IJE TRANSACTIONS A: Basics Vol. 34, No. 04, (April 2021) 999-1007

International Journal of Engineering

Journal Homepage: www.ije.ir

Experimental Damage Evaluation of Honeycomb Sandwich with Composite Face Sheets under Impact Load

D. Muniraj*, V. M. Sreehari

School of Mechanical Engineering, SASTRA Deemed to be University, Tamilnadu, India

P A P E R I N F O

Paper history:
Received 26 August 2020
Received in revised form 24 January 2021
Accepted 03 February 2021

Keywords:
Damage
Honeycomb Sandwich
Composite
Impact
Compression after Impact

A B S T R A C T

Aerospace structures are highly vulnerable to impact loads whose damage tolerance, and its resistance vary over the range of impact velocity. Honeycomb sandwich structures are used in aerospace industries where mass efficient and impact resistant structures are needed. However, the structural integrity of these structures is reduced by impact load due to tool drop, runway debris, hailstones and improper handling of the structure. A thorough investigation of the damage behaviour of honeycomb sandwich under low-velocity impact and the post-impact residual strength determination is required to design a crashworthy lightweight structure. This paper presents the experimental evaluation of specific energy absorption using Charpy impact, residual compressive strength by compression after impact and damage evaluation of honeycomb sandwich structures having composite face sheets. Parametric studies on composites and honeycombs are carried out by varying the cell size, cell thickness, core height, impact velocity, thickness and orientation of lamina. Densely packed thick honeycombs provide higher fracture energy. Under transverse compressive loading, the honeycomb core undergoes cell wall buckling, crushing and densification. Load-displacement history under in-plane compression and compression after impact for different impact energies is observed. The present study contributes for the understanding how various parameters affect the characteristics of face sheet indentation and plastic buckling of honeycomb sandwich structures with composite face sheets, thereby providing useful guidelines for its potential applications in impact engineering.

***doi**: 10.5829/ije.2021.34.04a.26*

1. INTRODUCTION

Honeycomb sandwich structures with composite face sheets are increasingly used in aerospace, automobile and marine industries due to their combined excellent mechanical properties and lightweight. For example, flight control surfaces, engine cowling, helicopter rotor blades, ship hulls, automotive rims, chassis components and spoilers are made up of honeycomb sandwich structures, which hugely reduce the vehicle weight and fuel consumption. These structures are subjected to low-velocity impact due to tool drop during maintenance, runway debris and also high-velocity impact due to hailstones, bird hit and micrometeoroids. This event leads to indentation, perforation, skin fracture, core detachment and complete penetration based on the impact energy. The compressive strength of the structure drastically reduces after an impact event. To avoid accidents and to endure impact loads, many lightweight materials that absorb energy and having very high strength to weight ratio are used as shields for aerospace structures. In recent years, structural crashworthiness has become a significant area of study for the benefits of public safety and social economy. Hence, it is essential to design a structure which is crashworthy and lightweight considering the safety of the crew and the cost of the mission. The solution for attaining these two competing parameters is by using the honeycomb sandwich composite structure.

Sandwiched composite belongs to a special family of composite materials that consists of two thin face sheets bonded to the top and bottom of the lightweight core, which performs like an I beam web to sustain the shear load and transfer load to the face sheets placed away from

---

*Corresponding Author Institutional Email: muniraj@sastra.ac.in (D. Muniraj)

Please cite this article as: D. Muniraj, V. M. Sreehari, Experimental Damage Evaluation of Honeycomb Sandwich with Composite Face Sheets under Impact Load, International Journal of Engineering, Transactions A: Basics Vol. 34, No. 04, (2021) 999-1007

the neutral axis. Composites made of glass, carbon, aramid fibers reinforcement with epoxy resin, polypropylene, and polyamide matrix are used as face sheets in sandwiched structure due to its high strength to weight ratio. Composites have high load-bearing and impact resistance in the fiber direction. Aluminium, steel, nomex honeycomb and few low-density foams are widely used as the core material in the sandwiched structure. Green composites are one of the important class of composite materials made from biodegradable polymers and natural fibers as reinforcement, which are used in the bicycle frame, fork, dashboard, false ceiling, safety helmet, wind turbine and cross arms in transmission tower [1-3]. The hybridisation of glass fibers with other high strength eco-friendly fibers like basalt fiber, treated sugar palm offers better mechanical and thermal properties [4, 5]. Aisyah et al. [6] studied the effect of hybridisation on thermal properties of carbon fiber with woven kenaf reinforced epoxy composite. Maraki et al. [7] performed the design of experiment on AZ31 magnesium alloy under Charpy impact test to investigate the failure energy. Steel-concrete composite beams, frames with hybrid connectors are widely used in civil structures like multi-storeyed buildings and bridges [8, 9]. Lightweight foamed concrete is a cellular concrete manufactured in cement-based slurry by combining foam with the desired density, which is hugely used for thermal and acoustic insulation [10]. Jinan et al. [11] characterised the axial compressive failure mode of composite concrete-steel plate shear wall by bucking, cracking and crushing. Saeed et al. [12] interpreted the dependence of structural performance and its matching inter-story drift in RC moment frames. Aisyah et al. [13] elaborated the fundamentals, prospects and present view of the creep test rig for a composite cantilever beam.

Sohel et al. [14] reported the damage characteristics and performance of sandwich beams with different spacing of shear connector under impact load. Cote et al. [15] reported the manufacturing route of metallic honeycombs and it's out of plane compressive behaviour. Sibeaud et al. [16] experimentally tested the honeycomb using a two-stage light gas gun at hypervelocity normal and oblique impact ranging from 2 to 10 km/s. Jankowiak et al. [17] studied the changes in failure mode for different projectile shape due to stress triaxiality state. Xie et al. [18] implemented the interlaminar damage models and crushable foam model to simulate the low-velocity impact event of a foam core sandwich panel. The contact duration required for the entire structure to respond is more in low-velocity impact (LVI); as a result, more amount of energy is absorbed elastically. Experimental and numerical simulations have been performed to understand the impact behaviour of S-glass polyester composite laminate plate under low energy impact. Hashin's failure criteria have been used to study the inter-laminar stresses and the delamination of composites by Zouggar et al. [19]. A numerical and experimental set of low energy impact tests was carried out on composite plates in a bending configuration. Compression after impact (CAI) has been performed experimentally by Zhang et al. [20] on woven carbon fibre-reinforced composite to examine the residual compressive strength at different temperature levels. Microscopic observations have been performed by Elias et al. [21] to study the damage mechanism due to LVI in 3D woven composite employing X-ray tomography. Schroder et al. [22] discussed the usage of crushable shield beneath the lander platform which is made up of sandwich structures with aluminium core numerically and validated experimentally. Mars et al. [23] investigated the response of LVI on glass fiber reinforced polyamide using ABAQUS and correlated with the experimental results. Recently, Palomba et al. [24], used multi-walled honeycomb sandwich structures to increase the energy absorption capabilities. High-velocity impact (HVI) was carried out on aluminium honeycomb sandwich panels using a gas gun and measured the residual velocity, energy absorption and its internal damage using X-ray tomography and 3D scanning by Sun et al. [25]. Honeycomb sandwich structure under HVI at elevated temperature was experimentally and numerically studied by Xie et al. [26]. Mertani et al. [27] observed that honeycombs have excellent energy absorption properties when an impact load is applied in the out of plane direction which progressively causes cell wall buckling, core crushing and densification of the core. Babaei [28] evaluated the experimental responses of the clamped mild steel, copper and aluminium circular plates under blast loading.

Extensive research was conducted in the field of impact engineering, but limited literature was reported for the study of post-impact behaviour and its residual strength. However, a thorough understanding of post-impact damage and CAI response is still required to improve the crashworthiness of the structure under various impact energies. This paper presents an experimental investigation of honeycomb sandwich with composite face sheet under impact load and the related fracture energy, damage behaviour and residual compressive strength. A parametric study was performed to study the toughness through fracture energy using Charpy impact. The reduction of compressive strength of impacted specimen at different impact energies through CAI was compared with the non-impacted specimen.

2. EXPERİMENTAL INVESTIGATION

2. 1. Materials Honeycomb sandwich structures are made with aluminium honeycomb AA 3003 and glass fiber composite face sheets. Honeycombs having various core height, cell size, cell thickness and E glass fibrous composite made of random and preferred orientations are used to study the impact resistance and residual compressive strength. Standard epoxy resin LY 556 and hardener HY 951 was used for sandwich construction. Aluminium honeycombs and composite constituents were procured from Eco Earth Solutions Pvt Ltd, Mumbai and New Era Composites, Chennai, respectively.

2. 2. Manufacturing Vacuum-assisted resin transfer mould VARTM technique was used to fabricate the composite plate. E glass bidirectional fibre having 200 gsm was cut and layed up one over another on the 30 cm x 30 cm mould (Figure 1) as per the requirement. LY 556 standard epoxy resin and HY 951 hardener in the ratio of 10:1 was mixed properly without bubble formation. The fiber-resin volume fraction of 60:40 is maintained for manufacturing. Polyvinyl coating is applied on the surface of the mould and allowed to cure for non-sticky purpose. The fibres are placed on the mould over which peel ply resin infusion mesh and breather is packed as vacuum bag. Vacuum pressure of 0.5 bar is maintained inside the bag for 15 minutes and checked for leakage. Then the resin hardener mixture is allowed to infuse and spread all over the fiber. Then the complete set up is allowed to cure for 12 hours in the atmospheric temperature. AA 3003 Aluminium honeycombs are used for the sandwich construction. Nine sandwich panels having three distinct stacking sequences, skin thickness and ply orientations are shown in Figure 2. For sandwich construction, the face sheets are bonded to the honeycomb using the resin hardener mixture.

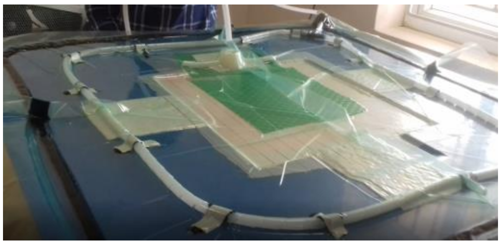


Figure 1. Vacuum-assisted resin transfer mould

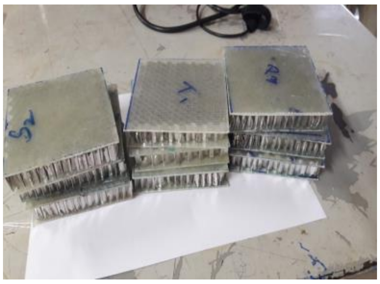


Figure 2. Constructed sandwich panel

2. 3. Charpy Impact Test Charpy impact is a pendulum type of low-velocity impact test in which the mass is raised to a height and released to swing about the pivot. The pendulum strikes the specimen, eventually fractures at a higher strain rate, during which the total energy absorption E_t can be evaluated. The fracture energy E* is used to study the fracture toughness properties of the sandwich structure.

2. 4. Freefall Impact Honeycombs have excellent energy absorption capabilities under impact load. Internally gained energy is dissipated through elastic deformation, permanent plastic deformation, heat and sound. A spherical cast iron ball is dropped from a height (h) in a hollow tube which produces low-velocity impact damage on the localized area of the test specimen. The damage mainly depends upon the mass and velocity of the indenter. A mass of 3.7 kg (S1) and 2.8 kg (S2) ball is dropped from a height of 1.3 m, creates an impact on 100 mm x 100 mm honeycomb sandwich structure.

2. 5. Compression After Impact Composites are highly prone to impact damage; even a blow with impact energy of 1 J creates irreversible damage. This operation damage may not be visible for the naked eye, but this could lead to complete failure during the in-service when other loads are acting. Especially, when the compressive load acts on a structure after an impact event, the compressive strength decreases. The specimen undergoes compression test after the impact event to evaluate the residual compressive strength. The impacted specimen using free-fall impact is cut into 100 mm x 50 mm with

TABLE 1. Fracture energy for different core parameters

Sample ID	Cell Size (mm)	Core Height (mm)	Cell Thickness (µm)	Composite Thickness (mm)	C.S area (mm^2)	E_t (J)	E^* (KJ/m^2)
H_1	3	8	50	1.5	110	7	63.63
H_2	6	10	50	1.5	130	5	38.46
H_3	9	21.5	50	1.5	230	7	30.43
T_1	6	16	80	1.5	190	5	26.31
T_2	6	16	70	1.5	190	4	21.05

impact location as center and in-plane compressive load is applied on the honeycomb sandwich structure.

2. 6. Out of Plane Compression Out of plane compressive load is applied to the sandwich structure to examine the failure load of the honeycomb. It is assumed that the composite face sheet bonded to the honeycomb has a negligible effect on failure load since Young's modulus of the honeycomb core is less than the face sheet. The compressive load is applied on the top face sheet of the 50 mm x 50 mm sandwich composite test specimen.

3. RESULTS AND DISCUSSION

3. 1. Effect of Geometrical Parameters of Honeycomb Core The standard Charpy test specimen of 80 mm length having three different cell size and core height H1, H2, H3 and two different core thicknesses T1, T2, before and after the damage is shown in Figure 3 and less deterioration is observed in H1. The toughness of a material is based on the energy absorption and plastic deformation, typically area under the stress-strain curve before failure. Toughness property of a sandwich structure is studied in terms of fracture energy E*. It is evident from Table 1 that, the increase in honeycomb cell size and core height results in the reduction of fracture energy and the increase in cell thickness results in the increase of fracture energy. The core is densely packed in sample H1 and hence relatively an increased value of fracture energy is observed. As the cell thickness increases, the cell wall buckling characteristics improve, due to which the fracture energy increased.

3. 2. Effect of Skin Thickness and Ply Orientation of the Composite Plate The drop tests for low-velocity impact are performed in a guided mass falling through a tube having 1 m height and eventually impacts the 100 mm x 50 mm sandwich panel. The impactor has a spherical shape with a 3.90 kg of weight. The free fall height, as well as the weight of the impactor, is modifiable to allow testing in a large energy range. Inplane compressive load is applied at the two edges of the impacted and non-impacted sandwich structure. The test fixture (Figure 4) is made as per the standard to conduct the compression test after impact.

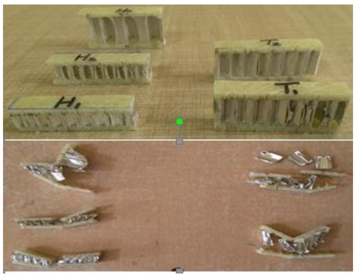


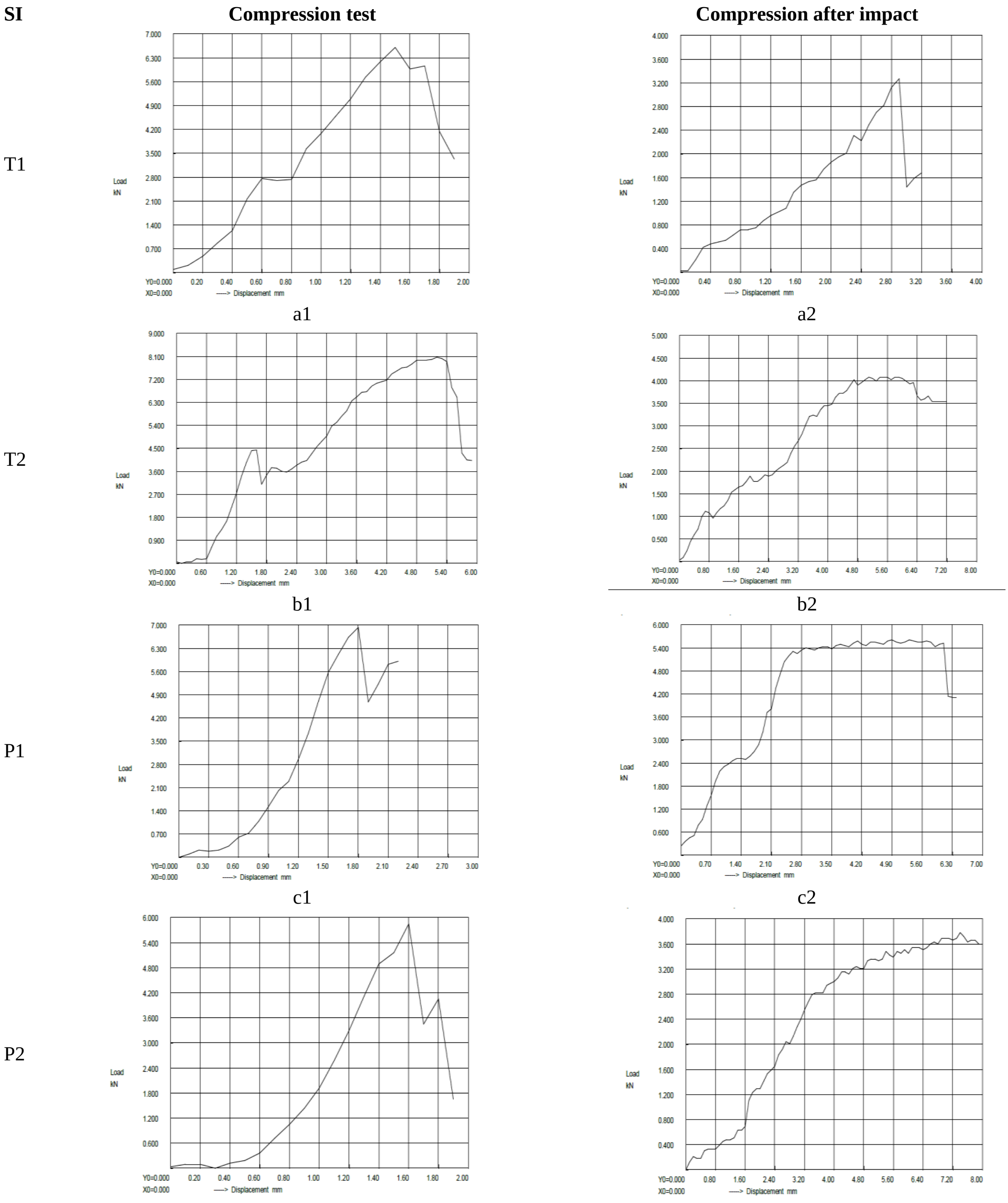
Figure 3. Sandwich structure before and after Charpy impact

The sandwich structure is supported at the two edges with the test fixture to avoid slipping and global buckling. The compression test is carried out in a universal testing machine (Figure 5) at constant strain rate. The composite plate failed in the middle and the crushing of the honeycomb core is shown in Figure 6. The compressive strength variation for two different skin thickness of 1.5 mm and 2.5 mm using 0/90 combinations of ply orientation for the sandwich structure is shown in Figure 7 a1, a2, b1 and b2. As the thickness of the composite skin is increased, the compressive strength increases for both impacted and non-impacted specimen. Upon comparing Figure 7 a1 and a2 the compressive strength decreases due to the damage in the impacted specimen. For damaged specimen, the displacement corresponding to the peak compressive strength is higher than the undamaged specimen. A positive drift is observed

Figure 4. Test fixture for CAI

Figure 5. Specimen under compression in UTM with the test fixture

Figure 6. Damaged honeycomb sandwich after CAI



a1 a2 b1 b2 c1 c2 d1 d2

Figure 7. Load (in kN) versus displacement (in mm) curves showing compressive strength variation in impacted and non-impacted specimen

between Figure 7 a1 and a2. Figure 7 c1, c2, d1and d2 shows the compressive strength variation for two different ply orientation at 0/90/30/45 combinations on the 3 mm thick honeycomb sandwich structure. The ply orientation P1 (0/90/45/-45)4 having 45-degree plies provides better compressive strength than 30-degree plies in P2 (0/90/30/-30)4. A sudden drop of load after the peak is observed in the undamaged specimen but occurs at a higher value of displacement owing to the enduring capability, whereas the load gradually varies in the damaged specimen at constant strain rate.

To study the transverse load-bearing capacity, out of plane compressive load is applied on the surface of the composite skin. Since the modulus of elasticity of the honeycomb core is less than the composite, initially the honeycomb core cell wall buckles and eventually fails by core crushing. Beyond straining this level, the core bulges in the sideward direction, so the ram of the UTM takes the load and hence the exponential variation is observed in the curve (Figure 8). The compressive strength reduction due to impact event has a huge dependency on ply orientation (Table 2).

3. 3. Damage under Compression and CAI at Various Impact Energy

As the spherical ball impacts the top face sheet, barely visible damage occurs and its fracture pattern is highlighted on the specimen. The fracture occurs at the edges of the dent diameter of the ball in the sample S1 for impact energy of 47 J and slight fracture occurs at the center in sample S2 for impact energy of 36 J as shown in Figures 10 a1 and b1, respectively. The cell wall buckling and the permanent deformation on the top of the honeycomb are shown in Figure 9. The impacted specimens (S1 and S2) and non-impacted specimen (S3) is compressed inplane and the corresponding damage is shown in Figures 10 a2, b2 and c2, respectively. The non-impacted specimen has not failed completely, whereas the damage occurs at the clamped edges and propagates progressively.

The damage due to out of plane compression in specimen C1 is shown in Figure 10 d2, in which the core deteriorated completely due to its lower modulus of elasticity when compared to the composite. The compressive force increases gradually reach its maximum and then reduces suddenly once the face sheet fails due to buckling, in the impacted specimens as shown in Figure 11 a and b. For non-impacted specimen, the curve reaches its maximum and remains the same with minor fluctuation even for the larger deformation (Figure 11 c). The compressive strength of the impacted specimen decreases when compared to the non-impacted specimen. Even though the impact energy of the specimen S1 is higher, the percentage reduction in compressive strength is lower than the specimen S2 (Table 3). This is due to the fact, that the contact area for S1 is larger due to the large diameter spherical ball. Under the in-plane compression, displacement increases till cell wall buckling and remains constant during core crushing. Finally, it reaches the densification phase where the load rapidly increases for smaller deformation.

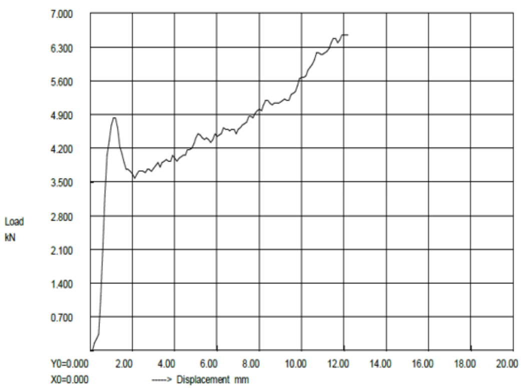


Figure 8. Out of plane compression test (Load (in kN) versus displacement (in mm) curve)

TABLE 2. Compressive strength reduction due to impact

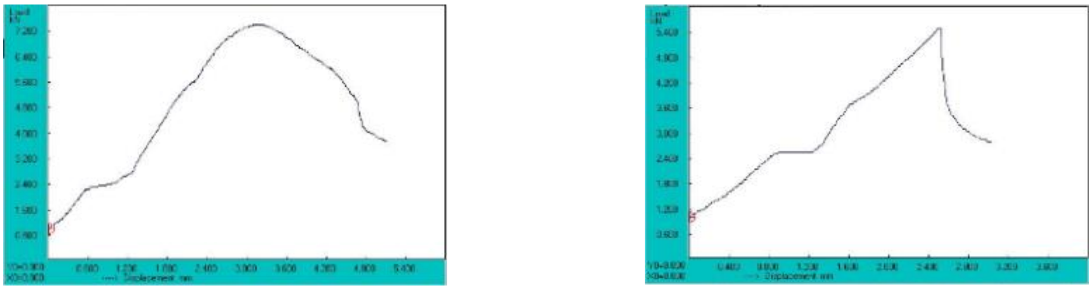
Specimen	Thickness (mm)	Orientation (Degree)	Compression test (KN)	Compression after impact (KN)	Percentage reduction in compressive strength
T1	1.5	$(0/90)_4$	6.7	3.3	50.74
T2	2.5	$(0/90)_6$	8.1	4.1	49.38
P1	3	$(0/90/45/-45)_4$	6.9	5.5	20.28
P2	3	$(0/90/30/-30)_4$	5.8	3.7	36.20

Figure 9. Plastic deformation of honeycomb

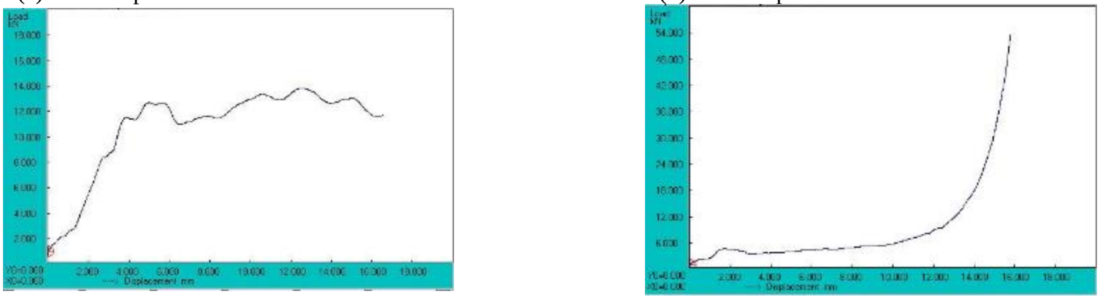
(a1) Impact at 47 J (a2) CAI at 47 J (c1) Non impacted specimen (c2) Inplane compression

(b1) Impact at 36 J (b2) CAI at 36 J (d1) Without impact (d2) Out of plane compression

Figure 10. Damaged pictures of honeycomb sandwich panels under various loading condition



(a) Load displacement curve for CAI at 47 J (b) Load displacement curve for CAI at 36 J



(c) Load displacement curve for non impacted specimen (d) Out of plane compression

Figure 11. Typical load (in kN)-displacement(in mm) curve under various loading

TABLE 3. Compressive strength reduction for different impact energies

Specimen ID	Maximum force Fmax (KN)	Displacement at Fmax (mm)	Compressive strength (MPa)	Percentage reduction of compressive strength
S1	7.4	3.09	6	50
S2	5.5	2.49	5	58.3
S3	13.8	12.38	12	-
C1	12	14	4.8	-

4. CONCLUSIONS

The ultimate goal of achieving the high strength/stiffness to weight ratio and crashworthy structure for the aerospace applications is attained through honeycomb sandwich composite structures. The significant conclusions made from the present study are mentioned below.

- Densely packed cells with higher cell thickness possess higher fracture energy E*. The contact area is also one of the main significant parameters that decide the damage.
- Due to an impact event, the compressive strength decreases to an enormous degree. Hence significant attention has to be paid for CAI, which may cause

failure during an in-service operation before it reaches the ultimate load.

- Out of plane compression test reveals that the honeycomb undergoes progressive damage and hence honeycomb core with composite face sheets can be used as an energy-absorbing sandwich structure to withstand impact load.
- Thus the present study contributes for the understanding how various parameters affect the characteristics of face sheet indentation and plastic buckling of honeycomb sandwich structures with composite face sheets, which are highly significant in several real-world applications. Present study has been carried out at room temperature, but the study may be extended to analyze the effect at higher temperature, which will be useful for aerospace applications.

5. ACKNOWLEDGEMENT

This research work was supported by the Science Engineering Research Board (SERB), Department of Science & Technology (DST), Government of India (Grant No. ECR/2018/001065) and Prof. T R Rajagopalan fund, SASTRA Deemed to be University. Authors express sincere thanks to the support from SERB-DST and SASTRA Deemed to be University.

6. REFERENCES

1. Mekonnen, B.Y. and Mamo, Y. J., “Tensile and Flexural Analysis of a Hybrid Bamboo/Jute Fiber-reinforced Composite with Polyester Matrix as a Sustainable Green Material for Wind Turbine Blades”, ***International Journal of Engineering, Transactions B: Applications***, Vol. 33, No. 2, (2020), 314-319. https://doi.org/10.5829/IJE.2020.33.02B.16
2. Asyraf, M. R. M., Ishak, M. R., Sapuan, S. M., Yidris, N., Ilyas, R.A., Rafidah, M. and Razman, M. R., “Potential Application of Green Composites for Cross Arm Component in Transmission Tower: A Brief Review”, ***International Journal of Polymer Science***, (2020), 8878300, https://doi.org/10.1155/2020/8878300.
3. Asyraf, M. R. M., Ishak, M. R., Sapuan, S. M., Yidris, N., Ilyas, R.A., Rafidah, M. and Razman, M. R., “Evaluation of Design and Simulation of Creep Test Rig for Full-Scale Crossarm Structure”, ***International Journal of Polymer Science***, (2020), 6980918, https://doi.org/10.1155/2020/6980918.
4. Nurazzi, N. M., Khalina, A., Sapuan, S. M., Ilyas, R. A., Rafiqah, S. A. and Hanafee, Z. M., “Thermal properties of treated sugar palm yarn/glass fiber reinforced unsaturated polyester hybrid composites”, ***Journal of Materials Research and Technology***, Vol. 9, No. 2, (2020), 1606-1618. https://doi.org/10.1016/j.jmrt.2019.11.086.
5. Sapuan, S. M., Aulia, H. S., Ilyas, R. A., Atiqah, A., Dele-Afolabi, T. T., Nurazzi, M. N. and Atikah, M. S. N., “Mechanical properties of longitudinal basalt/woven-glass-fiber-reinforced unsaturated polyester-resin hybrid composites”, ***Polymers***, Vol. 12, No. 10, (2020), 1-14. https://doi.org/10.3390/polym12102211.
6. Aisyah, H. A., Paridah, M. T., Sapuan, S. M., Khalina, A., Berkalp, O. B., Lee, S. H. and Ilyas, R. A., “Thermal Properties of Woven Kenaf/Carbon Fibre-Reinforced Epoxy Hybrid Composite Panels”, ***International Journal of Polymer Science,*** (2019). https://doi.org/10.1155/2019/5258621.
7. Maraki, M. R., Tagimalek, H., Azargoman, M., Khatami, H. and Mahmoodi, M., “Experimental investigation and statistical modeling of the effective parameters in Charpy impact test on AZ31 magnesium alloy with v-shape groove using Taguchi method”, ***International Journal of Engineering Transactions C: Aspects***, Vol. 33, No. 12, (2020), 2521-2529. https://doi.org/10.5829/ije.2020.33.12c.13.
8. Lu, S., Zhao, W., Han, P. and Hang, Z., “Mechanical Behavior of Hybrid Connectors for Rapid-Assembling Steel-Concrete Composite Beams”, ***Civil Engineering Journal***, Vol. 5, No. 10, (2019), 2081-2092. https://doi.org/10.28991/cej-2019-03091395.
9. Kuddus, M. A. and Dey, P. P., “Cost Analysis of RCC, Steel and Composite Multi-Storied Car Parking Subjected to High Wind Exposure in Bangladesh”, ***Civil Engineering Journal***, Vol. 3, No. 2, (2017), 95-104. https://doi.org/10.28991/cej-2017-00000076.
10. Wani, S. B., “Influence of Bi-directional Fibreglass Grid Reinforcement on Drying Shrinkage and Mechanical Properties of Lightweight Foamed Concrete”, ***International Journal of Engineering, Transactions A: Basics***, Vol. 34, No. 1, (2021), 10-18. https://doi.org/10.5829/ije.2021.34.01a.02.
11. Rastegarian, S. and Sharifi, A., “An investigation on the correlation of inter-story drift and performance objectives in conventional RC frames”, ***Emerging Science Journal***, Vol. 2, No. 3, (2018), 140-147. https://doi.org/10.28991/esj-2018-01137.
12. Abbas, J. L. and Allawi, A. A., “Experimental and Numerical Investigations of Composite Concrete-Steel Plate Shear Walls Subjected to Axial Load”, ***Civil Engineering Journal***, Vol. 5, No. 11, (2019), 2402-2422. https://doi.org/10.28991/cej-2019-03091420.
13. Asyraf, M. R. M., Ishak, M. R., Sapuan, S. M., Yidris, N., Shahroze, R. M., Johari, A. N. and Ilyas, R. A., “Creep test rig for cantilever beam: fundamentals, prospects and present views”, ***Journal of Mechanical Engineering and Sciences***, Vol. 14, No. 2, (2020), 6869-6887. https://doi.org/10.15282/jmes.14.2.2020.26.0538.
14. Sohel, K. M. A., Richard Liew, J. Y., Alwis, W. A. M. and Paramasivam, V., “Experimental investigation of low-velocity impact characteristics of steel-concrete-steel sandwich beams”, Steel and ***Composite Structures***, Vol. 3, No. 4, (2003), 289-306. https://doi.org/10.1016/S0263-8223(00)00098-2
15. Cote, F., Deshpande, V. S., Fleck, N. A. and Evans, A. G., “The out-of-plane compressive behaviour of metallic honeycombs”, ***Materials Science and Engineering A***, Vol. 380, No. 1, (2004), 272-280. https://doi.org/10.1016/j.msea.2004.03.051.
16. Sibeaud, J. M., Thamié, L. and Puillet, C., “Hypervelocity impact on honeycomb target structures: Experiments and modelling”, ***International Journal of Impact Engineering***, Vol. 35, No. 12, (2008), 1799-1807. https://doi.org/10.1016/j.ijimpeng.2008.07.037.
17. Jankowiak, T., Rusinek, A., Kpenyigba, K. M. and Pesci, R., “Ballistic behaviour of steel sheet subjected to impact and perforation”, ***Steel and Composite Structures***, Vol. 16, No. 6, (2014), 595-609. https://doi.org/10.12989/scs.2014.16.6.595.
18. Xie, Z., Yan, Q., and Li, X., "Investigation on low-velocity impact on a foam core composite sandwich panel", ***Steel and Composite Structures,*** Vol. 17, No. 2, (2014), 159-172. https://doi.org/10.12989/scs.2014.17.2.159.
19. Zouggar, K., Boukhoulda, F. B., Haddag, B. and Nouari, M., “Numerical and experimental investigations of S-Glass/Polyester composite laminate plate under low energy impact”, ***Composites***

Part B: Engineering, Vol. 89, (2016), 169-186. https://doi.org/10.1016/j.compositesb.2015.11.021.

20. Zhang, D., Fei, Q. and Zhang, P., “Drop-weight impact behaviour of honeycomb sandwich panels under a spherical impactor”, ***Composite Structures***, Vol. 168, (2017), 633-645. https://doi.org/10.1016/j.compstruct.2017.02.053.
21. Elias, A., Laurin, F., Kaminski, M. and Gornet, L., “Experimental and numerical investigations of low energy/velocity impact damage generated in 3D woven composite with polymer matrix”, ***Composite Structures***, Vol. 159, (2017), 228-239. https://doi.org/10.1016/j.compstruct.2016.09.077.
22. Schroder, S., Reinhardt, B., Brauner, C., Gebauer, I. and Buchwald, R., “Development of a Marslander with crushable shock absorber by virtual and experimental testing”' ***Acta Astronautica***, Vol. 134, (2017), 65-74. https://doi.org/10.1016/j.actaastro.2017.01.023.
23. Mars, J., Chebbi, E., Wali, M. and Dammak, F., "Numerical and experimental investigations of low-velocity impact on glass fiber-reinforced polyamide” ***Composites Part B: Engineering,*** Vol. 146, (2018), 116-123. https://doi.org/10.1016/j.compositesb.2018.04.012.
24. Palomba, G., Epasto, G., Crupi, V. and Guglielmino, E., “Single and double-layer honeycomb sandwich panels under impact loading”, ***International Journal of Impact Engineering***, Vol. 121, (2018), 77-90. https://doi.org/10.1016/j.ijimpeng.2018.07.013.
25. Sun, G., Chen, D., Wang, H., Hazell, P. J. and Li, Q., “High-velocity impact behaviour of aluminium honeycomb sandwich panels with different structural configurations”, ***International Journal of Impact Engineering***, Vol. 122, (2018), 119-136. https://doi.org/10.1016/j.ijimpeng.2018.08.007.
26. Xie, W. H., Meng, S. H., Ding, L., Jin, H., Du, S. Y., Han, G. K. and Chi, R. Q., “High-temperature high-velocity impact on honeycomb sandwich panels”, ***Composites Part B: Engineering,*** Vol. 138, (2018), 1-11. https://doi.org/10.1016/j.compositesb.2017.06.022.
27. Mertani, B. M. B., Keskes, B. and Tarfaoui, M., “Experimental Analysis of the Crushing of Honeycomb Cores Under Compression”, ***Journal of Materials Engineering and Performance***, Vol. 28, No. 3, (2019), 1628-1638. https://doi.org/10.1007/s11665-018-3852-2.
28. Babaei, H., "Prediction of deformation of circular plates subjected to impulsive loading using gmdh-type neural network", ***International Journal of Engineering-Transactions A: Basics***, Vol. 27, No. 10, (2014), 1635. https://doi.org/10.5829/idosi.ije.2014.27.10a.18.

Persian Abstract

چکیده

سازه های هوافضا در برابر بارهای ضربه ای که تحمل خسارت دارند و مقاومت آن در دامنه سرعت ضربه بسیار آسیب پذیر است. سازه های ساندویچی لانه زنبوری در صنایع هوافضا مورد استفاده قرار می گیرند که سازه های کارآمد در برابر جرم و مقاوم در برابر ضربه مورد نیاز است. با این حال ، یکپارچگی سازه ای این سازه ها به دلیل افت ابزار ، بقایای باند ، سنگ های تگرگ و کار با نامناسب سازه در اثر ضربه کاهش می یابد. بررسی دقیق رفتار آسیب ساندویچ لانه زنبوری تحت تأثیر سرعت کم و تعیین مقاومت پسماند پس از ضربه برای طراحی یک ساختار سبک خراب لازم است. در این مقاله ارزیابی تجربی جذب انرژی خاص با استفاده از ضربه شارپی ، مقاومت فشاری باقیمانده توسط فشار پس از ضربه و ارزیابی آسیب ساختارهای ساندویچ لانه زنبوری دارای ورق های ترکیبی صورت ارائه شده است. مطالعات پارامتریک در مورد کامپوزیت ها و لانه زنبوری ها با تغییر اندازه سلول ، ضخامت سلول ، ارتفاع هسته ، سرعت برخورد ، ضخامت و جهت گیری لایه ها انجام می شود. شانه های عسلی ضخیم بسته بندی شده انرژی شکستگی بالاتری را ایجاد می کنند. تحت بارگذاری فشاری عرضی ، هسته لانه زنبوری تحت کمانش ، خرد شدن و تراکم دیواره سلول قرار می گیرد. سابقه جابجایی بار تحت فشار و فشرده سازی درون صفحه ای پس از ضربه برای انرژی های مختلف ضربه مشاهده می شود. مطالعه حاضر به درک چگونگی پارامترهای مختلف بر خصوصیات تورفتگی ورق صورت و کمانش پلاستیکی ساختارهای ساندویچ لانه زنبوری با ورق های کامپوزیت صورت کمک می کند ، در نتیجه راهنماهای مفیدی برای کاربردهای بالقوه آن در مهندسی ضربه ارائه می دهد.