Mechanical Behavior of Sandwiches with Various Glass Fiber/Epoxy Skins under Bending Load

Emre Kara, Metehan Demir, Şura Karakuzu, Kadir Koç, Ahmet F. Geylan, Halil Aykul

***Abstract*—**While the polymeric foam cored sandwiches have been realized for many years, recently there is a growing and outstanding interest on the use of sandwiches consisting of aluminum foam core because of their some of the distinct mechanical properties such as high bending stiffness, high load carrying and energy absorption capacities. These properties make them very useful in the transportation industry (automotive, aerospace, shipbuilding industry), where the "lightweight design" philosophy and the safety of vehicles are very important aspects. Therefore, in this study, the sandwich panels with aluminum alloy foam core and various types and thicknesses of glass fiber reinforced polymer (GFRP) skins produced via Vacuum Assisted Resin Transfer Molding (VARTM) technique were obtained by using a commercial toughened epoxy based adhesive with two components. The aim of this contribution was the analysis of the bending response of sandwiches with various glass fiber reinforced polymer skins. The three point bending tests were performed on sandwich panels at different values of support span distance using a universal static testing machine in order to clarify the effects of the type and thickness of the GFRP skins in terms of peak load, energy efficiency and absorbed energy values. The GFRP skins were easily bonded to the aluminum alloy foam core under press machine with a very low pressure. The main results of the bending tests are: force-displacement curves, peak force values, absorbed energy, collapse mechanisms and the influence of the support span length and GFRP skins. The obtained results of the experimental investigation presented that the sandwich with the skin made of thicker S-Glass fabric failed at the highest load and absorbed the highest amount of energy compared to the other sandwich specimens. The increment of the support span distance made the decrease of the peak force and absorbed energy values for each type of panels. The common collapse mechanism of the panels was obtained as core shear failure which was not affected by the skin materials and the support span distance.

***Keywords*—**Aluminum foam, collapse mechanisms, light-weight structures, transport application.

I. Introduction

SANDWICH structures with aluminum core are suitable for lightweight transportation systems, such as for bus [1] and ship [2], [3] structures. The weight minimization influences the energy efficiency of the transport vehicles; by saving weight, fuel efficiency and load carrying capacity increase. Therefore, it is important to choose high-quality core material in the optimal design of sandwich. Most current sandwich structures are based on polymeric foams (such as *PVC*, *PUR*) and aluminum honeycomb bonded to glass fiber reinforced polymer (GFRP) skins. Recently a great number of metal foams have been developed to replace polymer foams in applications where multi-functionality is important. For instance, acting as a structural component in a sandwich composite but also as an acoustic damper, fire retardant or heat exchanger [4]. As a new multi-function engineering material, aluminum foams have many useful properties such as low density, high stiffness, good impact resistance, high energy absorption capacity, easy to manufacture into complex shape, good erosion resistance, etc. [5], [6]. This fact opens a wide range of potential applications for sandwich structures with aluminum foam core. The aluminum foam cored sandwiches with various skin materials consisting metals [7]-[9] or composites [10]-[12] were investigated under static and dynamic loading conditions in order to determine their influence to the mechanical behavior and to the failure mechanisms of the entire panel.

In a research paper of some of the authors [13], the structural response of aluminum foam sandwiches (AFS) under static and impact loading was compared with that of the PVC foam sandwiches. The failure mode and the damaged structure of the impacted panels have been also investigated by a Computed Tomography system [14]. An extensive series of experimental tests has been carried out by the same authors for analyzing the mechanical behavior and collapse failure of the aluminum honeycomb sandwiches under static bending and low velocity impact loading, comparing the energy absorbing capacity with the one of the AFS [15]. Static and dynamic bending tests have been performed on AFS panels with the skins bonded by acrylate adhesive and no strain rate sensitivity was found by Yu et al. [16].

Sandwich structures can fail with different collapse mechanisms under static and dynamic loading conditions, depending on the physical and geometrical properties of their components [8], [9]. The failure model of a sandwich with metallic foam core has been established by some of the authors [8], [17] and they estimated the failure expected to result by several modes (i.e. face yield, core shear, indentation and face wrinkling) corresponding to the minimum collapse loads, depending on the deformation forms. Their model has been confirmed by multiple parallel studies [18]-[21]. Moreover, it has been investigated that the most of the sandwiches failed due to core shear during flexural loading [3], [22], [23]. These studies reported in the literature showed that the use of GFRP skins with various orientation angles and types can also affect the response of the entire panel.

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The goal of this investigation was the analysis of flexural response of the sandwiches obtained by bonding of the glass fiber reinforced polymer (GFRP) skins to an aluminum alloy foam core with the use of epoxy based toughened adhesive and the comparison of the results respect to the influence of the variety of the skin type and skin thickness to the entire panel in terms of absorbed energy, energy efficiency and peak force values. Vacuum Assisted Resin Transfer Molding (VARTM) method was used to produce the GFRP skins consisting of two different types of [0º/90º] oriented woven glass fabrics (E-Glass and S-Glass) and a Bisphenol A based epoxy resin. The bonding process was performed using a press machine in order to obtain uniform adhesion thickness throughout the panel and to remove the air inside the adhesive. The static three-point bending tests were performed on the sandwich specimens by a universal testing machine with different values of support span distance (L = 55, 70, 80 and 125 mm) in order to determine its influence to the collapse modes.

II. Materials and Methods

The sandwich specimens used in this work were made bonding of two GFRP skins to aluminum alloy foam core (Alulight® International GmbH) with the use of an epoxy based toughened commercial adhesive (Loctite 9461 A&B) under press machine with the pressure of 0.01 bar without crushing the core in order to obtain uniform adhesion thickness throughout the panel and to remove the air inside the adhesive.

The skins made of two different [0º/90º] oriented woven glass fabrics (E-Glass and S-Glass with the areal density of 500 g/m^2 and 190 g/m^2, respectively) consisting of two different thicknesses (t = 1.5 and 1.75 mm) for each type of fabrics and a Bisphenol A based epoxy resin (Araldite® LY 1564) with a hardener (Aradur® 3486) in a mixture ratio by weight of 100/34 were produced via VARTM which is also known as Vacuum Infusion. For the curing of resin, aluminum lay-up surface was heated up 100 ºC during two hours.

In the bonding process, firstly, one skin material was bonded to one of the surface of aluminum foam core under press machine using a steel alignment plate with the thickness containing the sum of one skin (about 1.5 or 1.75 mm), core (10 mm) and one adhesive (about 0.5 mm) thicknesses. For the curing of first adhesion, it has been waited for about three hours. Then, another skin was bonded to another surface of the core under same pressure value using a secondary steel alignment plate produced respect to the total thicknesses of the whole panel. For the curing of second adhesion, the press machine was held under same pressure value about three hours.

In order to identify the sandwich typologies used in the current study, some of the abbreviations were done representing the base materials of a panel as shown in Fig. 1.

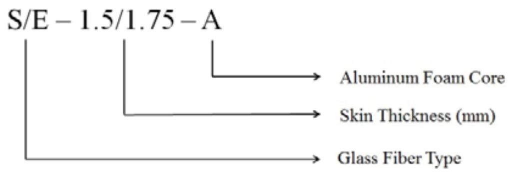

Fig. 1 Identification of sandwich typologies used in the study respect to the base materials

The physical and geometrical properties of the investigated panels and their base materials are reported in Table I.

TABLE I
Physical and Geometrical Properties of Sandwich Panels

Sandwich Typology	Skin			Core			Adhesive		
	Material	Density [kg/m^3]	Thickness [mm]	Material	Density [kg/m^3]	Thickness [mm]	Material	Density [kg/m^3]	Thickness [mm]
E1.5A	E-Glass Woven Fiber/Epoxy Resin	1480	1.5	AlSi10	530±60	10	Loctite 9461A&B	1400	0.5
E1.75A	E-Glass Woven Fiber/Epoxy Resin	1650	1.75	AlSi10	530±60	10	Loctite 9461A&B	1400	0.5
S1.5A	S-Glass Woven Fiber/Epoxy Resin	1580	1.5	AlSi10	530±60	10	Loctite 9461A&B	1400	0.5
S1.75A	S-Glass Woven Fiber/Epoxy Resin	1600	1.75	AlSi10	530±60	10	Loctite 9461A&B	1400	0.5

The static three-point bending tests were carried out on the sandwich specimens with the sizes of 150 x 50 x 14 mm and 150 x 50 x 14.5 mm using a servo-hydraulic universal load machine. All the tests were performed on the panels after one week of the production of the whole panels in order to get the best performance of the adhesive. The failure mode of the panels under bending load applied at different values of support span distances and the damage of the specimens have been also investigated as reported by some of the authors [8], [10], [24], [25].

III. Results and Discussion

Static three-point bending tests were performed on the sandwich panels using a servo-hydraulic load machine. The load was applied at a constant rate of 2 mm/min and with a preload of 20 N. The tests were performed on the specimens at different values of the support span distances (L = 55, 70, 80, 125 mm). Figs. 2-5 show the load-deflection curves obtained from bending tests carried out on all the sandwich typologies with different types and thicknesses of GFRP skins.

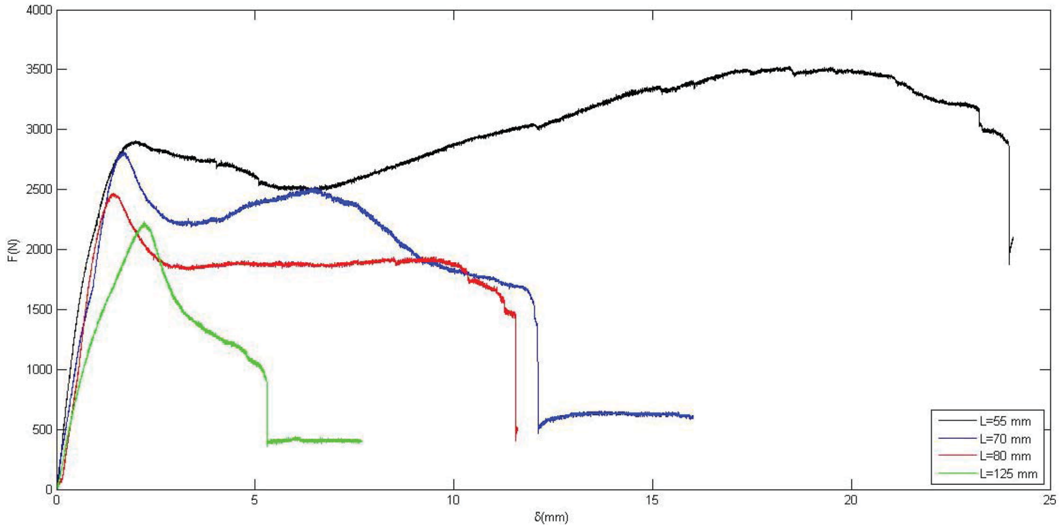

Fig. 2 Load-deflection curves measured under static three-point bending for the sandwiches named E1.5A

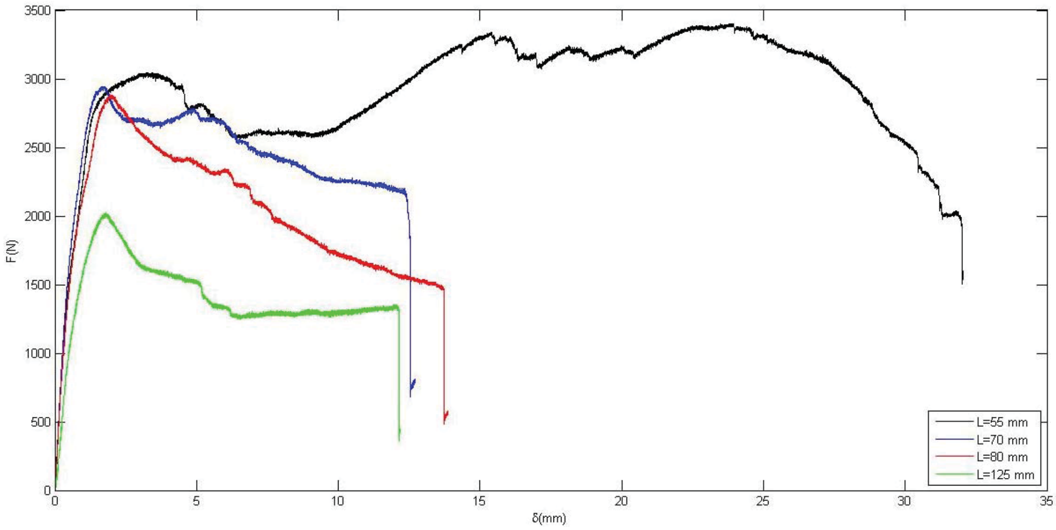

Fig. 3 Load-deflection curves measured under static three-point bending for the sandwiches named E1.75A

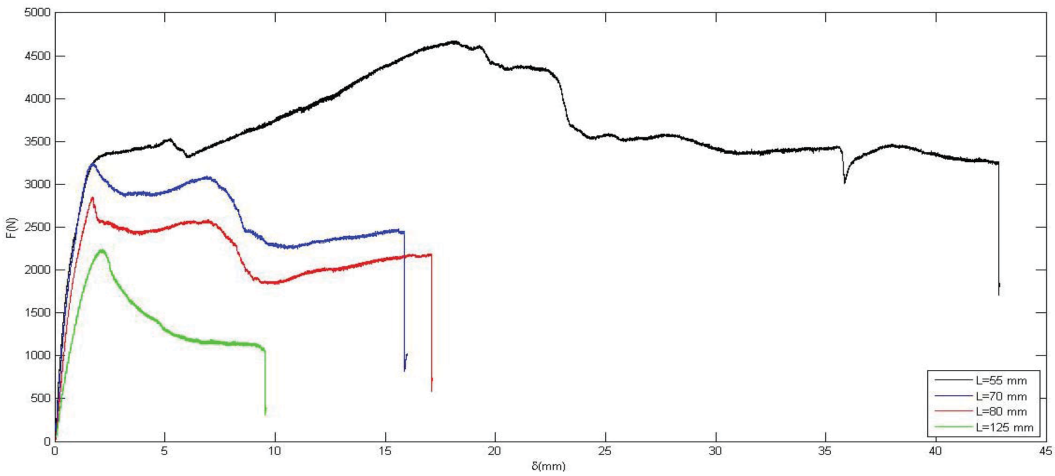

Fig. 4 Load-deflection curves measured under static three-point bending for the sandwiches named S1.5A

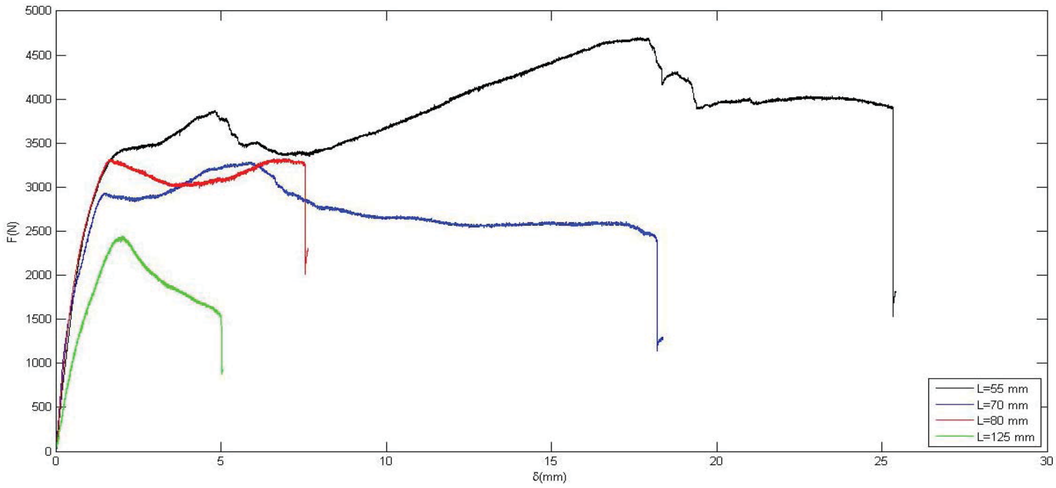

Fig. 5 Load-deflection curves measured under static three-point bending for the sandwiches named S1.75A

All the sandwich specimens collapsed after the bending tests are showed in Figs. 6-9.

Fig. 6 Collapsed sandwiches named E1.5A after the bending tests at different support span values (top to bottom: L = 55, 70, 80 and 125 mm)

Fig. 7 Collapsed sandwiches named E1.75A after the bending tests at different support span values (top to bottom: L = 55, 70, 80 and 125 mm)

Fig. 8 Collapsed sandwiches named S1.5A after the bending tests at different support span values (top to bottom: L = 55, 70, 80 and 125 mm)

Fig. 9 Collapsed sandwiches named S1.75A after the bending tests at different support span values (top to bottom: L = 55, 70, 80 and 125 mm)

From the Figs. 2-5, it is clear that all the sandwiches exhibit initial linear-elastic behavior which is followed by an elasto-plastic phase, due to the permanent plastic deformation of the aluminum alloy foam core. Afterward, the load decreases initially markedly, then it remains almost constant up to the local debonding of the upper and/or lower skin (Figs. 6-9) for all the sandwich typologies at L = 70, 80 and 125 mm while the load for the sandwiches at L = 55 mm tend to increase up to the failure of the upper or lower skin.

The failed sandwich specimens exhibit a significant permanent global deformation of the panel and core shear failure away from the loading points. Three point bending tests carried out by Reyes [10] on sandwich panels based on aluminum foam core and different types of composite skins revealed that the panels failed by different mechanisms and this suggests that a proper selection of the composite skin significantly influences the overall failure mode of the sandwiches and high capacity of absorbing energy.

Some theoretical models were developed by several authors [8], [24] to predict the failure mechanism of sandwiches. These authors have been particularly concerned with foam core sandwiches. Assuming a perfect bond between the faces and the core and eliminating the possibility of delamination, sandwich beams can fail by several modes in bending tests: core shear, face yield, indentation and face wrinkling.

The observed collapse mechanism of the sandwiches analyzed in the study which wasn't affected by the support span length and the types of the skin and adhesive occurred as core shear for all the sandwich typologies, as seen from the Figs. 6-9.

The amount of the energy absorption E was evaluated integrating the load - deflection curves obtained by the bending tests. The values of energy efficiency η were considered in order to compare the bending tests at different support spans L. The efficiency is defined as the absorbed energy up to failure deflection δ_{max} normalized by the energy absorption of the ideal absorber [26]:

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

where F_{max} is the highest force occurred during the bending test. The average values of the bending test results corresponding to the sandwich typologies are reported in Table II.

The experimental results confirm that the ability to absorb energy of the sandwiches with aluminum alloy foam core is obviously affected by the type and the thickness of skin and the support span value. The best response in terms of energy efficiency, as reported in Table II, was obtained for the sandwich typologies having thicker skins, subjected to bending loads with support span value of L = 55 mm. It is due to the peak force value which was influenced by the skin type and thickness, adhesion quality and hence the higher rigidity of the whole panel that was affected by the support span length.

TABLE II
RESULTS OF ALL THE BENDING TESTS

Sandwich Typology	L = 55 mm			L = 70 mm			L = 80 mm			L = 125 mm		
	F_{max} [N]	E_{abs} [J]	η [%]	F_{max} [N]	E_{abs} [J]	η [%]	F_{max} [N]	E_{abs} [J]	η [%]	F_{max} [N]	E_{abs} [J]	η [%]
E1.5A	3525	71	84	2813	28	62	2472	21	73	2238	8	48
E1.75A	3403	93	85	2944	31	82	2888	28	70	2025	17	69
S1.5A	4675	157	78	3256	41	79	2856	37	76	2241	13	61
S1.75A	4700	97	81	3288	49	82	3325	22	88	2444	9	72

IV. CONCLUSIONS

The flexural responses of the sandwiches with aluminum alloy foam core were investigated and the results were compared respect to the variety of the GFRP skin type and thickness and also support span values in terms of peak load and absorbed energy.

The experimental tests have demonstrated that the light-weight sandwiches with aluminum foam core and GFRP skins are efficient energy absorbers and that the amount of energy absorption under bending tests can be improved using different fiber type and thicker skin, which can be designed according to the application of the sandwich. From the results of the analyses, the sandwiches having thicker S-Glass skins presented the best flexural response under three point bending tests. The support span distance can also affect peak load and energy absorption values and also the behavior of the entire panel.

This experimental work has 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.

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