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Collapse Mechanism of Foam Cored Sandwich Structures Under Compressive Load

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In this work the moisture absorption capability, compressive properties, collapse modes of various types of composite sandwich structures are reported. The tested sandwich structures were constructed with varieties of hybridized skin materials and different compositions of the core materials. The moisture absorption, Flatwise compression and Edgewise compression tests are conducted for core as well as sandwich structures. Comparisons of results have been between the hybridized and non-hybridized sandwich structures. Two modes of collapse were noticed in the Edgewise compressive test, one of which being progressive end-crushing of the sandwich structure featured by significant crash energy absorption. This feature was highly desired for the parts of transportation vehicles. Microscopic analysis has been carried out to know the nature of failure under compressive loads. It has been observed that with increasing the debonding strength of the core–face interface, the failure mode changes from unstable collapse mode stable progressive crushing.

Keywords Composite sandwich structures; Compression properties; FRP; Polyurethane foam

INTRODUCTION

The use of composite sandwich structures in automotive and aerospace applications is constantly increasingly today because of their excellent stiffness to weight ratio that leads to weight reduction, lower fuel consumption and improved level of structural crashworthiness[1,2]. Also they are capable of absorbing large amounts of crash in the event of a sudden collision. Sandwich structure, consisting of two stiff, strong face sheets and a lightweight core, can be designed to possess a high bending stiffness and strength at a low weight[3].

To a good approximation, the face sheets carry the bending and in-plane loads, whilst the core carries traverse shear. The fundamentals of sandwich panel construction and design methods are given by Plantema[4], Allen[5] and Zenkert[3]; recent surveys on the use of foam cores are provided by Gibson and Ashby[6] and Ashby et al.[7] Various types of sandwich foam core and FRP faceplate materials have been tried by researchers worldwide in different structural schemes in an effort to achieve improved crashworthiness. Such sandwich structures vary from simple panels with two faceplates enclosing polymer foam to more complex structures that may include localized reinforcements in the form of FRP tubes, cones or corrugation connecting the external face plates[8–11].

Considerable amount of work was done in assessing the compressive behavior sandwich panels with artificial fibers as skin materials on upper and lower facings[12,13]. Natural fibers exhibit many advantageous properties as reinforcement for composites[14]. They are a low-density material, yielding relatively lightweight composites with high specific properties. Natural fibers also offer significant cost advantages and benefits associated with processing, as compared to synthetic fibers. Wool and co-workers[15] shown that sandwich beams made from natural fiber as skin material and foam as core can be successfully used in structural applications. Ashby and Brechet[16] demonstrate that better performance may be achieved by using hybrid sandwich beams comprising non-traditional pairs of materials. Arun et al.[17] have reported the failure mechanism of rigid

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PUF sandwich structures with varied skin materials under bending load. They have been demonstrated that the debond strength of the core–face and core plays an important role in enhancing the flexural property and controlling of the failure mechanisms.

Review of literature reveals that there is a scope to study the sandwich structures by varying composition of the constituents of core material and type of skin material. Hence an attempt has been made here to study the compression properties of sandwich structures. The core material used was rigid polyurethane foam prepared in 4 different compositions by varying the weight fractions of the constituent materials. The skin materials used were S-glass, jute, and bamboo fibers in epoxy resin. The failure modes of sandwich structures were noted during testing.

MATERIALS AND EXPERIMENTATION

Materials

The experiments have been carried out on rigid polyurethane foam for four varied proportions, composite laminates and sandwich structures for varying skin materials glass, jute, bamboo and hybrid structure by combinations of these. The matrix material used was an araldite LY-556, an unmodified epoxy resin based on Bisphenol-A and the hardener HY 951 (10% of total epoxy taken) an aliphatic primary amine both supplied by Ciba-Geigy, India. The composition of rigid polyurethane foam used for testing is represented as in Table 1; the primary chemicals used to produce the PU foam were methylene di-isocynate (MDI) and polyether polyol. The material composition of skin materials used for sandwich structures is shown in Table 2. The specimen preparation and testing were in accordance with ASTM standards.

Specimen Preparation

The laminates of skin materials were prepared by hand lay-up technique with a suitable weight fraction of the epoxy resin and the hardener. The PUF is prepared by a molded method. Four different varieties of PUF have been prepared with different weight fractions of MDI and polyol as shown in Table 1. The final PUF cores are obtained after passing the molds through hot press for a predefined pressure and time. The sandwich structures were obtained by glueing the required combinations of skin laminates on top and bottom face of the PUF core using epoxy. The skin thickness on each side is 2.5 mm. The final dimensions of the specimen were maintained as per ASTM standards. The sandwich specimen used for the compression and water absorption tests is as shown in Figure 1.

TABLE 1
Composition of rigid polyurethane foam

Type of rigid polyurethane foam	Weight fraction (in %)	
	MDI	Polyol
I	45	55
II	50	50
III	55	45
IV	60	40

TABLE 2
Material composition of skin

Material composition	Weight fraction (in %)	
	Fiber	Epoxy resin
Glass/epoxy composites	50	50
Jute/epoxy composites	50	50
Bamboo/epoxy composites	50	50

Experimentation

The experimentations have been carried out on sandwich structures as well as core material separately. Moisture absorption test and compressive properties of sandwich structures as well as core material are done as per standards.

Moisture Absorption Test. The test procedure for Moisture Absorption was according to ASTM C 272 standards. After properly conditioning and weighing the specimen, it is immersed completely in water at a specified temperature and time. After an immersion period, the specimen is removed, dried and weighed. Moisture absorption is reported as percentage of weight gain.

Compressive Properties. The experimentations were carried out on a computerized universal testing machine, to obtain the load versus deflection data. The test procedure for Flatwise and edge compressive properties were as per ASTM C 365 and ASTM C 364 standards, respectively.

In flatwise compression the test specimens should be loaded in such a way that the loaded ends will be parallel

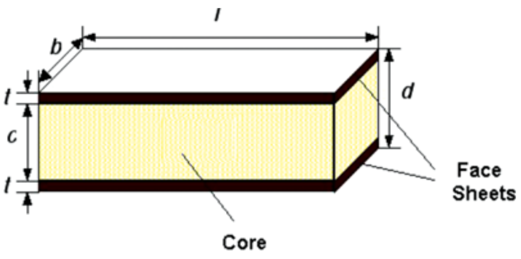

FIG. 1. Dimensions of the sandwich specimen. (Color figure available online.)

to each other and perpendicular to the sides of the specimen. Whereas, in the case of edgewise compression test specimens are laterally supported adjacent to the loaded ends on the facings of the sandwich to prevent early buckling failure due to separation of the facings from the core at the point of contact with the loading plates. Apply the load to the specimen through spherical loading block in such a manner that the block distributes the load as uniformly as possible over the entire loading surface of the specimen. Apply the load at constant rate of movement of cross-head at 0.50 mm/min of the testing machine. By using these test records compressive strength and facing compressive stress are calculated for core material and sandwich structures, respectively.

RESULTS AND DISCUSSION

Experimentations have been carried out on PUF core and sandwich structure with varied combination of skins. Moisture absorption tests were conducted to identify the percentage of moisture absorption of core as well as sandwich structures. The compression tests were conducted to identify compressive strengths of the core material and Flatwise compressive strength, facing compressive stress of sandwich structures. The results of experimental analysis are discussed here.

Results of the Moisture Absorption, Flatwise and Edgewise Compression Tests on PUF Core

The variation of percentage of moisture absorption on duration in days for different types of rigid PUFs is shown in Figure 2. It is clearly observed from the figure that for Type III percentage of moisture absorption is found to be more at the end of 15 days of immersion in water. Type II percentage of moisture absorption is found to be smallest. The percentage of moisture absorption of Type II is 0.4682, 0.1308, 0.1057 times lower than IV, I, III respectively.

It is inferred from Figure 3 that Type II rigid PUF foam possesses higher compressive strengths both in Flatwise and Edgewise compression tests. The compressive strength in Flatwise of Type II is 5.356, 1.912, 2.147 times higher than Type IV, I, III respectively. Whereas in the case of Edgewise of Type II proportion is 7.1926, 1.4013, 5.4641 times higher than IV, I, III proportions respectively.

Microscopic observations have been made with an aid of scanning electron microscope (SEM). Figure 4 shows scanning electron micrographs of molded rigid polyurethane foam in perpendicular to the direction of the foam rise. Figures 4 (a)–(d) refer to rigid polyurethane foam of Type I, II, III, IV respectively. For Type II of rigid PUF cell size is large, round and cells are equally spaced, closely packed, similarity type of structure is seen for Type I. But if the MDI proportion is more, then cell distributes irregularly that is not round and also size of cell is not same. This can be clearly inferred from b and d. The measured cells are represented by blocked arrows as marked in the figure. The cell size is approximately 800 μm for Type II and Type I, For Type IV foam a much variation in the cell size is identified. The smallest cell size is of 120 μm and the largest one is of 860 μm as indicated in the blocked arrows in Figure 4d, whereas in the case of Type III the cell size is 500 μm.

From these micrographs it is clearly inferred that the increase of MDI proportion have made the cell distribution irregular, which in turn have shown much influence on the mechanical properties and physical properties. It has been observed that increase of cell size and regular distribution

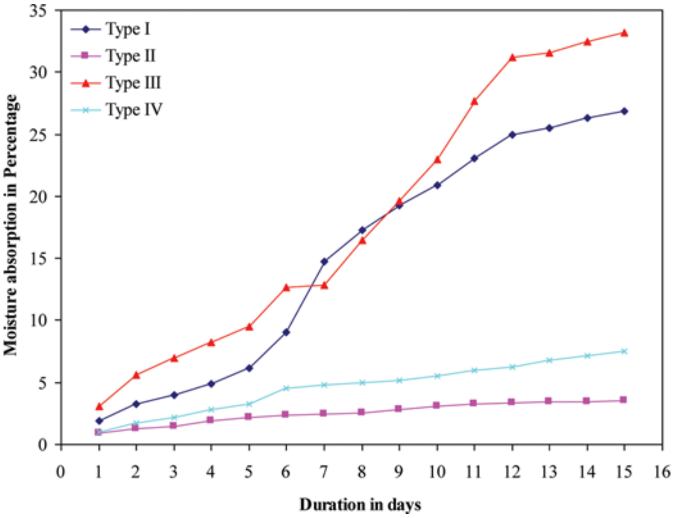

FIG. 2. Variation of percentage of moisture absorption versus duration of rigid PUF in moisture absorption test. (Color figure available online.)

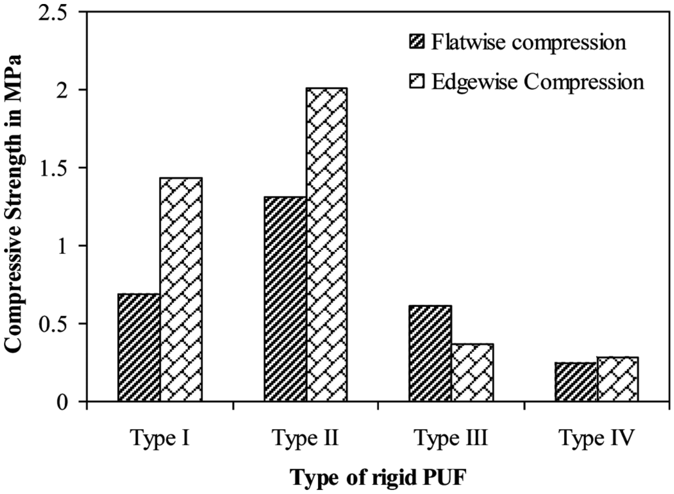

FIG. 3. Variation of compressive strength on type of rigid PUF in compression.

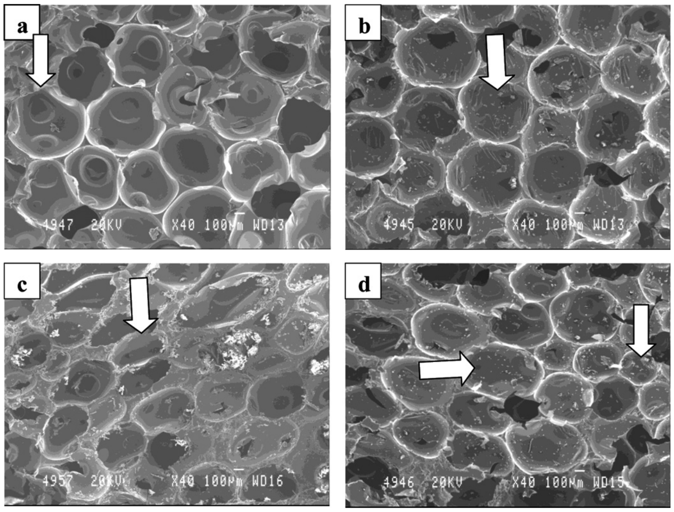

FIG. 4. Scanning electron micrographs of rigid PUF in the direction perpendicular to foam rise.

of cells increases the compressive strength, but lowers the penetration ability of moisture.

Results of the Moisture Absorption, Flatwise and Edgewise Compression Tests on Sandwich Structures

The variation of percentage of moisture absorption on Duration in days for sandwich structures is as shown in Figure 5. From Figure 5, it is noticed that the percentage of moisture absorption is found to be high for the jute/ bamboo hybrid sandwich structure, where as low for glass sandwich structure at the end of 20 days of immersion in water. The moisture absorption of glass sandwich structure is 0.54825, 0.53886, 0.547672, 0.33547, 0.51075 times lower than bamboo, jute, glass/jute, jute/bamboo and glass/ bamboo structures, respectively. Hydrophilic nature of Bio-fibers absorbs more moisture compared to artificial fibers.

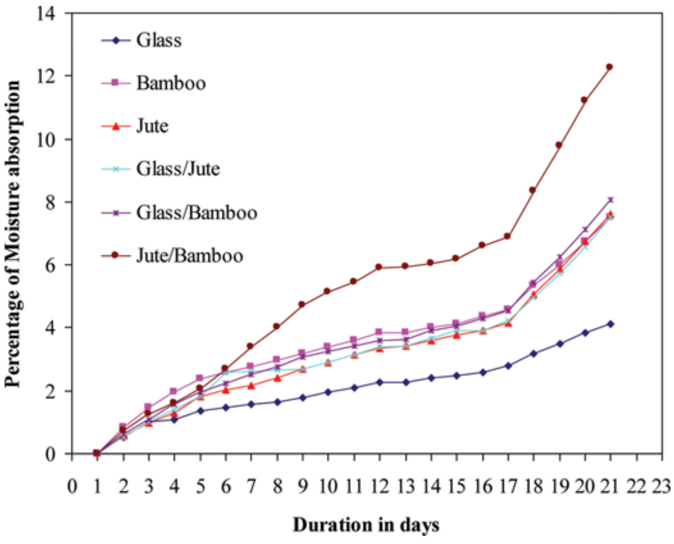

FIG. 5. Variation of percentage of moisture absorption on duration of sandwich structure in moisture absorption test. (Color figure available online.)

The variation of Flatwise compressive strength on type of sandwich structures is as shown in Figure 6a. Flatwise compressive strength was found to be high for glass/jute hybrid sandwich structure, which higher than the pure glass sandwich structure. The Flatwise compressive strength of jute/ bamboo hybrid sandwich structure found to be least compared to other types.

The glass/jute hybrid sandwich structure possess Flatwise compressive strength 1.0710, 1.1755, 2.050, 1.1099, 2.06390 times higher than glass, jute, bamboo, glass/bamboo, jute/bamboo sandwich structures, respectively. Figure 6b refers to variation of facing compressive stress on type of sandwich structures. Glass/jute hybrid sandwich structures possess higher value of Facing compressive stress compared to other types, whereas the

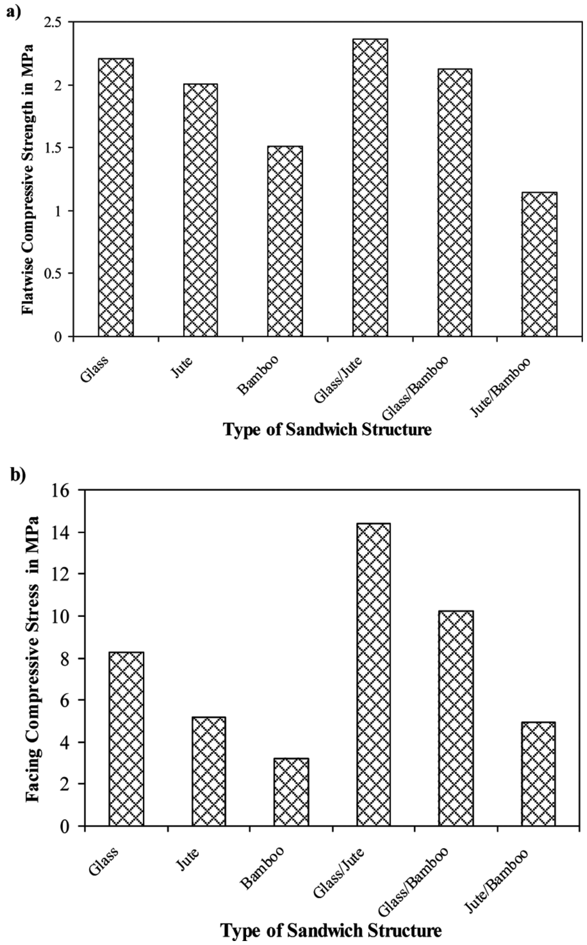

FIG. 6. Variation of compressive properties on sandwich structures (a) Flatwise compressive strength, (b) Facing compressive stress.

jute/bamboo hybrid sandwich structure possess lower value. Facing compressive stress of glass/ jute sandwich structure is 1.7426, 2.7730, 5.1812, 1.4046, 2.8990 times higher than glass, jute, bamboo, glass/bamboo, jute/bamboo sandwich structures, respectively.

This variation in Flatwise compressive strength and facing compressive stress are as results of variation in facing material combination. The factors affecting failure are type of skin material and its constituents, core material, dimension of the sandwich structure, facing to core interface, method of manufacturing, etc. It has been observed that core-face interface debonding is one of the important mode of failure in sandwich structures.

Modes of failure in Edgewise compression test plays very important role. Mamalis et al.[21] studied the crushing response of composite sandwich structure subjected to Edgewise compression and concluded that there were three modes of collapse;

- Mode I, unstable sandwich column buckling with foam core shear failure,
- Mode II, unstable sandwich disintegration with buckling of faceplates to opposite directions, and
- Mode III, progressive end-crushing of the sandwich panels.

In this study, unstable collapse mode II was observed in the case of glass, jute, glass/ jute sandwich structures. Stable progressive crushing mode III was observed in case of bamboo sandwich structures. Hybrid sandwich structures glass/ bamboo, jute/ bamboo fail in the mode which was the combination of II and III.

Interface between facing to core plays a vital role in assessing the properties, the failure of sandwich structures. Hence in this study facing to core interface has been studied with an aid of scanning electron microscope. The interface between the core and facing (skin) of the sandwich structures was represented in Figure 7 as indicated by blocked arrows.

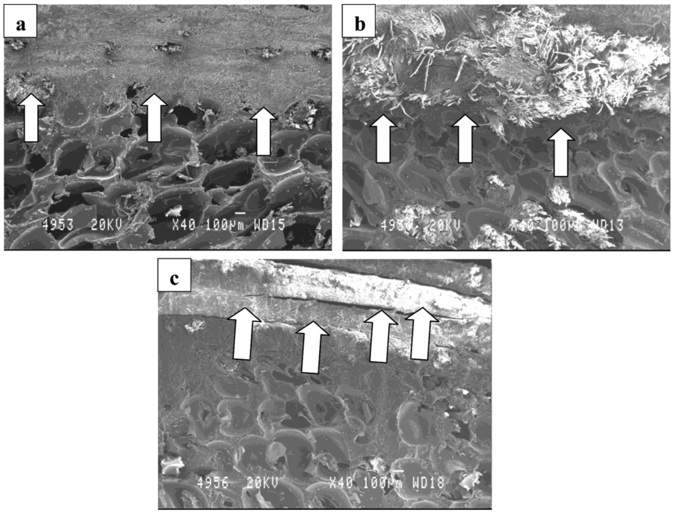

FIG. 7. Scanning electron micrographs of interface between core and facing: (a) Glass/PUF, (b) Jute/PUF, (c) Bamboo/PUF.

In Figure 7a, b, c refers to interface of rigid PUF to Glass, Jute, and Bamboo skins, respectively. Bonding between Interface of Glass / PUF was found to be high, whereas for bamboo / PUF bonding found to be poor. Due to good bonding pure glass sandwich structure possesses higher values of Flatwise compressive strength, Facing compressive strength compared to pure jute and bamboo. Even though jute sandwich structures possess lower bonding strength compared to glass, due to inherent properties of Jute results in more Flatwise and Facing compressive strengths for glass/jute hybrid sandwich structures.

CONCLUSIONS

Based on the results of the experimental analysis carried out on the core and sandwich structures, the following conclusions were derived.

- Percentage of moisture absorption of Type II foam is less compared to other types, but it was found more for Type III foam. Jute/bamboo sandwich structures absorb more percentage moisture compared to other types.
- Type II rigid polyurethane foam possesses higher value of compressive strength in Flatwise and Edgewise compression tests compared to other types, whereas Type IV possesses lower value.
- Glass/jute hybrid sandwich structures possesses higher value of Flatwise compressive strength compared to other types, whereas jute/bamboo possesses lower value.
- Glass/jute hybrid sandwich structure possesses higher value of facing compressive stress compared to other types, bamboo possesses lower value.
- The debond strength of the core–face and core plays an important role in enhancing the compression properties and controlling of the failure mode.

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