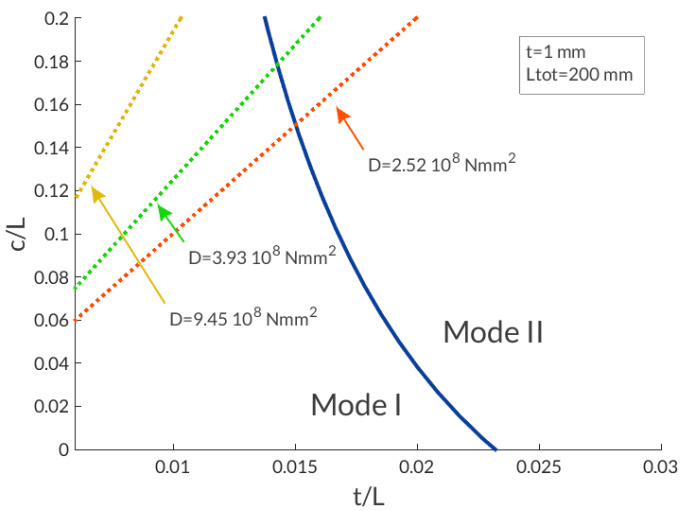

Figure 6: Failure map for the considered AHS, reporting three stiffness curves.

The values of $3.93 \cdot 10^8$ Nmm^2 and $9.45 \cdot 10^8$ Nmm^2 for *D* correspond to those of panels E and F from (De Marco Muscat-Fenech et al., 2014), respectively, which are the target 'baselines' for the current study. The value of D = $2.52 \cdot 10^8$ Nmm^2 is obtained for the considered honeycomb sandwich panels with a core thickness equal to 9 mm, as used in the previous studies by some of the present authors (Crupi et al., 2012; Palomba et al., 2019).

As an example of how Figure 6 may be used in practice, after establishing certain parameters such as skin thickness (which for commercially available all-metal sandwich structures is usually limited to a few discrete options) and stiffness and beam overall length (which could well be the critical design constraints) it is possible to select a core thickness and support span to ensure the preferred failure mode for the final application case.

Since weight is a crucial issue for marine structures, an optimal selection of sandwich panels in terms of weight is desirable.

A single-objective optimisation procedure, similar to that described in Refs. (Gibson & Ashby, 1999) and (Ashby, 2000), can be applied to aid the selection of the main structural sandwich design variables with the aim of minimising weight. Such an approach, despite being well known in materials science (Ashby, 2000; Gibson & Ashby, 1999), it is not reported in scientific literature to be used specifically for marine engineering, hence the current study aims at extending the application of a similar methodology to marine structures design.

The mass *m* of a sandwich panel is equal to:

$$m = bL(2\rho_f t + \rho_c c) \tag{11}$$

where ρ_f is the facing density.

This formulation of mass expressed in terms of *c/L* and *t/L* is:

$$\frac{c}{L} = \frac{m}{L^2 b \rho_c} - \frac{2\rho_f}{\rho_c}\frac{t}{L} \tag{12}$$

Some of these variables need to be set in order to proceed with the design. In the present work the variables to be set are ρ_f, ρ_c, *b* and *L*. To give a slightly different possible example to that shown in Figure 6, for the present mass goal-case it was decided to set the support span, *L* as a design requirement whereas the skin and core thicknesses, *t* and c, were problem variables.

A graphical approach is useful to visualise the effects of different parameter variations, which are often constrained both by product commercial availability and technological limitations.

An example is shown in Figure 7 where the following lines are plotted:

- the transition line between Mode I and Mode II, according to Eq. (8);
- a line representing the stiffness constraint of the design; a flexural rigidity of $2.52\ 10^8$ N mm^2, according to Eq. (10);
- the mass variation, according to Eq. (12): several of these (parallel) lines are shown, each for a different mass value.

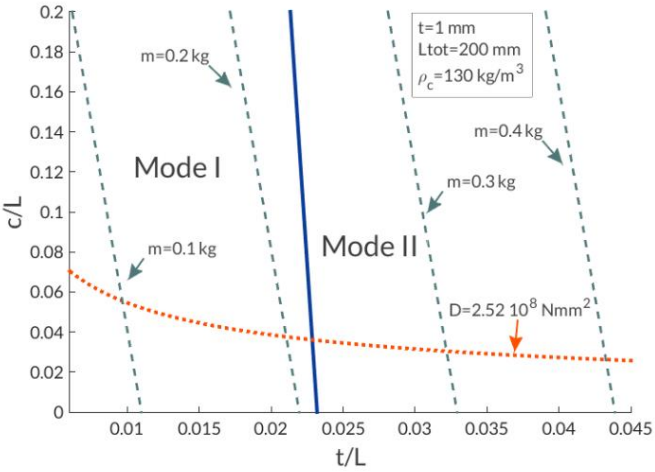

Figure 7: Graphical approach considering stiffness, weight and failure modes, for the analysed AHS.

The plot in Figure 7 presents the failure map, which allows the designer to distinguish between the zones of Mode I and Mode II failures, together with the stiffness constraint and also the panel weight. The designer may then select the point on the stiffness constraint line which meets a minimum weight requisite, whilst ensuring that the corresponding core and skin thicknesses are both commercially readily available. Further, if one failure mode is desirable over the other then the closest c/L – t/L combination both commercially available and falling within the relevant failure mode zone is readily identifiable from Figure 7.

3 Illustrative example: Ship balcony overhang

In order to suggest a simple procedure to perform a preliminary selection of sandwich structure design variables, and to show the potential of metallic sandwich structures, an example of the application of the previously discussed materials charts and properties comparisons in the design of a lightweight component for a real marine application is provided in this section.

A ship balcony overhang is selected as the structure for this case study, since this is a likely "entry point" where composites are very likely to enter into the structural design of cruise ships, ferries and other passengers ships (*MOSAIC project final publishable report*, 2015). The balcony structure used as a reference was deduced from the literature and, in particular, from the study by Kharghani and Guedes Soares (Kharghani & Guedes Soares, 2018) of a hybrid steel-GFRP balcony overhang.

This reference structure consists of a sandwich panel with balsa core and GFRP skins, integrated into a steel support which overlaps the sandwich panel for part of its length. The balcony from (Kharghani & Guedes Soares, 2018) is shown in Figure 8.

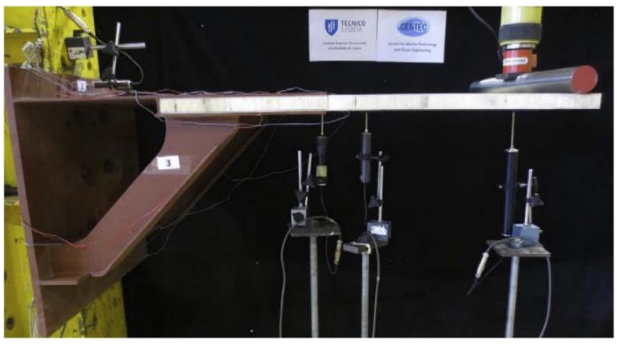

Figure 8: Balcony structure tested by Kharghani and Soares, reprinted from (Kharghani & Guedes Soares, 2018), with permission from Elsevier.

In the cited work the balcony structure was experimentally subjected to two types of loading condition: shear and bending; the former obtained by applying the load in the proximity of the steel-sandwich overlap area, the latter by applying the load at the overhang extremity (as shown in Figure 8). Only the bending condition was used for comparison and design purposes in the current section. The main characteristic of this reference structure are summarised in Table 5, with further details reported in (Kharghani & Guedes Soares, 2018).

Table 5: Main properties of the reference structure (Kharghani & Guedes Soares, 2018).

Skin material	GFRP
Core material	Balsa wood
Skin thickness [mm]	2.5
Core thickness [mm]	30
Width [mm]	750
Overall length [mm]	1050
Length not overlapped by steel [mm]	646
Skin Young's modulus in the longitudinal direction [MPa]	26400
Weight of the entire structure (steel frame included) [kg]	150
Sandwich panel weight [kg]	15

The aim of the present section is to evaluate the potential advantages of the substitution of the composite panel used as the balcony overhang in (Kharghani & Guedes Soares, 2018) with an all-metal sandwich structure. The re-design process will be focused solely on the sandwich panel, leaving the supporting steel frame, visible in Figure 8, unchanged.

As proposed in section 2.1, this substitution will be based on bending stiffness equivalence and aluminium honeycomb sandwich structures are selected to replace the composite sandwich panel.

The geometry of the sandwich panel used in the reference structure, suggests that in this case plate theory is more suitable than beam theory for bending stiffness evaluation. Therefore, the flexural rigidity of the composite panel tested by Kharghani and Soares (Kharghani & Guedes Soares, 2018) was evaluated according to Eq. (13), which is derived in (Allen, 1969) for sandwich panel cylindrical bending:

$$D_p = E_f \frac{tc^2}{2(1-\nu_f^2)} \tag{13}$$

where ν_f is the facings' Poisson's ratio. Based on the data reported in (Kharghani & Guedes Soares, 2018), the plate bending stiffness of the reference structure was evaluated as $3.15 \cdot 10^7$ N mm and this was hence set as the target stiffness requirement for the replacement aluminium honeycomb sandwich panels. The width, b and the length, L of the balcony overhang were kept the same as in the original structure, i.e. 750 and 1050 mm, respectively. The selection of the design variables, namely the core and skin thicknesses and the core density, can be supported by plotting the rigidity boundary and the mass objective function on a c/L – t/L chart. In order to summarise all the information in a bi-dimensional plot, it is necessary to set some of the variables. In particular, in this case the desired mass for the replacement sandwich structure was set at 7 kg, in order to obtain a 50% reduction of the sandwich panel weight in comparison to the original structure. Once the mass is established, several lines representing the weight objective function, one for each core density, can be drawn according to Eq. (12).

Since plate theory is applied here, the relevant stiffness boundary, expressed in terms of the variables c/L and t/L is expressed by Eq. (14) (cf. Eq. (10) for the beam bending case considered in Section 2):

$$\frac{c}{L} = \sqrt{\frac{D_p}{L^3}\frac{2(1-\nu_f^2)}{E_f}\left(\frac{t}{L}\right)^{-1}} \tag{14}$$

The obtained plot is shown in Figure 9.

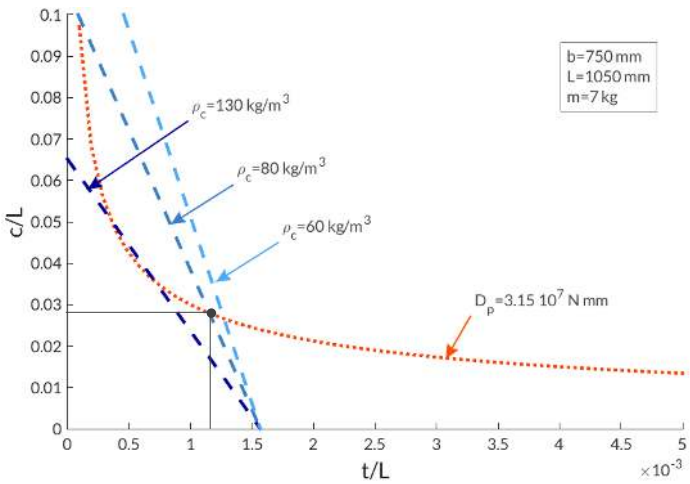

Figure 9: Graphical method for obtaining design variables from flexural rigidity and weight of the AHS panel.

The core density values (i.e. 130, 80 and 60 kg/m^3) displayed in Figure 9 were selected as examples of the commercially available solutions, but, in practice, this value could depend on several factors such as specific regulations or cost restrictions. Plotting different lines for different ρ_c is also useful to verify the effect of the variation of such a parameter on the other variables. Once the required core density is decided upon, the intersection between the stiffness constraint and the line representing the weight function allows the identification of the required core and skin thicknesses.

For instance, for a core density of 80 kg/m^3, as shown in Figure 9, the obtained design variables are summarised in Table 6 and compared with the original structure.

Table 6: Design variables for the AHS panel with $D_p = 3.15 \cdot 10^7$ N mm and m = 7 kg compared with the original composite solution.

	Core density ρ_c[kg/m^3]	**Core thickness *c* [mm]**	**Skin thickness *t* [mm]**	**Panel weight *m* [kg]**
AHS panel	80	30	1.2	7
Original GFRP-balsa panel	155	30	2.5	15

From Table 6 it is clear that, for the same bending stiffness, the aluminium honeycomb sandwich panel with ρ_c = 80 kg/m^3 allows both a weight and skin thickness reduction of approximately 50%.

An alternative approach could be to set the core density and then plot the objective function using the weight as a parameter, as shown in Figure 7.

The overhang balcony could be required to fulfil other constraints, which could affect the selection of the design variables. For instance, the deflection *w* of the overhang is a crucial aspect and it could be limited by specific comfort-related or other requirements.

The original composite structure tested by Kharghani and Soares (Kharghani & Guedes Soares, 2018) under bending conditions gave an initial linear response with a load-deflection stiffness ratio *P/w* equal to 230 N/mm.

A cantilever sandwich plate subjected to a linearly distributed transverse edge load $q=P/b$ applied at the edge opposite to the clamp, undergoes a deflection w, at the loaded edge, which is the result of a bending (w_b) and a shear (w_s) contribution, according to Eq. (15) (D Zenkert, 1995; Dan Zenkert, 2005):

$$w = w_b + w_s = \frac{qL^2}{2D_p}\left(L - \frac{L}{3}\right) + \frac{qL}{S} \tag{15}$$

where S is the shear stiffness of the sandwich plate, defined as:

$$S = \frac{G^* d^2}{c} \tag{16}$$

where G^* is the shear modulus of the cellular core.

Focusing on the bending contribution and substituting the formulation of D_p from Eq. (13), it is possible to express the ratio P/w in terms of c/L and t/L and, rearranging the equation in a convenient form, the following expression is obtained:

$$\frac{c}{L} = \sqrt{\frac{P}{w}\frac{2}{3}\frac{(1-\nu_f^2)}{E_f b}\left(\frac{t}{L}\right)^{-1}} \tag{17}$$

Hence, the design of the balcony overhang could aim not only to match the flexural rigidity of the original composite sandwich panels whilst reducing the weight, but also to limit the deflection of the balcony, i.e. ensuring high values of the ratio P/w.

Since Eq. (15) is valid for cantilever plates, it is assumed here that the sandwich panel is ideally clamped at one extremity with a length L equal to the free length of the original composite panels (i.e. the length not overlapped by steel equal to 646 mm). Clearly, the connecting structure between the sandwich panels and the superstructure has a significant effect on the balcony's mechanical response, but such considerations would require complex analyses which would also depend on the exact structural and geometric solution of this steel connecting part, which is beyond the scope of the current work. However, valid comparisons between the two sandwich structure solutions considered here may be made using this simplification.

The constraint on the ratio P/w can be plotted on a $c/L - t/L$ chart, together with the weight function, in order to identify the optimal design parameters. Since the considered length is reduced in comparison to the example reported in Figure 9, the target weight was set at 5 kg. The constraint on the ratio P/w was represented for three different values: 230 N/mm, which is the value reported for the composite structure of (Kharghani & Guedes Soares, 2018), 400 N/mm and 800 N/mm. The plot for the present case study is displayed in Figure 10.

As previously discussed, the design variables are determined by the intersection between the weight function and P/w constraint lines.

For example, for a ratio P/w=230 N/mm, which is the same of the original composite structure of (Kharghani & Guedes Soares, 2018), and for a density of aluminium honeycomb core of 80 kg/m^3 gives the resulting design variables indicated by the dark grey point and lines in Figure 10. The comparison of this solution with that of the original GFRP structure are reported in Table 7.

As shown in Table 7, the aluminium honeycomb sandwich structure with the same ratio P/w of the original composite GFRP-balsa balcony, gives a weight and skin thickness reduction of approximately 50% and a core thickness reduction of 30%.

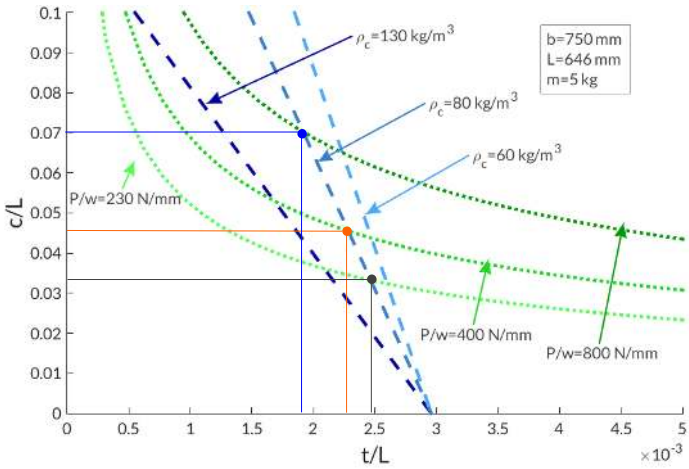

Figure 10: Graphical method for obtaining design variables from the ratio P/w and AHS panel weight.

Table 7: AHS panel design variables , with *P/w* =230 N/mm and m=5 kg, compared with the original GFRP structure.

	Core density ρ_c[kg/m^3]	**Core thickness *c* [mm]**	**Skin thickness *t* [mm]**	**Panel weight *m* [kg]**
AHS panel #1	80	21	1.6	5
Original GFRP-balsa panel	155	30	2.5	9.2

The potential advantages of AHS can be further demonstrated via a further example; for a *P/w* "stiffness" of 400 N/mm (almost double that of the original GFRP structure) and a core density of 80 kg/m^3 the resulting AHS properties summarised in Table 8 are obtained.

Table 8: Design variables for the AHS, panel with *P/w* =400 and 800 N/mm and m=5 kg, and comparison with the original structure.

	***P/w* [N/mm]**	**Core density ρ_c[kg/m^3]**	**Core thickness *c* [mm]**	**Skin thickness *t* [mm]**	**Panel weight *m* [kg]**
AHS panel #2	400	80	29	1.5	5
AHS panel #3	800	80	46	1.2	5
Original GFRP-balsa panel	230	155	30	2.5	9.2

The values in Table 8 show the significant performance improvement attainable with an AHS structure; with an almost identical core thickness and a significant reduction in skin thickness it is possible to reduce the weight by a half whilst doubling stiffness, both of which are important parameters for a balcony overhang.

Table 8 also includes the results achievable for a *P/w* "stiffness" of 800 N/mm and a core density of 80 kg/m^3, corresponding to the blue point in Figure 10 which shows that an increment in core thickness of 50% resulted in an almost 3.5 times higher stiffness whilst almost halving the mass of the original structure.

Another important design constraint could be the durability of the balcony overhang, which involves the investigation of impact, compression and contact events. Similar aspects are to be considered in future advances of this work

The above-performed graphical procedure allows simple identification of the pertinent design variables to achieve different goals, such as a specific weight reductions and bending deflection limitations, whilst also enabling a clear understanding of the effects on the physical and mechanical properties of changes to the

defining parameters. In addition, valuable information concerning the performance of the designed structures achievable can be deduced; as observed in Table 7 and Table 8, the AHS panels selected according to the developed procedure can improve the *P/w* stiffness significantly compared to that of the reference structure whilst halving the weight and hardly changing the panel size.

Hence, the information obtained using the above described method can offer very useful support in the design phase. However, this approach would need to be integrated with specific further analyses where required. For instance, as previously stated, the connection between the sandwich panel and the main frame plays a crucial role in the mechanical response of the balcony and this aspect should be thoroughly investigated since the bonding methodology suitable for AHS may not be the same as that which should be used for the GFRP reference structure (although, the bonding of metal to metal structures may well be less problematic than that between composites and metal). The failure mode(s) of cantilever aluminium honeycomb sandwich panels should also be investigated and then considered during the design phase, as reported in section 2.2. Indeed, to be included in the design approach, failure modes must be verified for the specific boundary conditions and structure typology. As far as the authors are aware, similar data are not available in the literature for AHS panels and therefore this aspect was not considered for the illustrative example.

However, although the methods described here obviously do not include all of the possible ensuing design issues, they do provide very useful and easy to use tools both to evaluate the potential advantages of AHS sandwich structures, and to guide the pertinent selection of their design parameters.

4 Conclusions

The current work compares aluminium honeycomb and GFRP-based sandwich structures for marine applications, and proposes a straightforward procedure to aid lightweight sandwich structure selection and design. In fact, all-metal sandwich structures, and in particular aluminium honeycomb sandwich structures, were seen to offer the possibility of combining lightweight properties with high environmental sustainability, which must be a crucial point to take into account in the design of future marine structures. The recyclability of aluminium was recognised as a crucial characteristic to guarantee the sustainability of the structure during its whole life-cycle, including disposal and/or recycling. Indeed, one of the objectives of the current work was to emphasise the importance of combining the search for higher-performance materials and structures with environmental requisites, such as recyclability and ease of disposal.

Since aluminium honeycomb sandwich structures are not commonly used for marine structures, their wider integration in marine structures requires the development of an effective procedure to assess their suitability and to guide their preliminary design. However, although the paper was focused on aluminium honeycomb sandwich structures, the developed procedure can be extended to other structural solutions and design criteria.

In order to guide the appropriate selection of all-metal sandwich structures for marine applications, an equivalence with more “traditional” structural solutions should be considered in order to give a suitable equivalent baseline from which valid and pertinent comparisons and design considerations can be drawn.

In the current work, the bending stiffness was considered as the “equivalence” parameter on which the all-metal sandwich structure selection was based. The specific bending stiffness to be used will depend on the specific design case being studied. In order to ensure realistic values of the bending stiffness for the preliminary phase of the analysis, these were based on data reported in the literature for GFRP panels commonly used in marine applications. The beam bending stiffnesses of several all-metal and hybrid lightweight sandwich candidate structures were then evaluated analytically, allowing the selection of candidate sandwich panels with bending stiffnesses within the range of those of the “reference” GFRP marine panels.

Subsequently, further design criteria were compared in order to evaluate various aspects of sandwich panel selection and design. In particular, for each sandwich structure solution the bending stiffness was plotted against the core thickness, the overall panel density and the areal density, to give materials charts which proved very useful for selection of the specific parameters of the sandwich structures. These charts identified that aluminium honeycomb sandwich structures offer the potential to provide significant savings in weight (density) and volume (core thickness) in comparison to "traditional" composite sandwich panels. Even though the materials charts approach is well-established in materials science, it is not currently applied to marine structures design, and therefore this is a novel approach in the field of marine engineering.

Further aspects of aluminium honeycomb sandwich panels design were considered via failure maps combined with stiffness and weight constraints, and the plots produced were seen to support the selection of design variables such as core and skin thickness, whilst also giving clear insights into the effect of each of these variables on the resulting mechanical and physical properties.

Finally, an illustrative example regarding a ship balcony overhang was outlined. A structure reported in the literature incorporating sandwich panels with composite GFRP skins and balsa core was used as a "baseline". The plate bending stiffness and the load/deflection ratio of this baseline structure were used as the constraints for an alternative aluminium honeycomb sandwich structure. The resulting AHS design, as compared to the "baseline" GFRP structure, demonstrated the potential of aluminium honeycomb sandwich structures in terms of both weight reduction and mechanical performance improvement. Therefore, in addition to sustainability advantages, aluminium honeycomb sandwich structures can also give improvements in terms of mechanical performance and weight reduction. This suggests that AHS are attractive competitors for GFRP sandwich structures, especially in terms of improved recyclability.

The outlined procedure facilitates the identification of the pertinent optimised main design variables and represents an innovative tool for marine engineering, via the introduction of effective tools, such as material charts and failure maps, which are not currently commonly applied in the marine industry. All steps in the procedure are graphical in nature, which facilitates the identification of the pertinent optimised main design variables in achieving various different goals - such as a specific weight reductions and bending deflection limitations - whilst also enabling a clear understanding of the effects on the physical and mechanical properties of any changes to the defining parameters. Hence, the information obtained using the developed method constitutes a very useful tool, especially in the early design phases.

In addition, the underlying principles of the work, namely the replacement of traditional marine structures with lightweight and more sustainable alternatives guided by an effective and practical procedure, can be easily adapted and extended to different cases or different structures. Hence, the developed approach could be of practical interest for marine structural designers since it enables a quick and effective procedure to evaluate and compare the advantages of several lightweight solutions, and then to select on a preliminary basis the most convenient alternative(s), according to the desired design goals.

Acknowledgements

The study reported in this paper is part of the research activities of the Research Project "THALASSA", funded by the PON (National Operative Programme) 2014-2020. Dr. Sutherland is funded by the FCT (Fundação para a Ciência e Tecnologia) 'Regime Transitorio' DL57-2016, Contract No. IST-ID/164/2018.

References

Abrate, S., Epasto, G., Kara, E., Crupi, V., Guglielmino, E., & Aykul, H. (2018). Computed tomography analysis of impact response of lightweight sandwich panels with micro lattice core. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, *232*(8), 1348–1362. https://doi.org/10.1177/0954406218766383

Allen, H. G. (1969). *Analysis and Design of Structural Sandwich Panels*. London: Pergamon Press.

Almet-marine. (2018). Fire resistance of aluminium. In *Aluminium users' guide* (pp. 135–144). Retrieved from https://almet-marine.com/en/technical-informations/aluminium-users-guide

Andric, J., Kitarovic, S., Radolovic, V., & Prebeg, P. (2019). Structural analysis and design of a car carrier with composite sandwich deck panels. *Ships and Offshore Structures*, *0*(0), 1–16. https://doi.org/10.1080/17445302.2018.1564536

Ashby, M. F. (2000). Multi-objective optimization in material design and selection. *Acta Materialia*, *48*, 359–369.

Bitzer, T. (1994). Honeycomb Marine Applications. *Journal of Reinforced Plastics and Composites*, *13*(4), 355–360. https://doi.org/10.1177/073168449401300406

Compocel®. (2021). Datasheet AL FR. Retrieved from https://www.honeycombpanels.eu/en/products/sandwich-panels/aluminium-coated-panels/compocel-al-fr

Conti, F., Le Sourne, H., Vassalos, D., Kujala, P., Lindroth, D., Kim, S. J., & Hirdaris, S. (2021). A comparative method for scaling SOLAS collision damage distributions based on ship crashworthiness–application to probabilistic damage stability analysis of a passenger ship. *Ships and Offshore Structures*, *0*(0), 1–17. https://doi.org/10.1080/17445302.2021.1932023

Crupi, V., Epasto, G., & Guglielmino, E. (2012). Collapse modes in aluminium honeycomb sandwich panels under bending and impact loading. *International Journal of Impact Engineering*, *43*, 6–15. https://doi.org/10.1016/j.ijimpeng.2011.12.002

Crupi, V., Epasto, G., & Guglielmino, E. (2013). Comparison of aluminium sandwiches for lightweight ship structures: Honeycomb vs. foam. *Marine Structures*, *30*, 74–96. https://doi.org/10.1016/j.marstruc.2012.11.002

De Marco Muscat-Fenech, C., Cortis, J., & Cassar, C. (2014). Impact damage testing on composite marine sandwich panels, part 1: Quasi-static indentation. *Journal of Sandwich Structures & Materials*, *16*(4), 341–376. https://doi.org/10.1177/1099636214529959

Di Bella, G. ., Galtieri, G., & Borsellino, C. (2018). Three-Point Flexural Properties of Bonded Reinforcement Elements for Pleasure Craft Decks. *Applied Composite Materials*, *25*(1), 21–34. https://doi.org/10.1007/s10443-017-9605-9

Fernandez, J. M., Vaz, M. A., & Cyrino, J. C. R. (2021). Numerical study on the collision of Platform Supply Vessel and Floating Production Storage and Offloading platform. *Ships and Offshore Structures*, *0*(0), 1–13. https://doi.org/10.1080/17445302.2021.1932022

Gaiotti, M., Ravina, E., Rizzo, C. M., & Ungaro, A. (2018). Testing and simulation of a bolted and bonded joint between steel deck and composite side shell plating of a naval vessel. *Engineering Structures*, *172*, 228–238. https://doi.org/10.1016/J.ENGSTRUCT.2018.06.008

Gibson, L. J., & Ashby, M. F. (1999). *Cellular Solids-Structure and Properties*. Cambridge University Press.

Grabovac, I., & Turley, D. M. (1993). Present and Future of Composite Materials for Marine Applications. *ICCM/9. Metal Matrix Composites.*, *1*, 89–96.

Hazizan, A., & Cantwell, W. J. (2003). The low velocity impact response of an aluminium honeycomb sandwich structure. *Composites: Part B*, *34*, 679–687. https://doi.org/10.1016/S1359-8368(03)00089-1

He, W., Liu, J., Wang, S., & Xie, D. (2018). Low-velocity impact response and post-impact flexural behaviour of composite sandwich structures with corrugated cores. *Composite Structures*, *189*(January), 37–53. https://doi.org/10.1016/j.compstruct.2018.01.024

He, W., Lu, S., Yi, K., Wang, S., Sun, G., & Hu, Z. (2019). Residual flexural properties of CFRP sandwich structures with aluminum honeycomb cores after low-velocity impact. *International Journal of Mechanical Sciences*, *161–162*(July). https://doi.org/10.1016/j.ijmecsci.2019.105026

He, W., Yao, L., Meng, X., Sun, G., Xie, D., & Liu, J. (2019). Effect of structural parameters on low-velocity impact behavior of aluminum honeycomb sandwich structures with CFRP face sheets. *Thin-Walled Structures*, *137*(August 2018), 411–432. https://doi.org/10.1016/j.tws.2019.01.022

Hulin, T., Karatzas, V., Mindykowski, P., Jomaas, G., Berggreen, C., Lauridsen, D., & Dragsted, A. (2019). Experimental assessment of the robustness in fire of lightweight ship bulkheads. *Marine Structures*, *64*(August 2018), 161–173. https://doi.org/10.1016/j.marstruc.2018.11.005

Jen, Y.-M., & Lin, H.-B. (2013). Temperature-dependent monotonic and fatigue bending strengths of

adhesively bonded aluminum honeycomb sandwich beams. *Materials & Design*, *45*, 393–406. https://doi.org/10.1016/J.MATDES.2012.09.028

Kaufman, J. G. (2016). *Fire Resistance of Aluminum and Aluminum Alloys*. ASM International.

Kesler, O., & Gibson, L. . (2002). Size effects in metallic foam core sandwich beams. *Materials Science and Engineering: A*, *326*(2), 228–234. https://doi.org/10.1016/S0921-5093(01)01487-3

Kharghani, N., & Guedes Soares, C. (2018). Experimental and numerical study of hybrid steel-FRP balcony overhang of ships under shear and bending. *Marine Structures*, *60*, 15–33. https://doi.org/10.1016/J.MARSTRUC.2018.03.003

Kortenoeven, J., Boon, B., & de Bruijn, A. (2008). Application of Sandwich Panels in Design and Building of Dredging Ships. *Journal of Ship Production*, *3*(24), 125–134.

Kujala, P., & Klanac, A. (2005). Steel sandwich panels in marine applications. *Brodogradnja*, *56*(4), 305–314.

Mahfoud, M., & Emadi, D. (2010). Aluminum recycling - Challenges and opportunities. *Advanced Materials Research*, *83–86*, 571–578. https://doi.org/10.4028/www.scientific.net/AMR.83-86.571

Maroun, W. J., Cao, J., & Grenestedt, J. L. (2007). Steel truss/composite skin hybrid ship hull, Part II: Manufacturing and sagging testing. *Composites Part A: Applied Science and Manufacturing*, *38*(7), 1763–1772. https://doi.org/10.1016/J.COMPOSITESA.2006.11.003

Mattsson, C., André, A., Juntikka, M., Tränkle, T., & Sott, R. (2020). Chemical recycling of End-of-Life wind turbine blades by solvolysis/HTL. *IOP Conference Series: Materials Science and Engineering*, *942*. https://doi.org/10.1088/1757-899X/942/1/012013

MOSAIC project final publishable report. (2015). Retrieved from https://cordis.europa.eu/docs/results/314/314037/final1-mosaic-final-publishable-summary-report_figures.pdf

Mouritz, A. P., Gellert, E., Burchill, P., & Challis, K. (2001). Review of advanced composite structures for naval ships and submarines. *Composite Structures*, *53*(1), 21–24. https://doi.org/10.1016/S0263-8223(00)00175-6

Mouritz, A. P., & Gibson, A. G. (2006). Fire properties of polymer composite materials. Solid mechanics and its applications. *Solid Mechanics and Its Applications*, 401.

Nasso, C., Monaca, U. la, Marinò, A., Bertagna, S., & Bucci, V. (2018). The strip planking: An eco-friendly solution for the end-of-life of ships. In *Technology and Science for the Ships of the Future - Proceedings of NAV 2018: 19th International Conference on Ship and Maritime Research* (pp. 444–451). https://doi.org/10.3233/978-1-61499-870-9-444

Noury, P., Hayman, B., McGeorge, D., & Weitzenböck, J. (2002). Lightweight construction for advanced shipbuilding-recent development. In *Proceedings of the 37th WEGEMT Summer School* (pp. 11–15).

Palomba, G., Crupi, V., & Epasto, G. (2019). Collapse modes of aluminium honeycomb sandwich structures under fatigue bending loading. *Thin-Walled Structures*, *145*, 106363. https://doi.org/10.1016/J.TWS.2019.106363

Palomba, G., Epasto, G., & Crupi, V. (2021). Lightweight sandwich structures for marine applications: a review. *Mechanics of Advanced Materials and Structures*, *0*(0), 1–26. https://doi.org/10.1080/15376494.2021.1941448

Palomba, G., Epasto, G., Crupi, V., & Guglielmino, E. (2018). Single and double-layer honeycomb sandwich panels under impact loading. *International Journal of Impact Engineering*, *121*, 77–90. https://doi.org/doi

Plascore. (n.d.). Lightweight Panel Solutions for Marine Vessel Interiors. Retrieved from https://www.plascore.com/markets/marine-honeycomb/commercial-marine-grade-honeycomb-core/

SANDCORe Co-ordination Action. (2013). *Best Practice Guide for Sandwich Structures in Marine Applications*.

Schlesinger, M. E. (2014). *Aluminum Recycling* (Second Edi). CRC Press Taylor & Francis Group.

Seo, J. K., Park, D. K., Jo, S. W., Kim, B. J., & Park, J. S. (2018). Experimental assessment of the structural behaviour of aluminium helideck structures under static/impact loads. *Ships and Offshore Structures*, *13*(0), 348–363. https://doi.org/10.1080/17445302.2018.1473745

Stenius, I., Rosén, A., & Kuttenkeuler, J. (2011). On structural design of energy efficient small high-speed craft. *Marine Structures*, *24*(1), 43–59. https://doi.org/10.1016/J.MARSTRUC.2011.01.001

Summerscales, J., Singh, M. M., & Wittamore, K. (2016). Disposal of composite boats and other marine composites. In *Marine Applications of Advanced Fibre-Reinforced Composites* (pp. 185–213). Woodhead

Publishing. https://doi.org/10.1016/B978-1-78242-250-1.00008-9

Sun, G., Huo, X., Chen, D., & Li, Q. (2017). Experimental and numerical study on honeycomb sandwich panels under bending and in-panel compression. *Materials & Design*, *133*, 154–168. https://doi.org/10.1016/J.MATDES.2017.07.057

Vinson, J. R. (2005). Sandwich Structures: Past, Present, and Future. In *Sandwich Structures 7: Advancing with Sandwich Structures and Materials* (pp. 3–12). Berlin/Heidelberg: Springer-Verlag. https://doi.org/10.1007/1-4020-3848-8_1

Wang, C., Cao, S., Lu, S., Hu, Z., Yao, L., & He, W. (2021). A CEL study of dynamic slamming response and failure mechanism on corrugated core composite-metal sandwich structures. *Ships and Offshore Structures*, 1–24. https://doi.org/10.1080/17445302.2021.1906195

Wang, H., Pei, D. ming, Zhang, P., & Gan, L. (2020). The plastic dynamics and failure analysis of ship broadside protection structures subjected to contacted UNDEX: energy dissipation model and simulation. *Ships and Offshore Structures*, *0*(0), 1–14. https://doi.org/10.1080/17445302.2020.1865715

Wang, Z., Lu, Z., Tian, H., Yao, S., & Zhou, W. (2016). Theoretical assessment methodology on axial compressed hexagonal honeycomb' s energy absorption capability. *Mechanics of Advanced Materials and Structures*, *23*(5), 503–512. https://doi.org/10.1080/15376494.2014.994150

Zenkert, D. (1995). *An Introduction to Sandwich Construction*. Engineering Materials Advisory Services. Retrieved from https://books.google.it/books?id=zc-GQgAACAAJ

Zenkert, Dan. (2005). *An Introduction to Sandwich Structures* (Second).

Zhang, Y., Li, Y., Guo, K., & Zhu, L. (2021). Dynamic mechanical behaviour and energy absorption of aluminium honeycomb sandwich panels under repeated impact loads. *Ocean Engineering*, *219*(June 2020), 108344. https://doi.org/10.1016/j.oceaneng.2020.108344

Zhao, Z., Liu, C., Sun, L., Luo, H., Wang, J., & Li, Y. (2021). Experimental and numerical study on the constrained bending-induced collapse of hexagonal honeycomb. *Composite Structures*, *277*(May), 114604. https://doi.org/10.1016/j.compstruct.2021.114604