Investigating the effect of honeycomb grid cell size on structural performance of stiffened syntactic foam core sandwich composite

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Abstract

Syntactic foam core composite sandwich structures are potential structural panels because of their high specific properties. The chief ingredient of a syntactic foam is dry fly ash cenospheres, which play a vital role in the mechanical properties of syntactic foam in relation to its volume fraction. In the present investigation, the concept of confining foam in the cells of a honeycomb grid structure was adopted to improve the mechanical properties of composite sandwich structural panels. Experimental investigations were carried out to evaluate the thermal stability and mechanical properties of a honeycomb grid stiffened syntactic foam core composite sandwich as per ASTM standards. The results of the investigations reveal that the syntactic foam confined in the hexagonal cells of the honeycomb grid structure considerably improves the mechanical properties by 20% to180% than compared with syntactic foam core sandwich composites without a honeycomb grid structure. The cell walls of the honeycomb grid structure hinder the propagation of cracks under loading conditions. The damage tolerance capacity is attributed to the cell size of the honeycomb structure. Interfacial bonding of the constituent materials leads to improved mechanical properties.

Keywords: honeycomb grid, syntactic foam, composite, sandwich, structure

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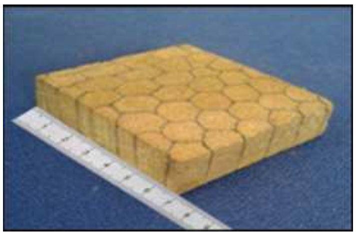
1. Introduction

Composite materials are widely being used in household, automobile, aerospace and marine structural applications. Composite materials offer high specific properties with good energy absorption capabilities. It will be possible to improve the physical, mechanical, thermal and acoustical properties, if the technique of sandwich construction is properly designed and implemented for the development of composite sandwich panels. Sandwich composites basically consist of two face skins on either side sides of a thicker core. The two thin face skins and the core occupy about 20% and 80% of the overall volume of composite sandwich panels, respectively. The core of composite sandwich panels prevents the face skins against buckling and improves the compressive properties. On the other hand, the face skins of the composite sandwich panels significantly improve the flexural properties. Under out-of-plane (flatwise) loading conditions, a composite sandwich can be used as structural panels, roofs, decks, among others, in which flexural loads will be carried by the face skins and shear loads will be carried by the core. However, under in-plane (edgewise) loading conditions, sandwich composites can be used as bulkheads. The low density characteristic of sandwich composites has potential advantages in weight critical structural applications. Researchers have attempted to develop composite sandwich panels with new materials for the face skins and the core. The face skins of composite sandwich panels may be made from a fiber-reinforced composite or metallic sheets. Nonetheless, the core of composite sandwich panels may be a honeycomb grid, balsa wood or foam. The foam core may be a metallic foam core or polymer foam one. There are two types of polymer foam cores (open-cell , closed-cell) that can be used as a potential core material for sandwich constructions. A closed-cell polymer foam called syntactic foam exhibits good physical and mechanical properties when compared to open-cell polymer foam. Syntactic foam is a composite prepared by reinforcing desired proportions of hollow micro-spherical particles (cenospheres) in polymer matrix. The potential advantages of syntactic foams make them suitable for the development of composite sandwich panels as the core material [1]. The literature reveals that the volume fraction of hollow micro-spherical particles does have a significant influence on the mechanical properties of syntactic foam [2- 10].The mechanical properties of syntactic foam deteriorate with a higher volume fraction of the hollow micro-spherical particles in the resin matrix. This may be due to a reduction in the interfacial thickness of the matrix material between the micro-spherical particles of syntactic foam. To overcome this problem, researchers have attempted to switch from two-phase compositions of syntactic foam to three-phase ones by incorporating nanoclay, carbon nanotubes and chopped fibers [11-13] to improve its mechanical performance. Furthermore, Heet al. [14] observed an increase in the fracture energy of a syntactic foam core by using carboxyl-terminated butadiene-acrylonitrile rubber constituents. The experimental results of Jin et al. [15] revealed that an increase in the compressive strength and the energy absorption capability of syntactic foam could be obtained by doping it with GFRP tubes. Brandtner-Hafneret al. [16] observed that the structural failure behavior of polymer foams is in the fracture zone and in its interfaces. The results of their investigations show that it is not the materials with the highest tensile strength that are most promising, but those with the most extraordinary fracture energy and damage tolerance. Manu et al. [17] found that the shape memory functionality of a shape memory polymer based syntactic foam can be utilized for the purpose of sealing damage along with shape recovery. In relation to the third phase constituent of syntactic foam, the present investigation focuses on integrating the hexagonal cells of a honeycomb grid structure as a third phase constituent in syntactic foam during manufacturing to overcome the problems associated with the foam.

2. Method of manufacturing

In the present work, the concept of confining foam in the cells of a honeycomb grid structure [18-23] is adopted to improve the mechanical properties of syntactic foam core composite sandwich panels. Syntactic foam is a composite prepared by reinforcing the desired proportions (50:50) of dry fly ash cenospheres in a phenol formaldehyde thermoset polymer resin matrix. Next, the blended mixture of syntactic foam was then packed in the hexagonal cells of a honeycomb grid structure to form a core. Afterwards, resin-impregnated glass fabrics were vacuum bonded to the core to form stiffened syntactic foam core composite sandwich panels (Figure 1).

(a) Syntactic foam core **(b) Syntactic foam core/glass/epoxy face skin sandwich**



(c) Honeycomb grid stiffened syntactic foam core

(d) Honeycomb grid stiffened syntactic foam core /glass/epoxy face skin sandwich

Figure 1. Sandwich composites with syntactic foam core with and without honeycomb grid structure

3. Testing of properties

Characterization of the thermal stability and mechanical properties of composite sandwich panels in the possible loading directions is performed by means of testing. The consequence of confining the syntactic foam in the cells of a honeycomb structure on the mechanical properties of composite sandwich panels is investigated experimentally under flatwise (out-of-plane) and edgewise (in-plane) loading configurations. As per ASTM standards, tests were executed to assess the physical and mechanical characteristics of the composite sandwich panels. With the intention of studying the effect of the cell size of the honeycomb grid structure, parametric analysis was carried out to evaluate the mechanical performance of the honeycomb grid stiffened syntactic foam core composite sandwich panels. The cell sizes of the honeycomb grid structure considered for the parametric study were 5 mm, 10 mm, 15 mm and 20 mm. The prepared composite sandwich panels were the syntactic foam core sandwich composite (SF), honeycomb grid stiffened syntactic foam core sandwich composite (SFK20) with a hexagonal cell size of 20mm, honeycomb grid stiffened syntactic foam core sandwich composite (SFK15) with a hexagonal cell size of 15mm, honeycomb grid stiffened syntactic foam core sandwich composite (SFK10) with a hexagonal cell size of 10mm and honeycomb grid stiffened syntactic foam core sandwich composite (SFK5) with a hexagonal cell size of 5mm.

3.1 Resin burnout test

The resin burnout test was conducted to verify the constituents of the reinforcement mass fraction in the composite sandwich specimens by burning it in a muffle furnace at 565°C as per ASTM D2584. Then after cleaning and drying the residues, the reinforcement constituents were weighed. Next, the actual volume fractions of the reinforcement and the matrix were evaluated.

3.2 Characterization of mechanical behavior

The mechanical behavior of the composite sandwich panel and its constituents, i.e. the face skins and core materials were evaluated under different loading and boundary conditions at a constant displacement rate of 0.5 mm/min using a universal testing machine, Instron 5982, with a capacity of 300 kN. Investigations were carried out in accordance with ASTM C365 and ASTM C364, to determine the flatwise (out-of-plane) and edgewise (in-plane) structural behavior of the composite sandwich panels under compression loading conditions, respectively. ASTM C297 [24] and ASTM D638 [25] were followed to examine the flatwise and edgewise structural response of the composite sandwich specimens under tensile loading conditions, respectively. The composite sandwich panels were subjected to the flexural test as per ASTM C 393 [24], in which the composite sandwich specimens were subjected to transverse load under flatwise and edgewise conditions. The composite sandwich panels were subjected to three-rail shear tests as per ASTM D4255M,in which the composite sandwich panels were subjected to transverse loading conditions under out-of-plane and in-plane configurations.

4. Results and discussion

4.1 Resin burnout results

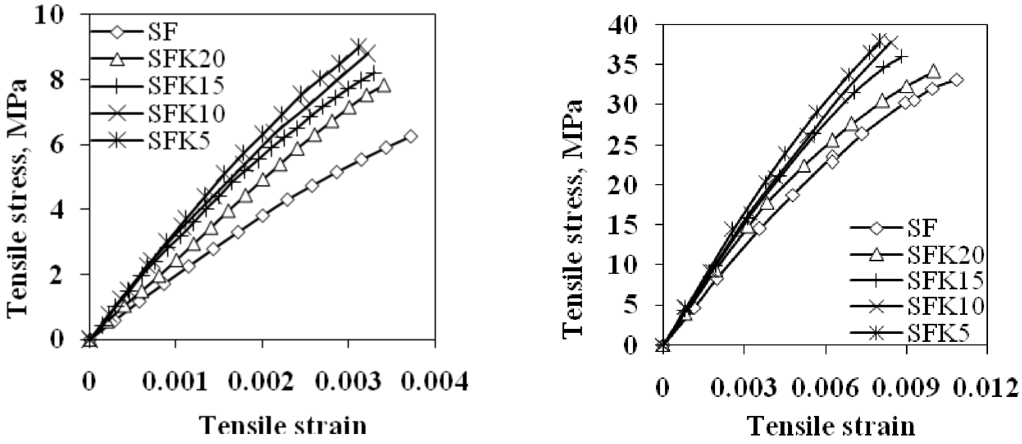
. The mechanical bonding of the phenolic resin matrix with the dry fly ash cenospheres in the syntactic foam composite and epoxy resin matrix with glass fiber in the glass/epoxy face skin composite was stable up to the temperature of 450°C and 350°C, respectively. By proceeding further with a rise in temperature, both the thermoset polymer resin matrices (the phenolic resin in the syntactic foam and the epoxy in the face skin) gradually decompose [26] till the temperature of 565°C. Then, after cleaning and drying the residues, the reinforcement constituents were weighed. Next, the actual volume fractions of the reinforcement and the matrix were evaluated. Table 1summarizes the results of the resin burnout test. The results reveal that the composite sandwich structure is stable with the core of stiffened syntactic foam up to450°C [26].

Table 1. Results of resin burnout test

Composite specimen	Mass of composite (g)	Mass of reinforcement after resin burnout test (g)	Volume fraction	
			Reinforcement	Matrix
Syntactic foam	5	2.36	0.70	0.30
E-glass/epoxy	5	2.37	0.30	0.70

4.2 Tensile behavior

The tensile stress-strain behavior of the composite sandwich specimens under flatwise and edgewise loading conditions is shown in Figure 2. Under flatwise tensile loading conditions (Figure 2a) there is a linear rise in the stress with respect to strain till failure of the composite sandwich specimen. Under edgewise tensile loading conditions (Figure 2b), the stress-strain plot exhibits linear response up to the point of yield stress. Beyond the point of yield stress, cracks initiate in the core, leading to non-linear behavior till failure. It was observed that the honeycomb grid stiffened syntactic foam core composite sandwich panels demonstrated significant improvement in the tensile strength and modulus in correlation with the hexagonal cell size of the honeycomb grid structure. This may be due to the hinderance of micro-cracks generated in the syntactic foam by the cell walls of the honeycomb grid structure. This is in correlation with similar observations revealed in the investigations conducted by Kumar et al. [29, 30]. The spread of cracks in the core was halted by the hexagonal cell walls of the honeycomb grid structure and led improvement of the tensile strength and tensile modulus of composite sandwich specimens. The tensile strength and tensile modulus of the composite sandwich specimens under flatwise and edgewise tensile loading conditions are listed in Table 2.



(a) Flatwise tension **(b) Edgewise tension**

Figure 2. Tensile stress-strain behavior of sandwich composites

Table 2. Tensile properties of sandwich composites under flatwise and edgewise loading conditions

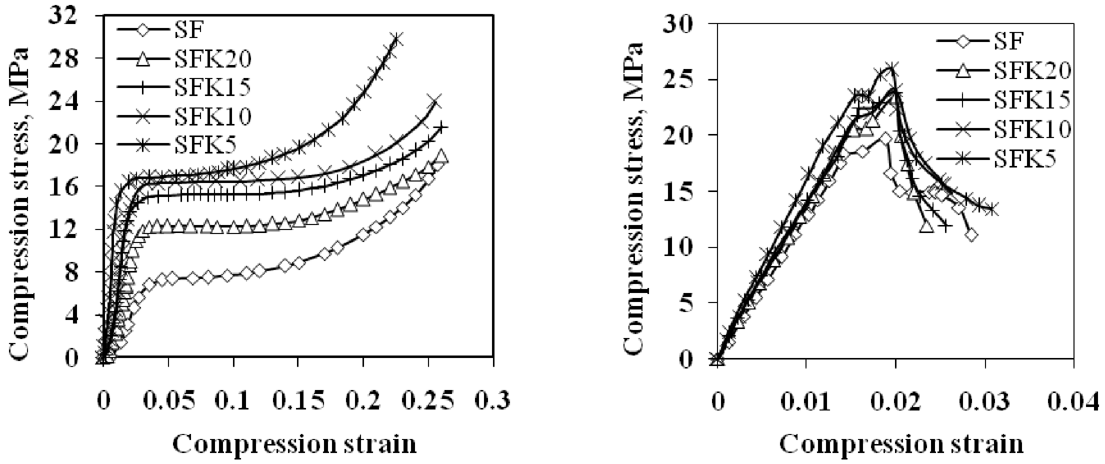
Property	Configuration	SF	SFK20	SFK15	SFK10	SFK5
Tensile strength, MPa	Flatwise	6.23	7.83	8.19	8.82	9.01
	Edgewise	33.21	34.25	36	37.82	37.93
Tensile modulus, GPa	Flatwise	1.87	2.34	2.69	2.74	3.38
	Edgewise	4.38	4.87	4.99	5.18	5.42

4.3 Compression behavior

The structural behavior of the composite sandwich specimens loaded under flatwise and edgewise compression loading conditions is shown in Figure 3. Under flatwise compression (Figure 3a), the core of the composite sandwich panel is the major load bearing member. All the composite sandwich specimens exhibited a similar flatwise compressive stress-strain response with a linear rise up to the point of yield stress, followed by densification. Nevertheless, under edgewise compression (Figure 3b), the sandwich composites exhibit a linear response up to the point of yield stress. Beyond the point of yield stress, cracks initiate in the core, leading to a sudden drop in the stress-strain curve. Similar observations were made by Kumar et al. [29]. It can be seen that (Figure 1c and 1d) syntactic foam confined in the hexagonal cells of the honeycomb grid structure leads to considerable improvement in the compression properties of the stiffened syntactic foam core sandwich composite. Furthermore, the significant improvement in the compressive properties of the composite sandwich specimens with the core of honeycomb grid stiffened syntactic foam are attributed to the cell size of the honeycomb grid structure [28,29,30]. The compression strength and compression modulus of the composite sandwich specimens under flatwise and edgewise compression loading conditions are presented in Table 3.

Table 3. Compressive properties of sandwich composites under flatwise and edgewise loading conditions

Property	Configuration	SF	SFK20	SFK15	SFK10	SFK5
Compression strength, MPa	Flatwise	7.09	12.42	14.98	15.72	16.79
	Edgewise	19.67	23.45	23.83	24.07	24.85
Compression modulus, GPa	Flatwise	1.32	2.46	3.24	3.28	3.87
	Edgewise	1.77	1.96	2	2.04	2.28



(a) Flatwise compression **(b) Edgewise compression**

(c) Crushed sandwich with continuous cracks **(d) Crushed sandwich with intermittent cracks**

Figure 3. Compression stress-strain behavior of sandwich composites

4.4 Flexural behavior

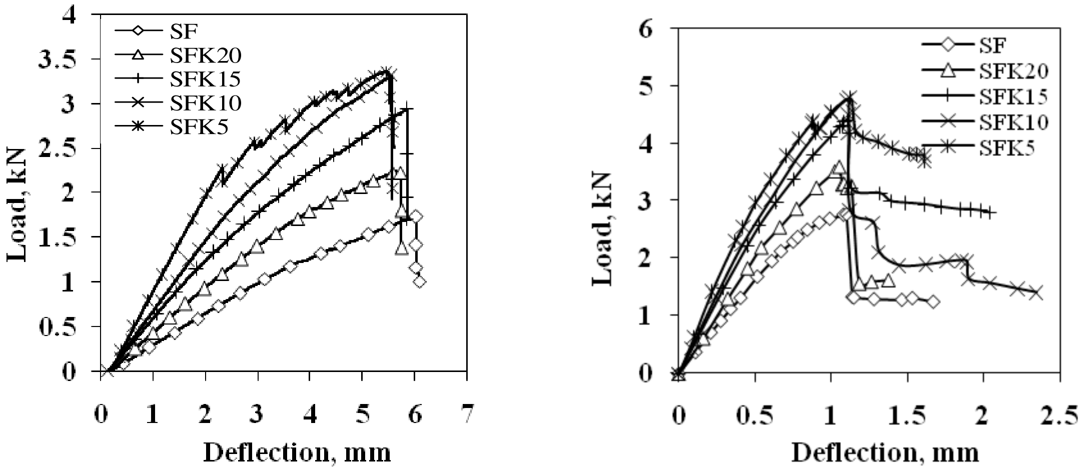
Figure 4 shows the flexural behavior of long and short span composite sandwich beam specimens, respectively, under out-of-plane loading configuration. The flexural behavior of the composite sandwich specimens is linear at the beginning and then exhibits non-linear behavior. The flexural strength of the composite sandwich specimens is governed by the composite face skins as the glass/epoxy face skins exhibit good resistance to the initiation of crack at the tensile side of the sandwich composite specimens under the out-of-plane flexure loading configuration. Once the crack is initiated on the tensile side of the composite sandwich specimen, it will propagate corresponding to the increase in load. This leads to shear failure of the core material [30]. The significant influence of the syntactic foam confined in the cells of the honeycomb grid structure on the flexural performance of the composite sandwich specimens is given in Table 4. It is worthhighlighting the fact that the integration of syntacticfoam in the honeycomb grid structure to form a core leads to significant improvement in the flexural properties of composite sandwich beams. Moreover, the long beam composite sandwich specimen exhibits high bending strength, while the short beam composite sandwich specimen exhibits high shear strength.

Table 4. Flexural properties of long beam composite sandwich beams

Property	Configuration	SF	SFK20	SFK15	SFK10	SFK5
Flexuralstrength, MPa	Flatwise	54	70.02	91.7	103.36	103.89
	Edgewise	27.33	34.37	36.62	37.34	38.26
Flexural modulus, GPa	Flatwise	5.16	6.7	7.79	8.69	11.49
	Edgewise	2.4	3.18	3.23	4.63	6.48

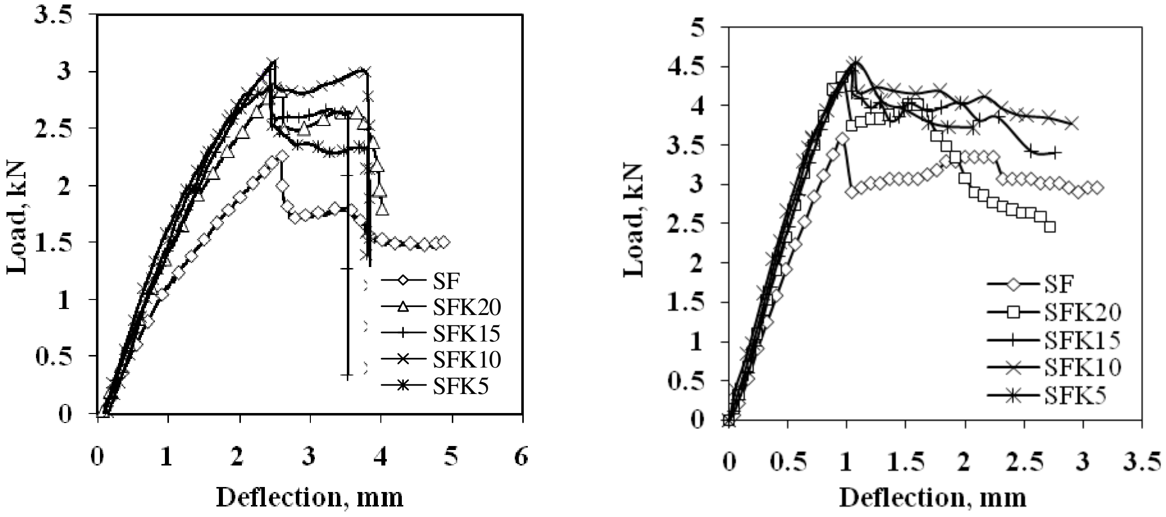
Table 5. Flexural properties of short beam composite sandwich beams

Property	Configuration	SF	SFK20	SFK15	SFK10	SFK5
Flexural strength, MPa	Flatwise	42.02	54.63	66.95	72.46	73.05
	Edgewise	33.2	40.5	41.25	41.76	42.28
Flexural modulus, GPa	Flatwise	1.97	2.63	2.92	3.24	3.47
	Edgewise	1.03	1.24	1.29	1.31	1.39



(a) Long-beam **(b) Short-beam**

Figure 4. Flatwise flexural behavior of composite sandwich beams



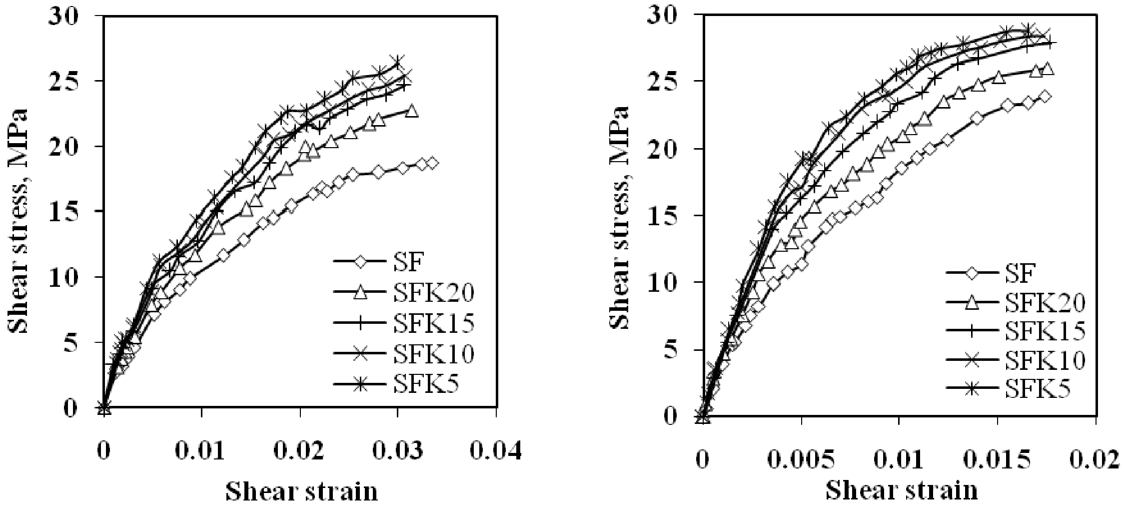
(a) Long-beam **(b) Short-beam**

Figure 5. Edgewise flexural behavior of composite sandwich beams

Thein-plane flexural response (Figure 5) of the composite sandwich specimen exhibits linear behavior at the beginning and then non-linear behavior. Under the in-plane loading configuration, both face skins as well as the core constituents of the composite sandwich specimens simultaneously resist the crack initiation. Once the crack initiates, it propagates due to the further increase in load and leads to the failure of the composite sandwich specimens. The flexural properties of the long beam composite sandwich specimens under out-of-plane and in-plane loading conditions are listed in Table 4. The flexural strength and modulus of the short beam composite sandwich specimens under out-of-plane and in-plane loading conditions are presented in Table5.

4.5 In-plane shear behavior

The flatwise and edgewise shear stress-strain behavior of the composite sandwich specimens are shown in Figure 6. Under the flatwise shear loading configuration, it can be observed that there is a linear rise in the stress with respect to low-strain and then followed by non-linear behavior till failure of the composite sandwich specimen. Under the in-plane shear loading condition, the stress-strain plot shows linear response up to the point of yield stress. Beyond the point of yield stress, cracks initiate in the core, leading to non-linear behavior till failure. A similar observation was made by Manalo et al. [31]. The out-of-plane and in-plane shear strength of composite sandwich specimens are given in Table 6.



(a) Flatwise shear **(b) Edgewise shear**

Figure 6. Shear stress-shear strain behavior of sandwich composite specimens

Table 6. Shear properties of sandwich composites

Property	Configuration	SF	SFK20	SFK15	SFK10	SFK5
Shear strength, MPa	Flatwise	18.74	22.75	24.7	25.43	26.34
	Edgewise	23.95	26.72	27.91	28.38	28.78
Shear modulus, GPa	Flatwise	0.96	1.15	1.21	1.28	1.36
	Edgewise	1.04	1.17	1.31	1.33	1.48

5. Conclusions

An attempt was made to develop and characterize the thermal stability and mechanical properties of composite sandwich panels with a core of syntactic foam in which the major reinforcing constituent is dry fly ash cenospheres. The authors further proceeded to stiffen the syntactic foam by integrating it with hexagonal cells of a honeycomb grid structure. Following conclusions were drawn based on the observations made in the investigations:

1. . The mechanical bonding of the phenolic resin matrix with the dry fly ash cenospheres in the syntactic foam composite and epoxy resin matrix with glass fiber in the glass/epoxy face skin composite was stable up to the temperature of 450°C and 350°C, respectively, and is attributed to the phenolic resin and epoxy resin matrix.
2. Under the out-of-plane (flatwise) loading conditions, the mechanical properties of the composite sandwich are significantly influenced by the integration of the honeycomb grid structure in the syntactic foam core composites from 20% to 180%.
3. Under the in-plane (edgewise) loading conditions, the strength and stiffness of the composite sandwich are significantly influenced by the glass/epoxy face skins from 5% to 80%.
4. The integration of the syntactic foam into the honeycomb grid structure led to noteworthy enhancement of the specific strength and specific stiffness.
5. The mechanical properties of the composite sandwich panels are considerably increased with the smaller cell size of honeycomb grid structure.

References

[1] Isaac M. Daniel., Ori Ishai., Engineering Mechanics of Composite Materials., Oxford University Press, 2nd Edition 2007., ISBN 978-0-19-515097-1.

[2] Ness D.S.R., Whiley D.A., Advanced Composites for High Performance Marine Craft., Marine Structure 1990, 3, 111-131., https://doi.org/10.1016/0951-8339(90)90007-E.

[3] Isao Kimpara., Use of Advanced Composite Materials in Marine Vehicles., Marine Structure 1991, 4,117-127., https://doi.org/10.1016/0951-8339(91)90016-5.

[4] Chalmers D.W., The Potential for the Use of Composite Materials in Marine Structures., Marine Structure 1994, 7, 441-456., https://doi.org/10.1016/0951-8339(94)90034-5.

[5] Shah Khan M.Z., Simpson G., Gellert E.P., Resistance of glass-fibre reinforced polymer composites to increasing compressive strain rates and loading rates., Composite Part A: Applied Science and Manufacturing 2000, 31, 57–67., https://doi.org/10.1016/S1359-835X(99)00051-2.

[6] Mouritz A.P., Gardiner C.P., Compression properties of fire-damaged polymer sandwich composites., Composite Part A: Applied Science and Manufacturing 2002,33, 609-620., https://doi.org/10.1016/S1359-835X(02)00022-2.

[7] Kootsookos A., Mouritz A.P., Seawater durability of glass- and carbon-polymer composites., Composite Science and Technology 2004,.64,1503–1511., https://doi.org/10.1016/j.compscitech.2003.10.019.

[8] Kunigal N. Shivakumar., Gowthaman Swaminathan., Mathew Sharpe., Carbon/vinyl ester composites for enhanced performance in marine applications., Journal of Reinforced and Plastics and Composites 2006,25,1101-1116., https://doi.org/10.1177/073168440606519

[9] Saud Aldajah., Ghydaa Alawsi., Safaa Abdul Rahmaan., Impact of sea and tap water exposure on the durability of GFRP laminates, Materials and Design 2009, 30,1835–1840., https://doi.org/10.1016/j.matdes.2008.07.044.

[10] Motley M.R., Liu Z., Young Y.L., Utilizing fluid–structure interactions to improve energy efficiency of composite marine propellers in spatially varying wake., Composite Structures 2009, 90, 304–313., https://doi.org/10.1016/j.compstruct.2009.03.011.

[11] Harald Osnes., Dag McGeorge., Experimental and analytical strength analysis of double-lap joints for marine applications, Composite Part B: Engineering 40, 29–40. (2009) https://doi.org/10.1016/j.compositesb.2008.07.002.

[12] He X.D., Hong Y., Wang R.G., Hydro elastic optimization of a composite marine propeller in a non-uniform wake. Ocean Engineering 2012, 39 ,14–23., https://doi.org/10.1016/j.oceaneng.2011.10.007.

[13] Jacques Nader., Habib J. Dagher., Roberto A. Lopez-Anido., Fadi El Chiti., Ghassan Fayad., Lawrence Thomson., Probabilistic Finite Element Analysis of Modified ASTM D3039 Tension Test for Marine Grade Polymer Matrix Composites., Journal of Reinforced Plastics and Composites 2008,27, 583-597., DOI: 10.1177/07316844070799152008

[14] Sammy He, Declan Carolan, Alexander Fergusson, Ambrose C. Taylor., Investigating the transfer of toughness from rubber modified bulk epoxy polymers to syntactic foams. Composite Part B: Engineering 2022, 245, 110209, https://doi.org/10.1016/j.compositesb.2022.110209.

[15] Qing Jin., Jun Wang., Jiye Chen., Fengling Bao., Axial compressive behavior and energy absorption of syntactic foam-filled GFRP tubes with lattice frame reinforcement. Composite Structures 2022,299, Research article: 116080, https://doi.org/10.1016/j.compstruct.2022.116080.

[16] Martin Brandtner-Hafner., Holistic structural analysis of polymeric foam systems. Construction and Building Materials 2023,368, Research article: 130428, https://doi.org/10.1016/j.conbuildmat.2023.130428.

[17] Manu John., Grid Stiffened Shape Memory Polymer Composite Structures. Encyclopedia of Materials: Plastics and Polymers 2022,2, 180-194, https://doi.org/10.1016/B978-0-12-820352-1.00203-0.

[18] Fallah A.S., Johnson H.E., Louca L.A., Experimental and numerical investigation of buckling resistance of marine composite panels. Journal of Composite Materials 2010, 45, 907–922., https://doi.org/10.1177/0021998310377942.

[19] Abhendra K Singh., Barry D Davidson., Effects of temperature, seawater and impact on the strength, stiffness, and life of sandwich composites., Journal of Reinforced Plastics and Composites 2010, 30, 269–277., https://doi.org/10.1177/0731684410393053.

[20] Manujesh B.J., Vijayalakshmi Rao., Sham Aan M.P., Moisture absorption and mechanical degradation studies of polyurethane foam cored E-glass-reinforced vinyl-ester sandwich composites. Journal of Reinforced Plastics and Composites 2014, 33, 479–492., https://doi.org/10.1177/0731684413503720.

[21] Nilanjan Mitra., Marine Sandwich Structures. Wiley Encyclopaedia of Composites, John Wiley and Sons Inc, 2nd Edition 2012, https://doi.org/10.1002/9781118097298.weoc241.

[22] Zhou G., Hill M.D., Impact damage and energy-absorbing characteristics and residual in-plane compressive strength of honeycomb sandwich panels., Journal of Sandwich Structures and Materials 2009, 11, 329-356., DOI: 10.1177/1099636209105704.

[23] Kwang Suk Kim., In-Joo Chin., Curing of nomex/phenolic and kraft/phenolic honeycombs, Polym. Korea.Korea Polymer Journal 1995, 3, 35-40.

[24] Space simulation; aerospace and aircraft; composite materials. Annual book of American society for testing and materials standard, West Conshohocken, PA, 15.03.2007.

[25] ASTM Standard D638., Standard test method for tensile properties of plastics., ASTM D638-91., West Conshohocken, Philadelphia, Pa, ASTM International 1991.

[26] Amith Kumar S.J., Ajith Kumar S.J., Bharath K. Nagaraja., Thermal stability and flammability characteristics of phenolic syntactic-foam core sandwich composites., J. Sandw. Struct. Journal of sandwich structures and materials 2020, https://doi.org/10.1177/1099636220926661.

[27] Sebastian Heimbs., Sebastian Schmeer., Peter Middendorf., Martin Maier., Strain rate effects in phenolic composites and phenolic-impregnated honeycomb structures. Composite Science and Technology 2007,67, 2827–2837., https://doi.org/10.1016/j.compscitech.2007.01.027.

[28] Amith Kumar S.J., Ajith Kumar S.J., Low-velocity impact damage and energy absorption characteristics of stiffened syntactic-foam core sandwich composites., Construction and Building Materials 2020, 246, Research article: 118412. https://doi.org/10.1016/j.conbuildmat.2020.118412.

[29] Amith Kumar S.J., Sabeel Ahmed K., Compression behavior and energy absorption capacity of stiffened syntactic-foam core sandwich composites., Journal of Reinforced Plastics and Composites 2013, 32,1370-1379, doi: 10.1177/0731684413492867.

[30] Amith Kumar S.J., Sabeel Ahmed K., Flexural behavior of stiffened syntactic-foam core sandwich composites, Journal of Sandwich Structures and Materials 2014, 16,195-209, doi:10.1177/1099636213512498.

[31] Manalo A.C., Aravinthan T., Karunasena W., In-plane shear behaviour of fibre composite sandwich beams using asymmetrical beam shear test., Construction and Building Materials 2010,24,1952–1960., https://doi.org/10.1016/j.conbuildmat.2010.04.005.