Lightweight aluminium sandwich structures for marine vehicles

Giulia PALOMBA[a,1], Gabriella EPASTO[a], Leigh SUTHERLAND [b] and Vincenzo CRUPI[a]
[a] *Department of Engineering, University of Messina, C.da di Dio. 98166 Messina, Italy*
[b] *Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Lisboa, 1049-001, Portugal*

Abstract. One of the most important design strategies for increasing the speed and/or efficiency of marine vehicles is that of weight reduction. This can be achieved by optimising structural design via judicious distribution of the most apt materials and via the application of innovative lightweight structures.
Sandwich structures are ideal candidates for structural lightening since they provide excellent mechanical properties at low densities, and a wide range of properties via intelligent selection of face-sheet and core materials, and configurations. Further, sandwich structures selection for marine vehicles needs to consider manufacturing feasibility for large structures, sustainability issues and materials compatibility with the aggressive marine environment.
As a possible alternative to the ubiquitous glass reinforced plastic (GRP) fibre composite sandwich materials used for marine vehicles, all-aluminium sandwich structures have several attractive properties such as light weight, high mechanical properties, sustainability, and corrosion resistance. Common architectures for metallic cores include: honeycomb, foam, corrugated and lattice.
This work aims to evaluate the effectiveness of aluminium honeycomb sandwich structures in marine applications by providing a comparison with other lightweight solutions. Bending stiffness was used as the criterion to select honeycomb sandwich panels allowing valid comparisons with typical marine GFRP sandwich panels.
A case study based on a possible replacement of a GFRP ship balcony with an equivalent aluminium honeycomb sandwich structure was introduced. The proposed balcony was analysed with a simplified numerical model, which gives useful information for the design of the proposed structure and the experimental set up of full scale tests. The acquired information can be applied to support the design of lightweight honeycomb sandwich panels to be used for balconies, decks, floors, ceilings and other structural elements of marine vehicles.

Keywords. Lightweight sandwich structures, aluminium honeycomb, ship balcony, marine structures

1. Introduction

As the demand for speed increases in the marine vehicles industry more attention is paid to all the possible approaches to achieve such result.
Weight reduction is unquestionably one of the most straightforward and promising methods to contribute to increases in the speed of marine vehicles, and also simultaneously introduces additional advantages such as [1,2] displacement decreases, payload capacity increases, fuel savings, stability enhancements, reduced materials use, and easier transport of raw components.

[1] Giulia Palomba, Department of Engineering, University of Messina, C.da di Dio. 98166 Messina, Italy; E-mail: gpalomba@unime.it

Reductions in the weight of marine structures can be achieved by introducing innovative lightweight structures and by selecting the most pertinent materials.

Sandwich structures are ideal candidates for structural lightening since they combine a low density with excellent mechanical and physical properties. An appropriate selection of skin and core materials and configurations enables tailoring of the properties, which, for marine vehicles must take into account the aggressive marine environment. Other constraints to consider for marine applications are technological limitations for large-scale structures and materials environmental sustainability, the latter of which is rapidly gaining considerable importance.

At present, the most common sandwich structures applied in the marine industry consist of glass fibre reinforced plastic (GFRP) skins with a polymeric foam core. However, a significant downside of these composite sandwich panels is their poor recyclability and difficult waste management [3].

In this scenario, a promising solution for lightweight purposes is offered by all-metal sandwich structures, and in particular by aluminium sandwich panels with cellular cores. Aluminium alloys are low-density, can be selected to withstand corrosion in a marine environment, and their sustainability and recyclability are widely recognised [4,5]. Current uses of all-aluminium sandwich structures include partition walls, overheads, decks, roofs, and stairs [6], but further structural applications require a more thorough knowledge of their mechanical properties, especially when complex loading conditions are involved, and more consistent design procedures and selection methodologies.

Aluminium honeycomb sandwich (AHS) panels were investigated by a group of the present authors considering different loading conditions (impact loading [7], static [7]and fatigue [8] bending loading) and configurations (double layer panels under impact loading [9], glass fibre reinforced AHS panels under bending and impact loading [7]).

The current works is aimed at evaluating the benefits of using aluminium sandwich structures for marine applications. In particular, aluminium sandwich structures with a honeycomb core were considered and compared to other ‘traditional’ solutions. Bending stiffness was used as the criterion to select honeycomb sandwich panels allowing valid comparisons with typical marine GFRP sandwich panels. Some guidelines for the substitution of existing structures with aluminium sandwich structures were drawn up and a case study regarding a ship balcony overhang was outlined. A preliminary numerical model was built to evaluate both the main criticalities and the expected performance of aluminium honeycomb sandwich panels used in ship balcony structures.

2. Bending stiffness as an equivalence criterion

In order to achieve a weight reduction of a marine vehicle, and hence the consequent speed increase, by means of the use of aluminium sandwich structures, a reliable and valid comparison between aluminium sandwich structures and more typical (and less sustainable solutions), such as GFRP sandwich structures, is required.

In the present paper, the potential substitution of existent structures with AHS was evaluated starting from the equivalence of bending stiffness. Indeed, stiffness constraints are often the driving parameter in the design of GFRP sandwich structures, and further, the bending stiffness of a sandwich panel is relatively easy to evaluate, both experimentally and analytically. The well-known formulation [10,11] for the bending stiffness of a sandwich structures is given in Equation (1) (assuming skins of equal thickness and material):

$$D = E_f \frac{bt^3}{6} + E_f \frac{btc^2}{2} + E_c^* \frac{bc^3}{12} \quad (1)$$

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 skin thickness and c is the core thickness.

However, the first and third terms of Equation (1) are negligible for common sandwich structures [10], where the skins are considerably thinner than the core and the Young's modulus of the core is significantly smaller than that of the skins. Therefore, the bending stiffness reduces to:

$$D \cong E_f \frac{btc^2}{2} \quad (2)$$

If the bending stiffness of an existing structure is known, equivalence of this parameter can be used to aid the selection of an alternative solution, such as an aluminium honeycomb sandwich structure. This substitution should be supported by other constraints and design choices, regarding for example weight, geometrical constraints or other physical properties of the replacing structure.

3. Case study: aluminium honeycomb sandwich structure for a ship balcony

The evaluation of the potentials for weight reduction and improvements in mechanical performance due to the use of aluminium honeycomb sandwich structures was performed via a realistic case study. A ship balcony overhang has been identified as a commercially interesting component for the plausible integration of the sandwich structure concept into marine structure designs [12]. The reference balcony structure was that investigated by Kharghani and Soares [13], consisting of a hybrid steel-GFRP structure. In particular, the balcony studied in Ref. [13] has a steel support frame whereas the balcony floor consists of a sandwich panel of balsa core and GFRP skins. Part of the experimental investigation performed in [13] included the application of a bending load at the free extremity of the balcony.

The main properties of the reference balcony overhang are reported in Table 1.

Table 1. Main characteristics of the reference structure [13]

Skin thickness *t* [mm]	2.5
Core thickness *c* [mm]	30
Width *b* [mm]	750
Overall length L_{tot} [mm]	1050
Length not overlapped by steel L_{free} [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

In the present study, the possibility of replacing the GFRP sandwich panel of the balcony with an aluminium honeycomb sandwich panel was investigated. Hence, only the sandwich panel was considered in the replacement procedure, which was based on flexural rigidity equivalence. The dimensions of the sandwich panel (except for thickness) were kept equal to those of the reference structure.

The bending stiffness of the reference structure was evaluated using Equation (1) as $2.6\cdot10^{10}$ N mm^2. This value represents the constraint that the replacing AHS must satisfy. The bending stiffness is a function of the geometrical characteristics of a sandwich panel, and hence this target value can be used to guide the selection of the main sandwich geometric design variables, i.e. the core and skin thicknesses (the width b and the length L_{tot} of the panel are already fixed). A graphical approach can be applied for such a purpose where the bending stiffness D is plotted in a c/L against t/L chart, according to Equation (2).

The bending constraint can be combined with other requirements, such as the mass of the structure, which for a sandwich panel can be expressed according to Equation (3):

$$m = bL(2\rho_f t + \rho_c c) \tag{3}$$

where ρ_f is the density of the skins and ρ_c is the density of the cellular core.

For this balcony case study a reduction of the original mass of approximately 50% was considered a feasible goal, and therefore a mass of 7 kg was set as a further design requirement for the replacing AHS. The mass constraints can be plotted in a c/L - t/L graph together with the stiffness constraint. Nevertheless, it is important to remember that the mass is dependent on the densities of the skins and the core. In the current study, aluminium skins (AA 5754) were selected for the replacing structure with a density of 2680 kg/m^3. The core density was left as a free parameter, and hence in the c/L against t/L plot several lines represented the mass objective function, one for each core density (which were selected as candidate examples from commercially available solutions).

The graphical method for the selection of the design variables (namely the core and skin thicknesses), in terms of the stiffness and the mass constraints, is shown in Figure 1. Once a suitable core density has been decided upon the intersection between the stiffness constraint and the mass function identifies the required core and skin thicknesses.

In Figure 1, after a core density of 80 kg/m^3 was chosen, the intersection of the mass and the bending stiffness curves allowed the identification of the the corresponding values of t/L and c/L from the respective axes. Since the length of the panel, L, was known (1050 mm), c and t could hence then be found.

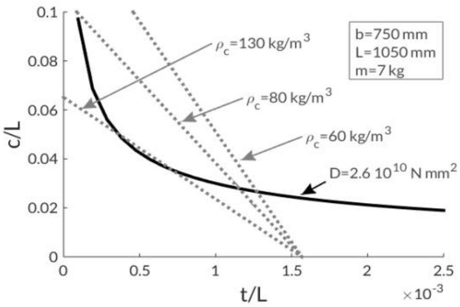


Figure 1: Graphical method for AHS design variables definition.

The density value of 80 kg/m^3 was chosen because it is easily available from common honeycomb manufacturers, it is cheap and it offers good mechanical properties, for instance under impact and compression loading.

For the considered case, the obtained design variables and the comparison with the original structure are summarised in Table 2.

Table 2. Design variables for the replacing AHS structure and comparison with the original panel.

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

According to the results reported in Table 2, an AHS with ρ_c equal to 80 kg/m^3 is able to provide a reduction in weight of approximately 50% as well as a reduction in skin thickness of 50%. These results highlight the potential weight reduction benefits of the use of aluminium honeycomb sandwich structures in marine structures.

In addition, the suggested graphical method based on bending stiffness and weight constraints is a practical tool to support AHS design and the substitution of 'traditional' structures with more lightweight and sustainable alternatives.

3.1. Numerical investigation

Once the equivalent aluminium honeycomb sandwich panel for the balcony case study has been selected according to the procedure outlined above, a further investigation of the replacement balcony structure's mechanical performance should be performed. A full-scale mechanical test would be the most reliable method to evaluate the structural effectiveness of the suggested AHS-based balcony. However, some more cost effective preliminary investigations regarding the entire balcony structure should be first performed, in order to guide the assembly of the balcony components and to define the testing setup and conditions.

Therefore, a numerical analysis was performed with the aims of evaluating the AHS panel effectiveness, and of selecting and verifying the connection method between the panel and the supporting frame. The analysis was performed using Altair Hypermesh® for the pre-processing and Optistruct® as solver. The modelled structure is displayed in Figure 2 along with the main geometrical characteristics. The dimensions of the AHS panel were kept equal to those reported in Ref. [13] in order to provide a valid comparison.

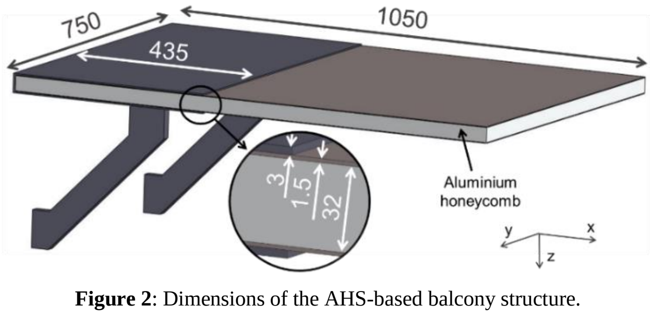


Figure 2: Dimensions of the AHS-based balcony structure.

Two aluminium plates, used to connect the balcony to the surrounding structures, were placed at the top and at the bottom of one end of the AHS panel, in keeping with the reference structure reported by Khargani and Soares [13]. Two aluminium brackets were welded to the bottom plate in order to improve the structural stability and functionality, similary to the original structure [13].

In order to avoid excessively time-consuming numerical analysis solutions, the aluminium honeycomb panel can be modelled with an equivalent core sandwich panel [14,15] where the honeycomb core is replaced with an orthotropic solid layer with equivalent properties to those of the honeycomb. In the current work some of the honeycomb properties were provided by the fabricator, with the others evaluated according to the analytical formulation reported by Gibson and Ashby [16].

The equivalent honeycomb core, the skins, the adhesive layer between the skins and the supporting plate, and the brackets were all modelled with CHEXA solid elements, whereas the plates were modelled with CQUAD4 shell elements. All of the connections were modelled, as a first approximation, by simply tying the nodes of the adjacent faces. The connections between the sandwich panels and the external elements can be critical, although the joining of metallic components should be less challenging than that between composites and metal parts, where the large stiffness mismatch can initiate debonding and other problems. However, the stress in the adhesive layer needs to be evaluated in order to select an adequate structural adhesive and to guarantee the structural functionality. Since the main purpose of the model was to evaluate the adhesive performance and the general response of the assembly, rather than modelling the failure mechanisms, a linear elastic analysis was used. The honeycomb sandwich structures used in the model was selected taking into account the results obtained in section 3 (on the basis of stiffness equivalence and mass constraint) and the commercially available configurations of the main manufacturers. The honeycomb has a cell size of 6 mm and a density equal to 83 kg/m^3. The equivalent elastic parameter of the selected honeycomb core, used as input data for the numerical analysis, are summarised in Table 3.

Table 3. Equivalent elastic parameters for the selected aluminium honeycomb core.

E_1 [MPa]	E_2 [MPa]	E_3 [MPa]	G_{12} [MPa]	G_{23} [MPa]	G_{31} [MPa]	ν_{12}	ν_{23}	ν_{31}
2.7	2.7	1310	0.68	245	565	0.99	0.0001	0.3

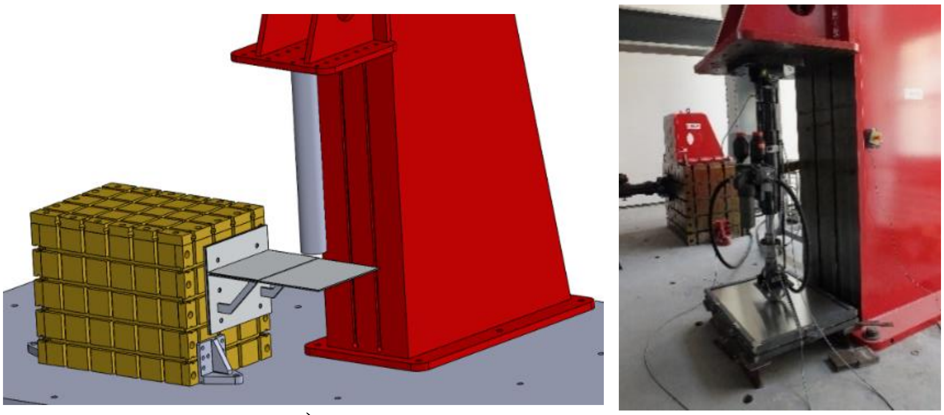
The overall mass of the entire sandwich panel is estimated to be approximately 8.8 kg, i.e. almost 50% lighter than the original structure (15 kg) of Ref. [13].

The adhesive selected for the analysis was a two component, room temperature curing methacrylate adhesive system, with a tensile modulus of 1350 MPa and a tensile lap shear strength on aluminium of approximately 20 MPa.

On the free extremity of the balcony a load directed in the z direction (downwards) of 6 kN was applied. This value was selected because it was the load level at which the initiation of non-linearity was recorded for the structure in Ref. [13]. Indeed, the numerical analysis was used to verify that the AHS-based balcony guarantees at least the same elastic range of the original structure. The opposite end of the sandwich panel and the supporting plates enclosing it were fully fixed in rotation and translation.

According to FEM results, the maximum principal stress when a 6 kN downward load is applied at the free extremity of the balcony, does not reach the yield stress of the aluminium, and therefore it is reasonable to assume that the structure is able to behave elastically for higher loads than does the original balcony design. In addition, the maximum shear stress in the adhesive layer is significantly lower than the tensile lap shear strength of the applied adhesive. This means that the integrity of the assembly and its elastic behaviour is at least comparable to those of the original structure. The maximum displacement in the z-direction obtained with the numerical model is equal to 20 mm, which corresponds to the value reported at the same load level by Kharghani and Soares [13] confirming the correct application of the bending stiffness equivalence approach. Another advantage of the AHS-based design to consider is that its supporting plates are of aluminium and are only 3 mm thick, whereas the original structure had steel plate each 6 mm thick. As a result, the aluminium plates of the AHS balcony have a mass equal to 5.5 kg compared with the 42 kg of the steel plates of the original structure. From the numerical analysis it was observed that these plates are also subject to low stress levels, and consequently their use, combined with that of the AHS panel, would be beneficial to obtain a significant weight saving.

The preliminary numerical model allowed verification of the feasibility of the AHS-based balcony, with respect particularly to the response of the adhesive. Such information is very useful for the design of the experimental setup and procedure, which will be required to thoroughly and reliably investigate the mechanical performance of the AHS balcony. The full-scale tests will be performed at the CERISI Laboratories of the University of Messina; the designed setup for the full-scale test on the AHS balcony, along with the existing laboratory systems are shown in Figure 3.



a) b)

Figure 3: a) Designed setup for full-scale tests, and b) part of the CERISI laboratories equipment.

Further developments will include full-scale test of the AHS balcony and its integration with bi-metallic structures, which will form part of the supporting frame.

4. Conclusions

Weight reduction is one of the main strategies used to achieve an increase in the speed of marine vehicles, and the current work aimed to investigate the possibility of this via the introduction of aluminium honeycomb sandwich structures.

The bending stiffness was suggested as an 'equivalence' parameter for the selection of the new lightweight structure. An example application regarding a ship balcony overhang was presented. The replacement of the original structure [13] which used GFRP skins and a balsa core, with an AHS design was guided by stiffness equivalence, driven by a desired weight reduction, and achieved via a simple graphical procedure. The new AHS balcony design was then analysed using a simplified numerical model, which gave invaluable information for the design of the experimental set-up of future full-scale tests. The capability of the selected adhesive to bear the same load that caused the initial non-linear response in the original GFRP structure was verified. At this load the stress in the skins, in the plates and brackets were all far below the aluminium yield stress.

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