FLEXURAL BEHAVIOUR OF GLASS FIBER REINFORCED ALUMINIUM HONEYCOMB SANDWICHES IN FLATWISE AND EDGEWISE POSITIONS

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Abstract

The goal of this research was the analysis of edgewise bending response of sandwiches, which consists of aluminium honeycomb sandwich reinforced by outer skins made of glass fiber reinforced epoxy matrix. The test results at different values of support span distances in terms of peak loads and absorbed energy were compared with those obtained by flatwise bending tests and by similar tests on aluminium honeycomb sandwiches without outer skins. The failure mechanisms have been also investigated. The experimental results presented that the sandwiches in the edgewise position failed at a higher load with less deflection compared to the specimens tested in the flatwise position. The current work has an important role in several areas, such as transport industry, in which lightweight structures with high capacity of energy dissipation is required.

1. Introduction

Sandwich structures fabricated by combining two thin but stiff skins with a low density but thick core offer widely potential use in aerospace, automotive, marine, defense and other industrial applications. The most interesting benefits of using these structures are their high bending stiffness, high load carrying capacity and high strength to weight ratios [1]. With the use of these lightweight materials in transport industry, it is possible to increase payload, to reach higher speed and to obtain a lower fuel consumption. Altenbach presented a review of the mechanics of advanced composite materials for lightweight structures in [2]. In a previous research paper of some of the authors [3], the structural response of AFS under static and impact loading was compared with that of the PVC foam sandwiches using the Infrared thermography (IRT) technique. The currently used PVC foam core or balsa wood cores are soft and crush under high compressive loads [4] while honeycomb and lattice truss cores have strongly efficient compressive behaviour [5, 6]. Moreover, it has been investigated that the most of sandwiches failed due to core shear during flexural loading [7-9]. The use of composite sandwich constructions with high strength and light-weight core material could be a novel structural material for applications in transport industry (automotive, aerospace, shipbuilding industry).

Recently, a new generation sandwich composites with glass fiber reinforced aluminium sandwich panels has been introduced by the authors and their response to static bending and impact loads was investigated [10, 11].
The structural behaviour and failure modes of sandwiches under flexural loading have been investigated by some of the authors [4, 7, 12-14]. Sandwich specimens in these works are tested under bending test in the flatwise position as it is mostly used as structural applications for transport industry, floor, roof, walls and bridge decks. The upper and lower skins carry the flexural load while the core material carries the shear in flatwise orientation. Currently, the structural components have been also utilized under bending load in edgewise position in order to obtain higher stiffness and strength for civil infrastructures [15-17]. It is clear that there is an application on composite sandwiches in edgewise position. It could be possible to use edgewise oriented composite sandwich panels such as energy bumpers in transport industry in order to achieve higher performance respect to flatwise position. The failure mode and the damaged structure of the AHS panels after flatwise bending have been investigated using a Computed Tomography system by some of the authors [10, 18].
The novelty of the present study is the analysis of edgewise bending response of sandwiches, which consists of aluminium honeycomb core reinforced by outer skins made of glass fiber reinforced epoxy matrix. The results in terms of peak loads and absorbed energy were compared with those obtained by flatwise bending tests and by similar tests on aluminium honeycomb sandwiches without outer skins. The glass fiber reinforced skins can be easily bonded to the sandwich and it is possible to design the best configuration (base materials, fiber angle orientation, number of layers) for a specific application. Hand lay-up method was used to produce the outer skins, made of glass fiber reinforced epoxy matrix, and the skins were bonded onto the aluminium faces of AHS using SikaFlex-265 commercial adhesive. The bending static tests were carried out on GFR-AHS specimens at different values of support span in flatwise and edgewise orientations in order to investigate the collapse modes, as it was already done for honeycomb panels in flatwise position [18].
The obtained results have particular importance for applications that require lightweight structures with a high capacity of energy dissipation, such as the transport industry, where problems of collision and crash have increased in the last years.

2. Materials and methods

2.1. Materials

The specimens were made bonding two GFRP skins to AHS panels using a commercial adhesive. Two different aluminium honeycomb sandwich typologies have been investigated: 1/8-5052-0.0020 and 1/4-5052-0.0025; the designation corresponds to cell size (inch) – alloy – foil thickness (inch).
The physical and geometrical properties of the GFR-AHS panels are reported in Table 1.
The outer skins, made of glass fiber reinforced epoxy matrix, were fabricated using hand lay-up method and the skins were bonded onto the aluminium faces of AHS panels using SikaFlex-265 commercial adhesive with the thickness about 1.5 mm (Table 2).
Hand lay-up method was chosen because of its easy feasibility for the production period of GFRP outer skins. As a starting point, the fiber orientation type and the number of the layers were considered according to the dimensions of *AHS* samples and the epoxy resin was prepared according to the mixture ratio given by the company. Then, a release agent was applied to the lay-up surface and finally glass fibers were laid up and impregnated with epoxy resin. It has been waited for about forty eight hours for curing of *GFRP*. After curing, *GFRP* outer skins were bonded onto aluminium faces of *AHS* using *SikaFlex-265* commercial

adhesive in order to produce *GFR-AHS* test specimens. For curing of adhesive, it has been also waited for about forty eight hours.
The presence of the outer skins produces an increment of weight and thickness of about 2.3 and 1.6 times for both typologies of *AHS* panels, respectively.

	Sequence	Number of layers	Material	Fiber Orientation / diameter and thickness of honeycomb cell	density [kg/m^3]	thickness [mm]
Upper skin	1	2	GFRP	[0°/90°/Mat]	1180	1.5
	2	1	AA5754 H32		2730	1
Core	3	1	AA5052	d = 3 mm; t_c = 0.05 mm d = 6 mm; t_c = 0.06 mm	130 80	9
Lower skin	4	1	AA5754 H32		2730	1
	5	2	GFRP	[0°/90°/Mat]	1180	1.5

Table 1. Configuration and properties of the GFR-AHS panels

Type	Density [kg/m^3]	Shear Modulus [MPa]	Shear Strength [MPa]	Shear Strain [%]
Polyurethane	1200 (Uncured)	0.7	4.5	450

Table 2. Mechanical properties of the adhesive *SikaFlex-265*.

2.2. Methods

The static bending tests were carried out on *GFR-AHS* specimens using a servo-hydraulic load machine in flatwise and edgewise positions. The failure mode and the damage of the specimens have been investigated by a stereomicroscope.

3. Experimental investigation

Static three-point bending tests in flatwise and edgewise positions were performed on GFR-AHS panels (150 x 50 x 18 mm) at different support span distances (L= 55, 70, 80, 125 mm), applying a constant rate of displacement equal to 2 mm/min and with a preload of 10 N.

3.1. Edgewise compressive tests on honeycomb panels

The static (bending and penetration tests) and dynamic (low velocity impact tests) behaviour of AHS panels was already analyzed by some of the authors [13].
In the present study edgewise compressive tests were performed on AHS panels with d = 6 mm, applying a constant rate of displacement equal to 3 mm/min. Fig. 1 shows the load-displacement curves of two edgewise compressive tests.
The load-displacement curve is characterized by an initial linear-elastic behaviour until a peak value is reached, after which there is an abrupt load loss, due to delamination. It is evident that the skin-core adhesion is very important for the collapse strength of the sandwich panels [19]. Figure 2 shows an undamaged panel and another one after the edgewise compressive test. The failure mode corresponds to the shear crimping [20, 21]. A microscopy of the damaged panel is shown in Figure 3, where the skin debonding and the cell damage are clearly visible.

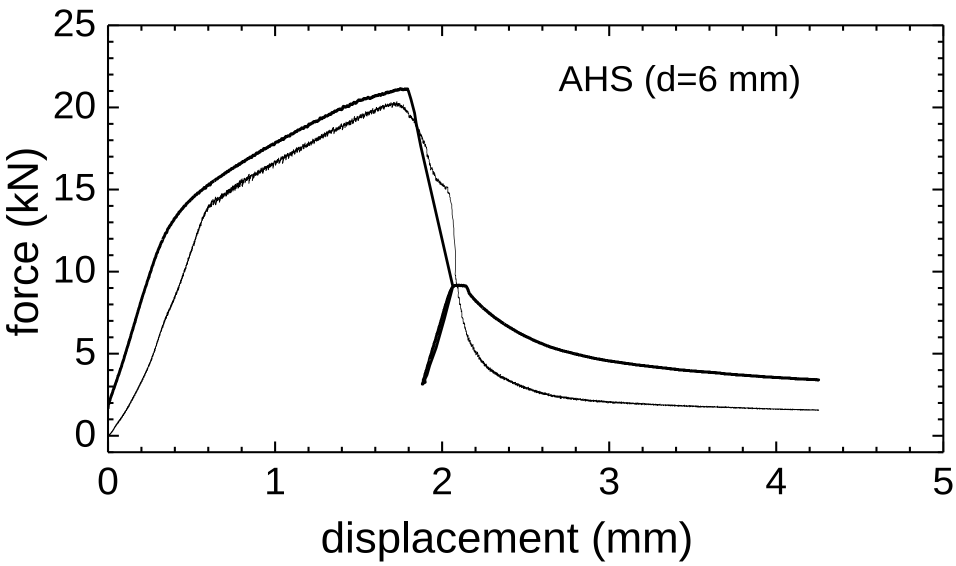

Figure 1. Load-displacements curves measured under edgewise compressive tests for AHS (d=6 mm).

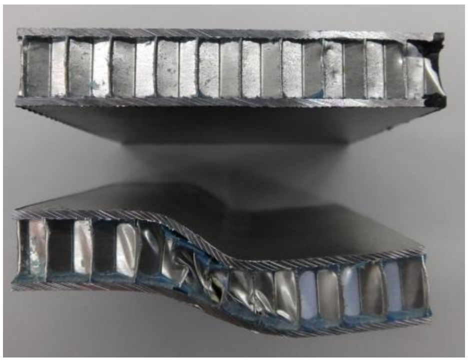

Figure 2. Undamaged AHS (d=6 mm) panel and another one after edgewise compression test.

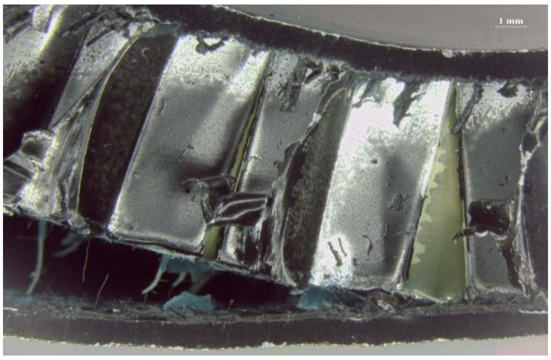

Figure 3. Microscopy of a AHS (d=6 mm) panel after edgewise compression test.

3.2. Static bending tests in flatwise position on GFR-AHS panels

The investigated sandwich panels with the average values of the weight under bending tests in flatwise position are: 53.41 g for AHS panels (d = 3 mm) and 125.18 g for the same panels with GFRP skins, 51.09 g AHS panels (d = 6 mm) and 119.97 g for the same panels with GFRP skins. Figs. 4 and 5 show the load deflection curves obtained under bending tests in flatwise position carried out at different values of support span on the two typologies of GFR-AHS (cell diameter d = 3 and 6 mm).

The initial linear-elastic behaviour is followed by an elasto-plastic phase until a peak value is reached, after which there is an abrupt load loss, which is more evident respect to the behaviour of sandwich panels with similar skins, made of glass fiber reinforced epoxy matrix, and aluminium foam core [10]. This different behaviour is due to the honeycomb core shear. After the peak load and the subsequent load loss, the behaviour differs for the honeycomb panels with different cell sizes: in the curves for the sandwiches with d = 3 mm the load increases smoothly, while for the panels with d = 6 mm load remains almost constant. The same trend was observed in the load- deflection curves for AHS panels without the outer skins, under three point bending tests at the same support span values [18].

Assuming a perfect bond between the faces and the core and eliminating the possibility of delamination, sandwich beams can fail by several modes under bending tests in flatwise position: core shear, face yield, indentation and face wrinkling, this last mode occurs generally only for sandwich beams with corrugated or honeycomb core. The specimens after the bending tests in flatwise position are shown in Fig. 6.

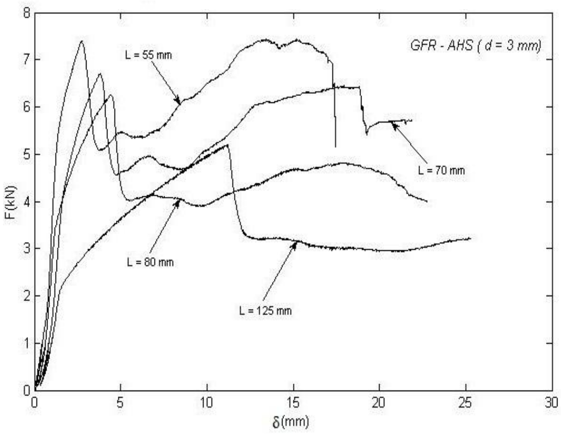

Figure 4. Load-deflection curves measured under static three-point bending in flatwise position for GFR-AHS (d=3 mm).

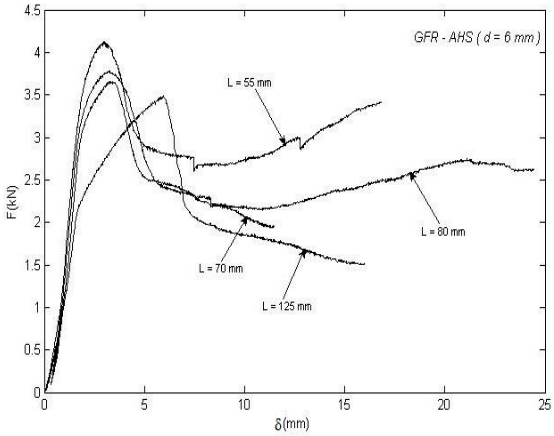

Figure 5. Load-deflection curves measured under static three-point bending in flatwise position for GFR-AHS (d=6 mm).

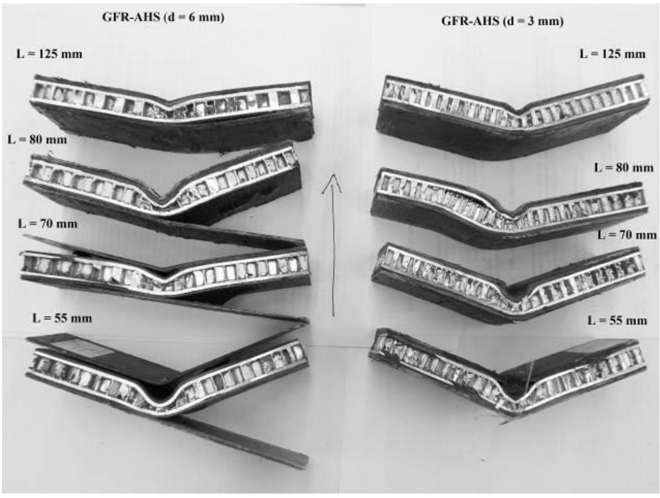

Figure 6. GFR-AHS panels (d = 3, 6 mm) after flatwise bending tests at different support span values (L= 55, 70, 80, 125 mm).

The analyses of the panels after flatwise bending tests show that the most frequent failure mode is indentation for the 2 typologies of sandwich. The observed collapse mode differs from the traditional mechanism of indentation, reported in literature [22], because it is accompanied by the rotation of the two halves of the sample around the mid-plane and by the formation of a plastic hinge also in the tensioned face. Core shear is also evident in the panel with d = 3 mm at a support span of 80 mm (Fig. 6).

The partial debonding of the glass fibre reinforced/epoxy skins occurs for all the panels with d = 6 mm (Fig. 6). It is probably due to the fact that the skins cannot follow the core deformation, that is obviously greater for the panels with d = 6 mm.

3.3. Static bending test in edgewise position on GFR-AHS panels

The average values of the weight for the investigated panels are: 52.51 g for AHS panels (d = 3 mm) and 123.85 g for the same panels with GFRP skins, 50.54 g AHS panels (d = 6 mm) and 123.02 g for the same panels with GFRP skins.

The load deflection curves were obtained, as reported in Figs. 7 and 8, under bending tests in edgewise position performed at different values of support span on the two typologies of GFR-AHS with the cell diameter d = 3 and 6 mm. The specimens after the bending tests in edgewise position are shown in Fig. 9.

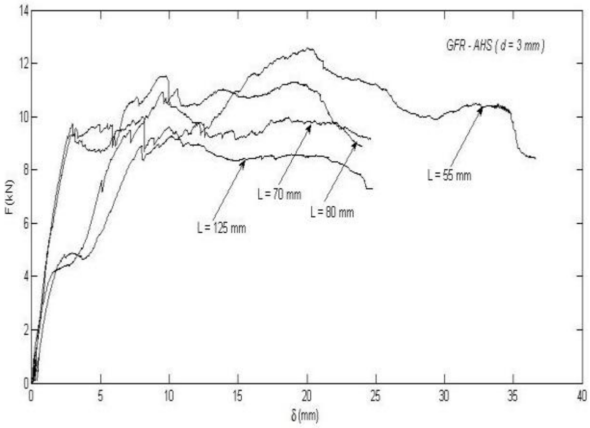

Figure 7. Load-deflection curves measured under static three-point bending in edgewise position for GFR-AHS (d=3 mm).

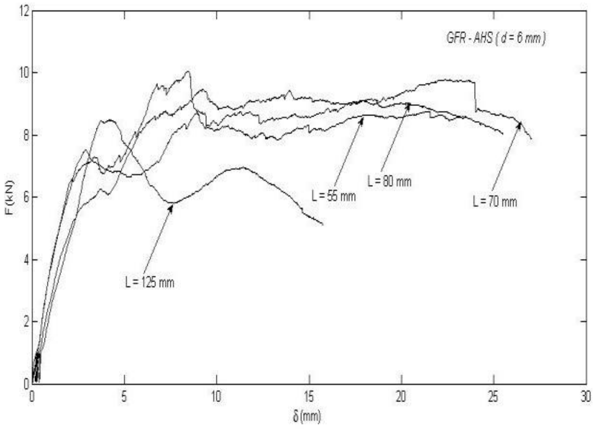

Figure 8. Load-deflection curves measured under static three-point bending in edgewise position for GFR-AHS (d=6 mm).

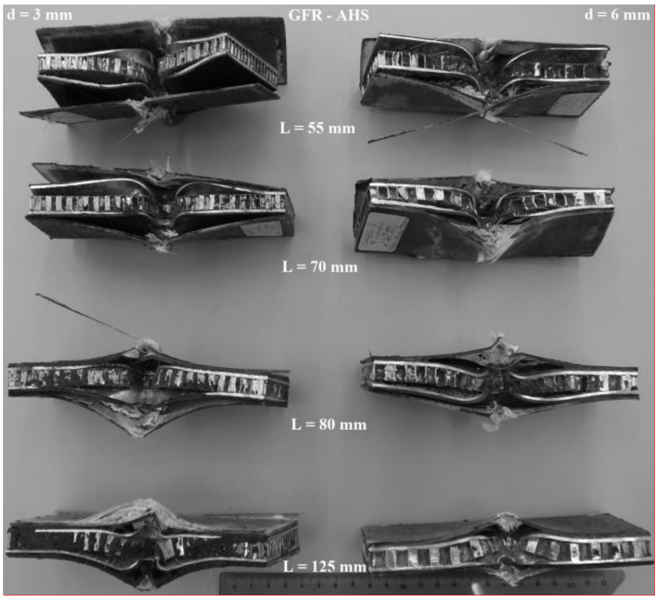

Figure 9. GFR-AHS panels (d = 3, 6 mm) after edgewise bending tests at different support span values (L= 55, 70, 80, 125 mm).

The amount of the energy absorption E was evaluated integrating the load - deflection curves, obtained by all the bending tests. The values of energy efficiency η were considered in order to compare all the bending tests at different support spans L. The efficiency η is defined as the absorbed energy up to failure deflection δ_{max} normalized by the energy absorption of the ideal absorber [23]:

$$\eta = \frac{E}{E_i} = \frac{\int_0^{\delta_{\max}} F d\delta}{F_{\max} \cdot \delta_{\max}} \tag{1}$$

where F_{max} is the highest force occurring during the bending test. The average values of all the bending results corresponding to the GFR-AHS sandwiches are reported in Table 3 and compared to the values obtained for AHS [18]. The experimental results confirm that the ability to absorb energy of the honeycomb sandwiches is obviously affected by the cell size, the presence of GFRP outer skins and the bending test position.

		AHS (d = 3 mm)			**AHS (d = 6 mm)**			**GFR-AHS (d = 3 mm)**			**GFR-AHS (d = 6 mm)**		
	L [mm]	**F_{max} [N]**	**E [J]**	**η [%]**	**F_{max} [N]**	**E [J]**	**η [%]**	**F_{max} [N]**	**E [J]**	**η [%]**	**F_{max} [N]**	**E [J]**	**η [%]**
Flatwise	55	4135	40	65	2797	30	72	7438	107	82	4119	49	70
	70	3640	38	70	2395	20	55	6700	115	79	3778	28	65
	80	3815	44	63	2230	21	53	6263	99	69	3659	60	67
	125	3063	37	67	1669	12	40	5194	84	64	3484	33	60
Edgewise	55	8672	183	74	6297	114	81	12581	373	81	8759	195	87
	70	8119	225	82	5978	131	84	9988	220	89	10031	225	82
	80	5675	143	83	5291	106	85	11309	217	80	9472	186	84
	125	7225	112	79	6459	63	59	9259	184	80	8482	95	71

Table 3. Results of all the bending tests.

The best response in terms of energy efficiency, as reported in Table 3, was obtained for the GFR-AHS with d = 3 mm, subjected to bending loads in flatwise position with support span values L = 55 and 70 mm. It is due to the peak force value which was influenced by the cell size of the honeycomb and GFRP skins and hence the higher rigidity of the whole panel that was affected by the support span length.

4. Conclusions

The study presented in this paper is part of a larger project aimed at the introduction of lightweight structures, made of GFR-AHS sandwiches, in the transportation industry (automotive, aerospace, shipbuilding industry).

The mechanical behaviour under flatwise and edgewise bending of AHS panels reinforced by GFRP outer skins was investigated and a comparison with the AHS panels (without GFRP skins) was done in terms of peak load value and energy absorption capacity.

The experimental tests have demonstrated that the light weight AHS panels have good properties of energy dissipation and the amount of energy absorption under bending tests in flatwise and edgewise positions can be highly improved reinforcing them by means of GFRP outer skins, which can be designed according to the application of the sandwich.

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