Modelling and Simulation of Compression Behaviour of 3D Woven Hollow Composite Structures Using FEM Analysis

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ABSTRACT

Three-dimensional (3D) woven spacer composites have the advantage of being lightweight and strong for use in various segments of structural engineering and automobiles due to their superior mechanical properties than conventional counterparts. In this investigation, the influence of different cell geometries of 3D woven spacer fabrics, namely rectangular, triangular and trapezoidal with woven cross-links, upon their mechanical behaviours, especially compression energy, was studied through FEM (finite element method). Cell geometries were changed into different heights and widths and evaluated through simulation and experiments. Simulation of the structure was carried out by the Abaqus platform, and validation of the results was done for the rectangular structure. It was found that compression energy increases with an increment in width, while initially, it shows the tendency to increase and subsequently decrease with an increment in height for the rectangular structure. Compression energy increases with an increase in the angle of the triangular structure; however, it shows the opposite trend in the case of the trapezoidal structure. The outcome of the result shows good agreement between simulation and experimentation values of more than 94% accuracy.

KEYWORDS

3D woven spacer fabric, cell geometry, lightweight composites, compression energy, simulation

INTRODUCTION

In the broad spectrum of novel engineering studies, researchers are using composites, which have become an inevitable alternative because of their favourable properties and superior integrity over their conventional counterparts. Excellent durability, high-bending stiffness, thermal insulation, the resistance of high skin-core debonding, acoustic damping, and secure processing make sandwich structures vastly accessible and preferable than isotropic components in varied and sophisticated industries like aerospace, locomotives, automobiles, structural engineering, windmills, and marine. In composite research, a distinct inclination towards low cost ‘‘out-of-autoclave’’ manufacturing methods has recently come into trend, especially in the aerospace and vehicle industry, for producing different components with superior structural integrity, high energy absorption and minimal delamination, as well as exploring the potentiality of the robotic manufacturing processes [1–6]. These structures are becoming popular as an integrated part of the automotive industry as it is shifting towards electric vehicle (EV) manufacturing to reduce carbon footprint from the environment by nulling fossil fuel consumption, where the reduction in weight of the vehicle compliments with low engine energy consumption, desired speed per hour, larger pay loads, and sustainable economy [7]. Typical sandwich structures are made of a variety of core materials like honeycomb core, expanded polymeric foams, and balsa wood, which have low density and face sheets of high modulus [8]. Although those core materials have the benefits of being lightweight and having superior damage resistance, the limited surface area of the poorly bonded face-core interface and physical dissimilarity cause delamination inexorably under external impacts [9, 10]. Sandwich composites made of fibrous preforms have a few obstacles if they are manufactured by the stitching process. Stitching allows the sewing needle to pierce the preform and damages the fibres in the piled fabric layers, which entangle with stitched thread. Consequently, the resin gets drained from the rich resin areas at the resin infusion stage. However, weaving and knitting methods can be the alternative for producing consolidated sandwich structures without damaging fibres in stacking the fabric and compromising with a fibrous resin matrix, which may lead to delamination. These three-dimensional (3D) sandwich structures are also known as woven/knitted spacer or hollow fabrics [8, 11–16]. Through weaving technology, near net shape preforms can be made by eliminating any joining steps. 3D woven spacer fabrics are constructed with pile yarns or fabrics, which maintain hollow space between layers [17–19]. 3D woven spacer composites have better compression and shear features than conventional counterparts [20, 21].

Furthermore, compression and low-velocity impact study were carried out by Vaidya et al., where it was found that with the increment of thickness and the presence of core piles in 3D woven spacer composites, the peak load and fracture under compression and low-velocity impact reduced respectively [22, 23]. Belingardi et al. investigated that the sandwich structures which incorporate resin net walls in the foam core can be sustained in a remarkable increment of the dynamic impact response [24, 25]. Furthermore, Torre et al. talked about ridged cores in their research, where cores are made of the same material as the face sheets. The channelled cores were filled with phenolic foams in the sandwich composites, which performed exponentially well than their conventional counterparts [26]. An extensive study was carried out by several researchers regarding the influence of the presence of corrugated cores in the sandwich structures. Jin et al. recorded very high delamination resistance of sandwich structures, which were incorporated with ridged cores along with face and bottom surfaces in his studies [27]. These corrugated cores enhance the mechanical performance of spacer structures such as high resistance to bending deformation, especially over the direction of corrugation. Therefore, woven cross-links in spacer woven composites can withstand better under bending loads than the structures connected with yarns [19, 28, 29]. Different geometrical shapes such as triangular [30, 31], trapezoidal [19], and rectangular [32, 33] can be found in the woven spacer composites which have core-face interfaces and are connected with woven cross-links. The structures may consist of a single layer of the same cell or multiple layers of cells vertically [19]. However, it is necessary to study the mechanical behaviour of different structures of the spacer composite through simulation [34].

In this research work, the compression energy of the sandwich structure with different cell geometrical shape was predicted through simulation by using the Abaqus platform. The dimensions of cell shapes were also varied within the shape, such as height, width, and angle, to find their effect on compression energy. The model is validated experimentally by analysing the rectangular spacer sample with different cell structural parameters.

EXPERIMENT

Materials and Methods

Materials

A composite sandwich structure of the rectangular shape was manufactured from 3D woven spacer fabrics which have woven cross-links. Rectangular structures of different height and width were produced from E-glass tow of 600 Tex. A customized weaving machine was used to produce the fabric. Epoxy (LY556) resin and hardener Aradur HY951 were used to form the composite.

Production of spacer fabric and composite manufacturing

The primary requirement to produce the fabric is the weave design. The cross-sectional representation of the rectangular structure is shown in figure 1. The structure has a connecting fabric layer and two skin fabrics. The number of picks changed the cell dimensions of the fabric. EPI and PPI of the single-walled fabric was 10x10 and when the layers combined to form a double layer, then EPI becomes 20, and PPI remains the same.

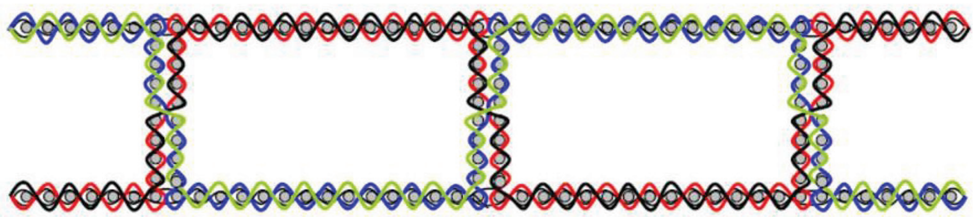


Figure 1. Cross-sectional representation of a rectangular structure

Vacuum-assisted resin infusion moulding technique (VARIM) was used to make the composite structure, in which resin impregnates the fabric. Customized wooden blocks were used to make the composites. They were inserted inside the cavities of the fabric according to the requirement of the shape of the structure. Teflon paper was wrapped around these wooden blocks so that during resin impregnation fabric would not stick to the blocks. Figure 2 shows the composite structure produced in the rectangular shape.

Figure 2. Composite sample of the rectangular structure

Lateral compression test

Lateral compression testing of rectangular composite samples was carried out on a universal testing machine (Instron 5982) shown in figure 3, according to the ASTM365 method. The speed of testing was 2 mm/min at the quasi-static loading rate. This test method covers the determination of compressive strength and modulus of sandwich cores. These properties are usually determined for design purposes in a direction normal to the plane of facings as the core would be placed in structural sandwich construction.

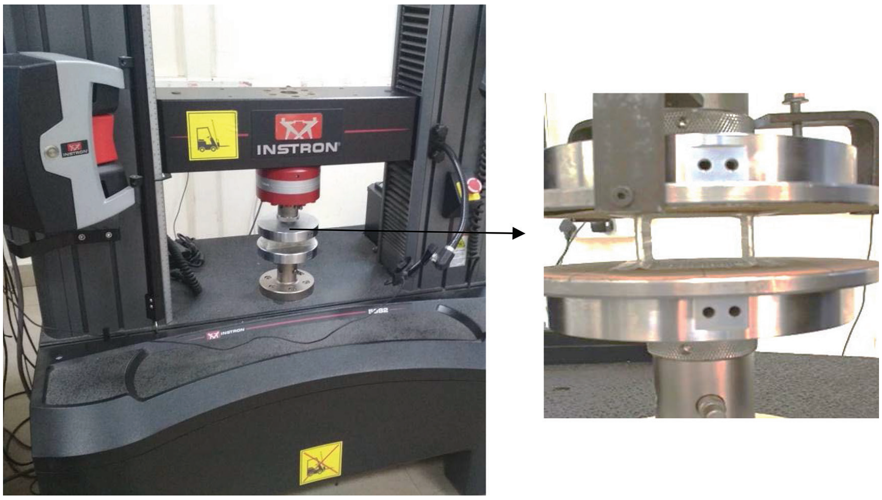


Figure 3. Experimentation setup for the compression test

Development of the 3D model through FEM

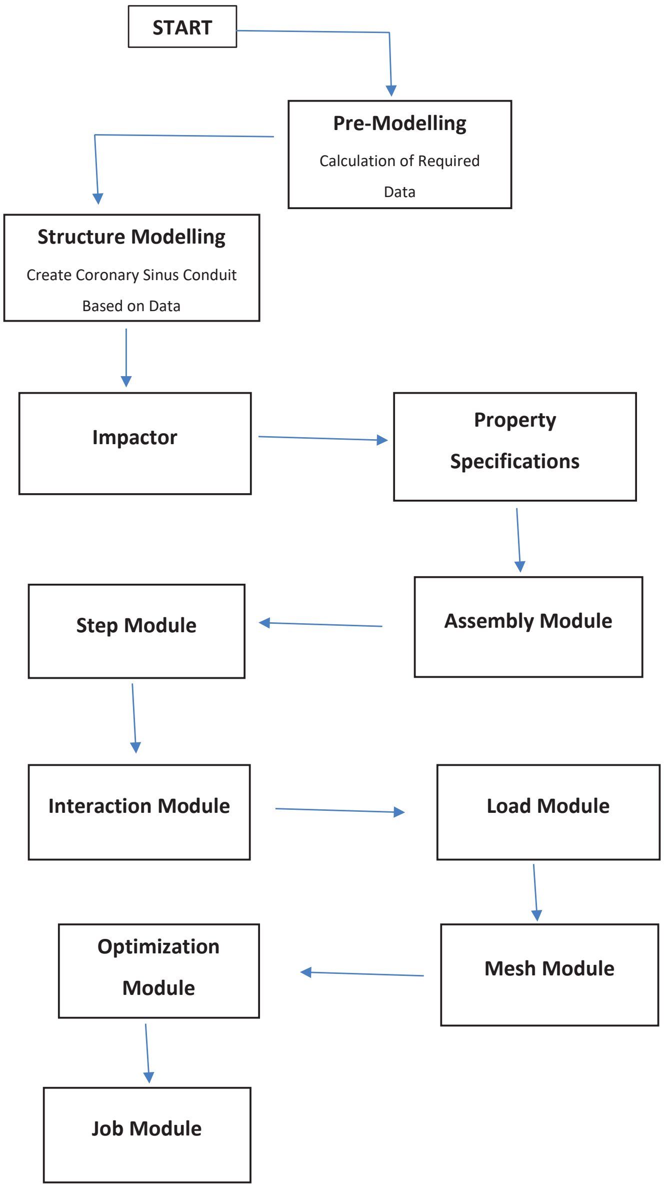


Figure 4. Steps for the modelling of the 3D hollow structure

The compression energy of the textile preforms depends on various parameters which can be categorized as:

1. Mechanical properties of the composite (elastic modulus, shear modulus)
2. Structural properties
3. Geometry parameters
4. Structure surface condition.

Three-dimensional models of different structures were developed using Solid Works. Then this model was imported to the Abaqus platform for the simulation of all the structures. The following physical properties like density, elastic moduli, Poisson's ratio, and bending properties of the composite structure were entered as input parameters. Meshing tool was used to mesh the 3D model structures. It is the process of converting complex structures into thousands of finite elements. The boundary condition of fixed support is to be imposed on the structure for finding out the solution of the structure, and compression energy was calculated using the Finite Element Method (FEM). Steps for the simulation of the 3D hollow structure on the Abaqus platform is shown in figure 4. Figure 5 has shown the stepwise development of a 3D woven hollow composite structure and its behaviour under compression by using the Abaqus platform.

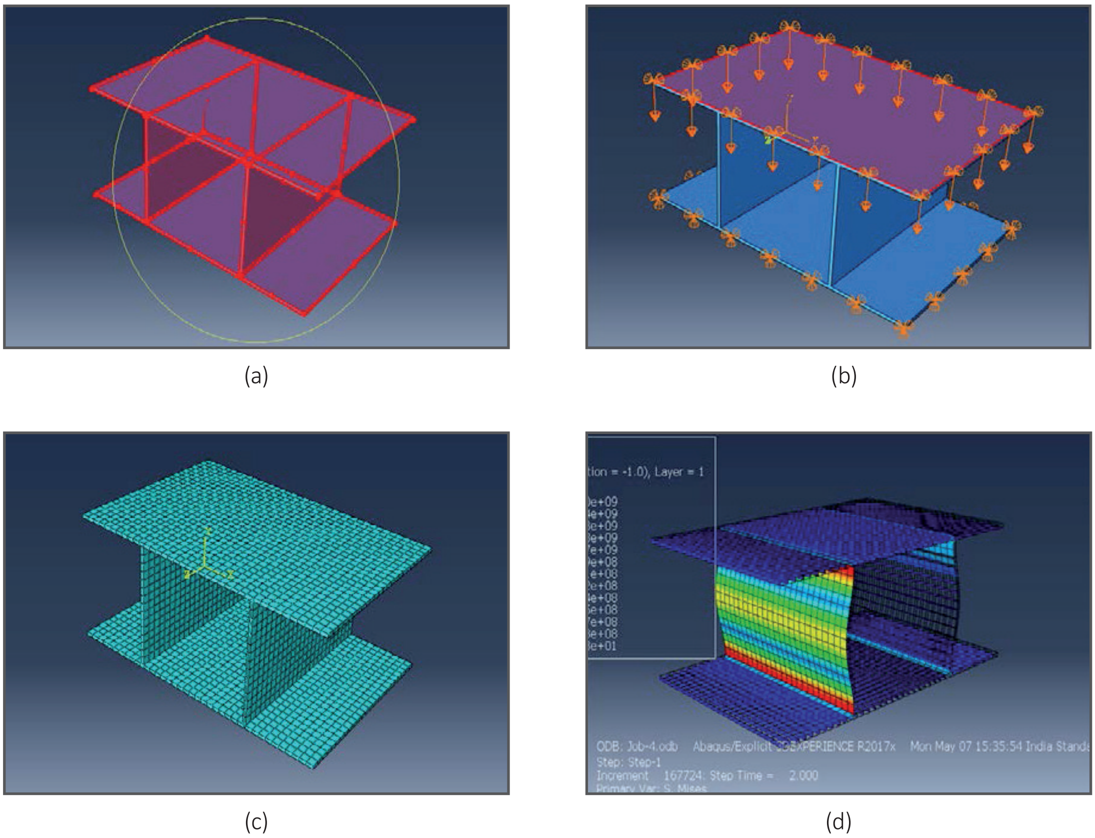


Figure 5. Compression behaviour analysis by simulation (a) Developed 3D model with input parameters (b) Applying node values (c) Meshing (d) Deformation of the structure under simulation

RESULTS AND DISCUSSION

Compressional behaviour of the rectangular structure

The compression energy was calculated from the area under the curve of stress-strain by using equation 1 until the first peak, because after the first peak the material starts to yield or break both in the case of experiment (as shown in figure 6) and simulation.

Compression energy (joule, J) $=\int_0^{\mathcal{E}} \sigma(\mathcal{E})d\mathcal{E}$ Equation 1

Where σ =stress, Ɛ= strain

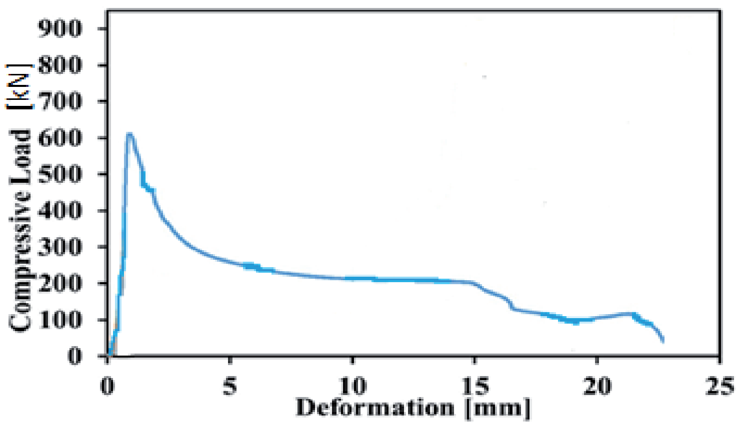


Figure 6. Stress strain curve behaviour of rectangular structure determined experimentally

FEM Analysis

The 3D model developed in the Solidwork platform was imported to the Abaqus platform, as shown in figure 7. After that, a simulation was performed, and lateral compression was applied, as shown in figure 8, to get the desired results with proper constraints and settings for the structure. In this way, simulations of other structures, namely rectangular, trapezoidal, and triangular shape composites of different dimensions, were also carried out.

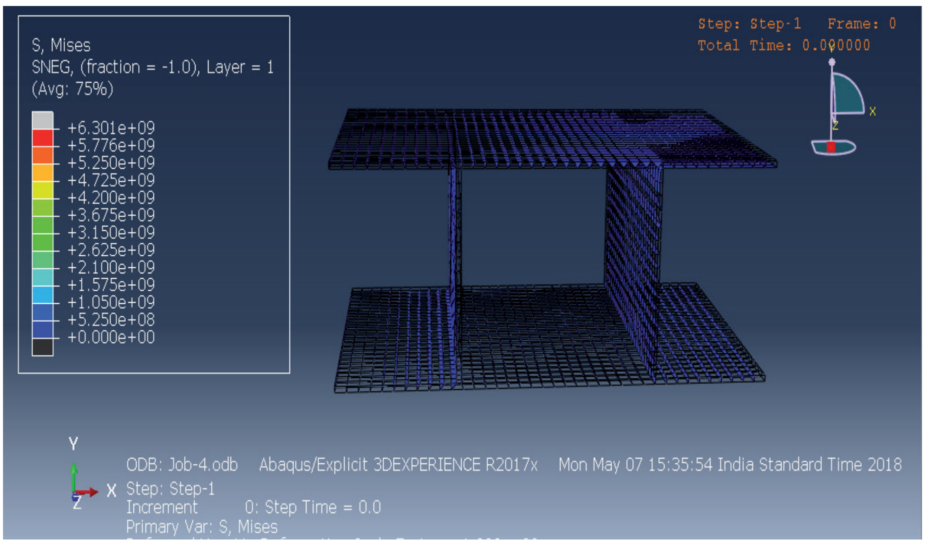


Figure 7. 3D model on the Abaqus platform

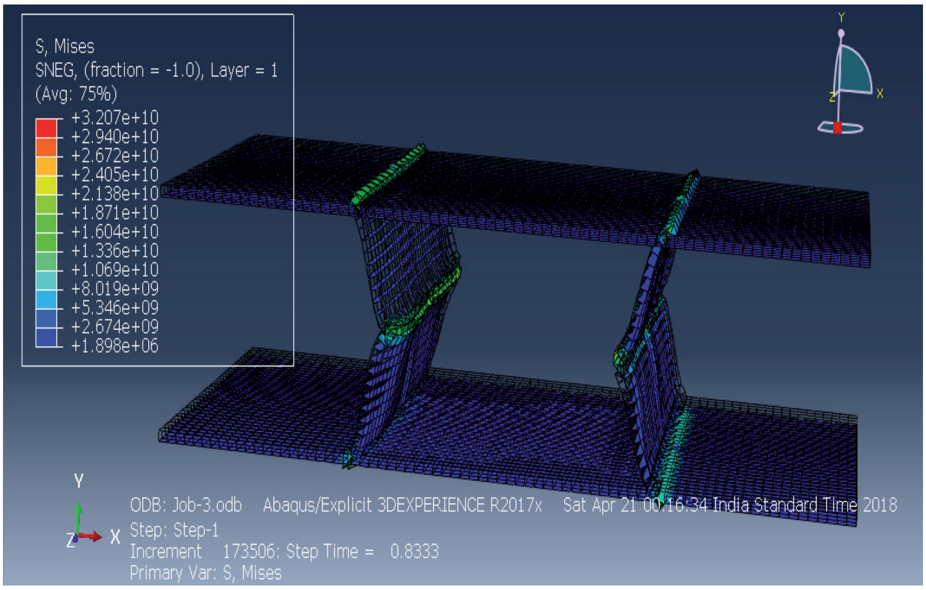
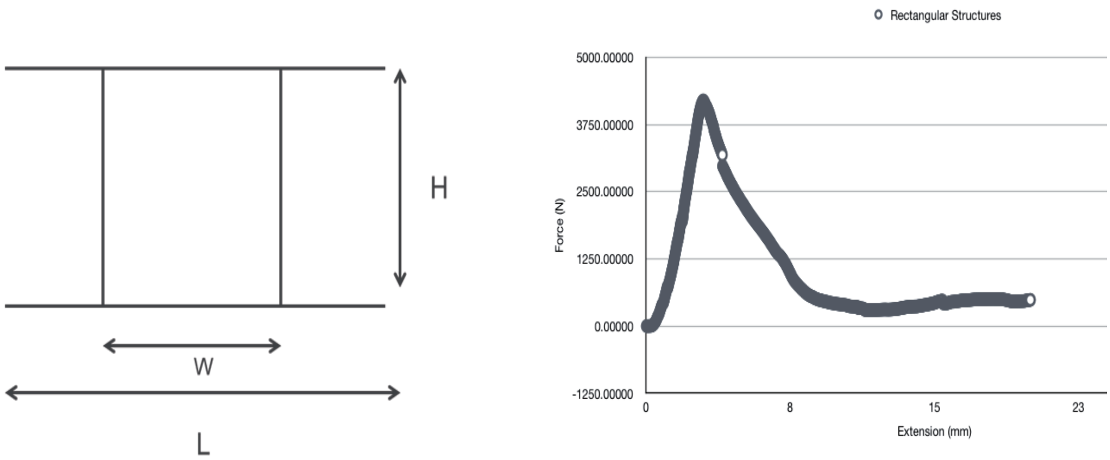


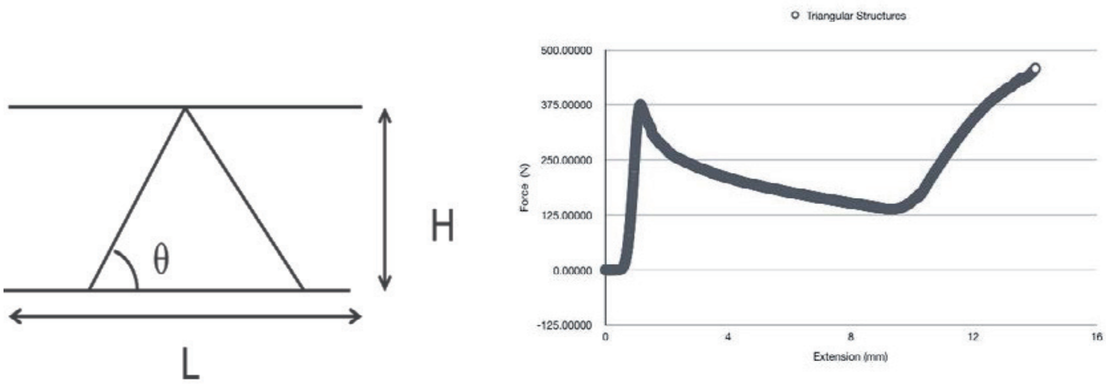
Figure 8. Simulation of rectangular composite structure

The stress strain graphs obtained from the simulation performed to calculate the compression energy of different structures are shown in figures 9, 10 and 11 respectively.



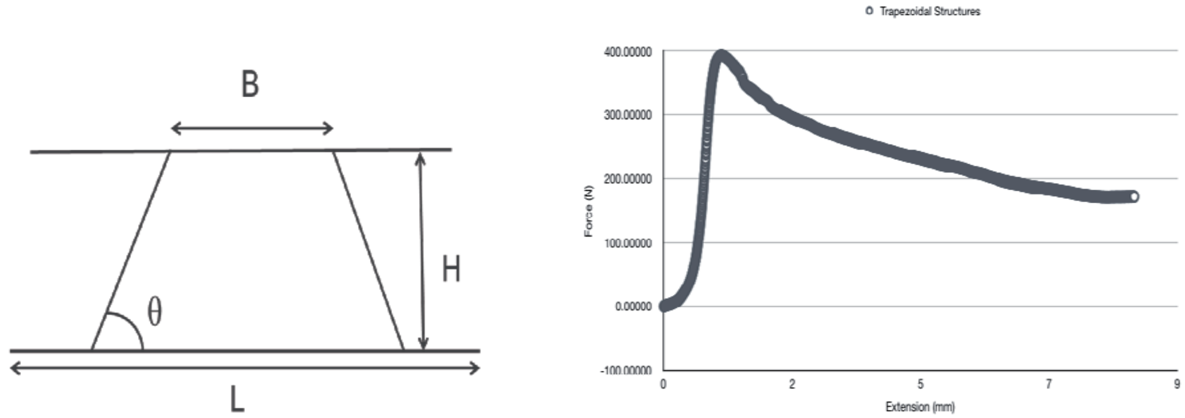
(a) (b)

Figure 9. Rectangular structure (a) Schematic diagram (b) Stress-strain graph by simulation



(a) (b)

Figure 10. Triangular structure (a) Schematic diagram (b) Stress-strain graph by simulation



(a) (b)

Figure 11. Trapezoidal structure (a) Schematic diagram (b) Stress-strain graph by simulation

Prediction of compression energy

Rectangular structures

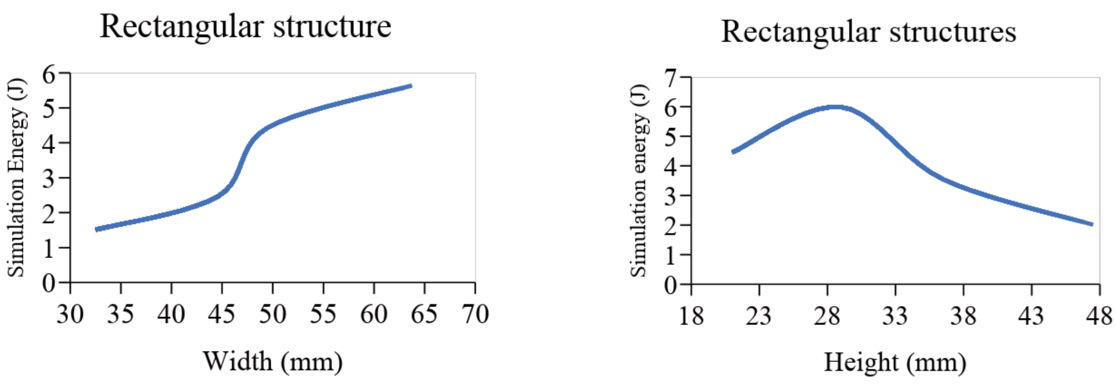
In rectangular structures, width and height of the structure are varied and finally the results obtained both from the experiment and the simulation are given in table 1 and table 2. Table 1 gives the compression energy for different widths of the composite cell at the constant height, whereas table 2 shows the energy values for different cell heights at the constant width. Figure 12 (a) and (b) show that compression energy increases with increase in width, while, with increase in height, energy initially increases and then decreases. This behaviour reveals that the composite cell under compression load becomes unstable after a certain height and then starts buckling.

Table 1. Compression energy of rectangular structures with variation in width

S. No.	Length(L) (mm)	Width(W) (mm)	Height(H) (mm)	Energy(J) (Experimentation)	Energy(J) (Simulations)
1	51	32.5	30	1.6	1.5
2	69	44.6	30	2.5	2.5
3	76	49.5	30	4.6	4.4
4	97.5	63.8	30	5.7	5.6

Table 2. Compression energy of rectangular structures with variation in height

S. No.	Width(W) (mm)	Height(H) (mm)	Length(L) (mm)	Energy(J) (Experimentation)	Energy(J) (Simulations)
1	50	21	74	4.6	4.5
2	50	29	76	6.1	6.0
3	50	36.5	78	3.4	3.5
4	50	47.5	78	2.0	2.0



(a) (b)

Figure 12. Simulation energy of rectangular structure by varying (a) width (b) height

Triangular structure

In the triangular structure, compression energy was found out by simulation for various angles of the cell structure. The results obtained from the simulation are given in table 3 for different dimensions and figure 13 shows that with increase in angle, compression energy increases.

Table 3. Compression energy of triangular structures with variation in the cell angle

S No	Length(L) (mm)	Height(H) (mm)	Angle(θ) (degree)	Simulation Energy (J)
1	100	27	35	0.16
2	83.0	27	43	0.22
3	70	27	47	0.27

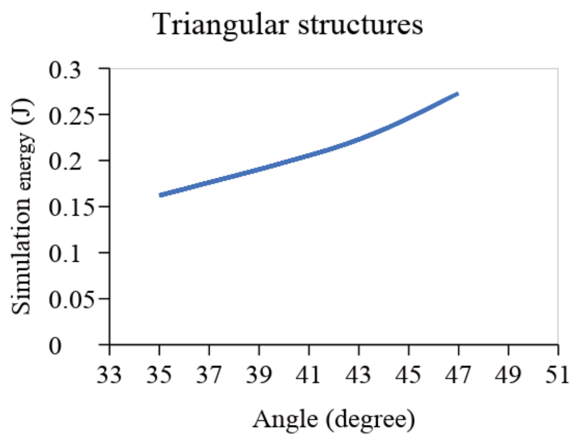


Figure 13. Simulation energy of the triangular structure by varying angle

Trapezoidal structure

In the trapezoidal structure, compression energy was found out by simulation for different cell angles. The obtained results are given in table 4 for different dimensions. Figure 14 shows that with the increase in angle, compression energy decreases.

Table 4. Compression energy of trapezoidal structures with variation in angle

S. No.	Base(B) (mm)	Height(H) (mm)	Angle (θ) (degree)	Length(L) (mm)	Simulation Energy (J)
1	28.25	28	45	96	0.49
2	28.8	28	50.5	85	0.45
3	31.5	28	57	85	0.34
4	28.6	28	65	67.5	0.22

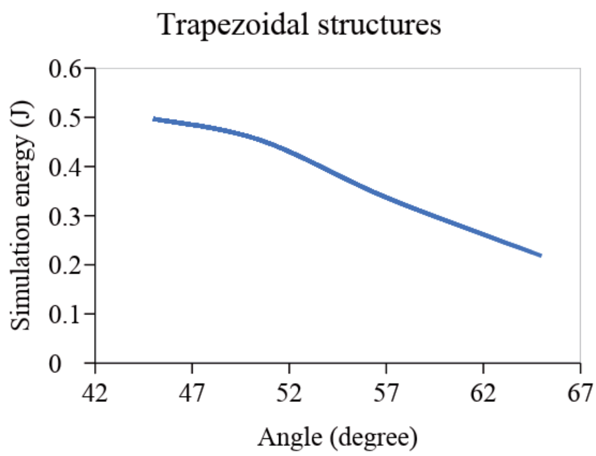


Figure 14. Simulation energy of the trapezoidal structure by varying angle

Validation of the simulation results

In order to validate the simulation result, the experimentation and predicted values of compression energy of the rectangular shaped hollow composite structure were plotted in a bar chart. Figure 15 and figure 16 show the results for different widths and heights of the rectangular cell respectively. It may be observed from the figures that there is a good agreement between the simulation and experimentation results with prediction accuracy of more than 94%.

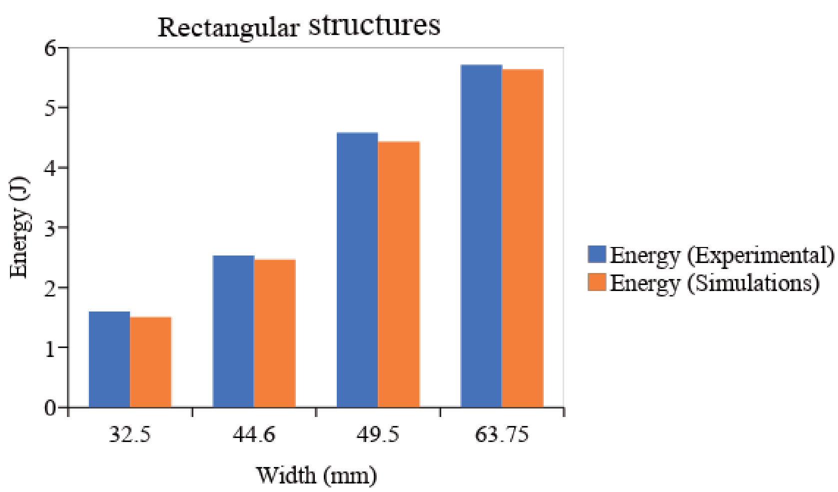


Figure 15. Comparison of experimentation and simulation results for rectangular structures of different width

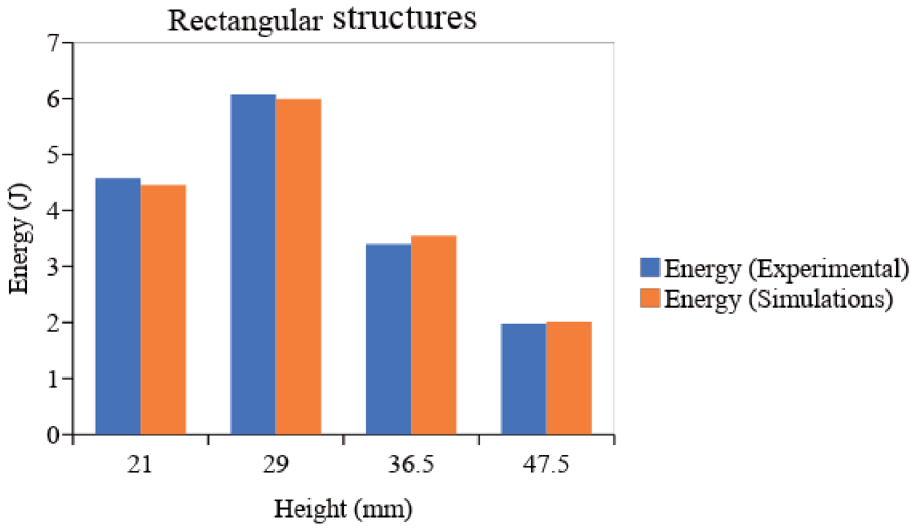


Figure 16. Comparison of experimentation and simulation results for rectangular structures of different height

CONCLUSION

Compression energy for a sandwich structure is very crucial for the overall performance of the composite. Among various mechanical parameters, compression energy shows influence over the changes of cell geometries of the crosslinks in hollow structures. Therefore, for the numerical study of sandwich structures, different geometrical cell shapes were developed on Solidworks and subsequently imported to the Abaqus platform to predict the compression energy by FEM. The compression behaviour of hollow structures of different cell shapes and different dimensions within the same shapes were studied, and compared with the experimentation data of the rectangular shape for rationalizing. The results show that the compression energy increases with an increment in the width of the rectangular cell, whereas it initially increases with the increment of the cell height and decreases after a specified height while the cell becomes unstable as well. In the case of a triangular structure, compression energy increases with the increase of angle. However, in trapezoidal structures the energy decreases with the increase in angle. The consistency in trends in the simulation and experimentation data signifies the reliability of the results obtained with a prediction accuracy of more than 94%.

REFERENCES

[1] Li M, Wang S, Zhang Z, Wu B. Effect of structure on the mechanical behaviours of three-dimensional spacer fabric composites. Appl Compos Mater. 2009 Feb;16(1):1–14.

[2] Mouritz AP, Cox BN. A mechanistic interpretation of the comparative in-plane mechanical properties of 3D woven, stitched and pinned composites. Compos Part A Appl Sci Manuf. 2010 Jun;41(6):709–28.

[3] Bogdanovich AE, Karahan M, Lomov S V., Verpoest I. Quasi-static tensile behaviour and damage of carbon/epoxy composite reinforced with 3D non-crimp orthogonal woven fabric. Mech Mater. 2013; 62:14–31.

[4] Choi SW, Li M, Lee W Il, Kim HS. Analysis of buckling load of glass fibre/epoxy-reinforced plywood and its temperature dependence. J Compos Mater [Internet]. 2014 Aug 19 [cited 2020 Jan 18];48(18):2191–206. Available from: http://journals.sagepub.com/doi/10.1177/0021998313495071

[5] Awerbuch J, Madhukar MS. Notched Strength of Composite Laminates: Predictions and Experiments—A Review. Vol. 4, Journal of Reinforced Plastics and Composites. 1985. p. 3–159.

[6] Toribio MG, Spearing SM. Compressive response of notched glass-fibre epoxy/honeycomb sandwich panels. Compos - Part A Appl Sci Manuf. 2001 Jun 1;32(6):859–70.

[7] Potluri P, Kusak E, Reddy TY. Novel stitch-bonded sandwich composite structures. Compos Struct. 2003 Feb;59(2):251–9.

[8] Karlsson KF, Åström BT. Manufacturing and applications of structural sandwich components. Compos Part A Appl Sci Manuf. 1997;28(2):97–111.

[9] Vaidya AS, Vaidya UK, Uddin N. Impact response of three-dimensional multifunctional sandwich composite. Mater Sci Eng A. 2008 Jan 15;472(1–2):52–8.

[10] Vaidya UK, Nelson S, Sinn B, Mathew B. Processing and high strain rate impact response of multi-functional sandwich composites. Compos Struct. 2001 May;52(3–4):429–40.

[11] Neje G, Behera BK. Lateral Compressive Properties of Spacer Fabric Composites with Different Cell Shapes. Appl Compos Mater. 2018 Aug 1;25(4):725–34.

[12] Mouritz AP, Leong KH, Herszberg I. A review of the effect of stitching on the in-plane mechanical properties of fibre-reinforced polymer composites. Compos Part A Appl Sci Manuf. 1997;28(12): 979–91.

[13] Maschinenwesen F. Development of the Weaving Machine and 3D Woven Spacer Fabric Structures for Lightweight Composites Materials.

[14] Arumugam V, Mishra R, Tunak M, Militky J. In-plane shear behaviour of 3D warp-knitted spacer fabrics: Part II—Effect of structural parameters. J Ind Text [Internet]. 2018 Oct 9 [cited 2020 Jan 19];48(4):772–801. Available from: http://journals.sagepub.com/doi/10.1177/1528083717747332

[15] Abounaim M, Hoffmann G, Diestel O, Cherif C. Thermoplastic composite from innovative flat knitted 3D multi-layer spacer fabric using hybrid yarn and the study of 2D mechanical properties. Compos Sci Technol. 2010 Feb;70(2):363–70.

[16] Hassanzadeh S, Hasani H, Zarrebini M. Thermoset composites reinforced by innovative 3D spacer weft-knitted fabrics with different cross-section profiles: Materials and manufacturing process. Compos Part A Appl Sci Manuf. 2016 Dec 1; 91:65–76.

[17] Mouritz AP, Bannister MK, Falzon PJ, Leong KH. Review of applications for advanced three-dimensional fibre textile composites. Compos Part A Appl Sci Manuf. 1999;30(12):1445–61.

[18] Xiaogang Chen, Taylor LW, Tsai L-J. An overview on fabrication of three-dimensional woven textile preforms for composites. Text Res J [Internet]. 2011 Jun 26 [cited 2020 Jan 19];81(9):932–44. Available from: http://journals.sagepub.com/doi/10.1177/0040517510392471

[19] Chen X, Wang H. Modelling and computer-aided design of 3D hollow woven reinforcement for composites. J Text Inst. 2006;97(1):79–87.

[20] Styles M, Compston P, Kalyanasundaram S. The effect of core thickness on the flexural behaviour of aluminium foam sandwich structures. Compos Struct. 2007 Oct;80(4):532–8.

[21] Lacy TE, Hwang Y. Numerical modelling of impact-damaged sandwich composites subjected to compression-after-impact loading. Compos Struct. 2003;61(1–2):115–28.

[22] Vaidya UK, Hosur M V., Earl D, Jeelani S. Impact response of integrated hollow core sandwich composite panels. Compos Part A Appl Sci Manuf. 2000;31(8):761–72.

[23] Fan H, Yang W, Zhou Q. Experimental research of compressive responses of multi-layered woven textile sandwich panels under quasi-static loading. Compos Part B Eng. 2011 Jul;42(5):1151–6.

[24] Belingardi G, Cavatorta MP, Duella R. Material characterization of a composite-foam sandwich for the front structure of a high speed train. Compos Struct. 2003;61(1–2):13–25.

[25] Vinson JR. Sandwich structures. Appl Mech Rev. 2001;54(3):201–14.

[26] Torre L, Kenny JM. Impact testing and simulation of composite sandwich structures for civil transportation. Compos Struct. 2000;50(3):257–67.

[27] Jin F, Chen H, Zhao L, Fan H, Cai C, Kuang N. Failure mechanisms of sandwich composites with orthotropic integrated woven corrugated cores: Experiments. Compos Struct. 2013 Apr; 98:53–8.

[28] Van Vuure AW, Ivens JA, Verpoest I. Mechanical properties of composite panels based on woven sandwich-fabric preforms. Compos Part A Appl Sci Manuf. 2000;31(7):671–80.

[29] Yokozeki T, Takeda S ichi, Ogasawara T, Ishikawa T. Mechanical properties of corrugated composites for candidate materials of flexible wing structures. Compos Part A Appl Sci Manuf. 2006 Oct;37(10): 1578–86.

[30] Torun AR, Mountasir A, Hoffmann G, Cherif C. Production principles and technological development of novel woven spacer preforms and integrated stiffener structures. Appl Compos Mater. 2013 Jun;20(3):275–85.

[31] US3090406A - Woven panel and method of making same - Google Patents [Internet]. [cited 2020 Jan 19]. Available from: https://patents.google.com/patent/US3090406A/en

[32] Badawi SS. Development of the Weaving Machine and 3D Woven Spacer Fabric Structures for Lightweight Composites Materials. 2007;186. Available from: http://www.qucosa.de/fileadmin/data/qucosa/documents/761/1195729741274-9389.pdf

[33] Torun AR, Hoffmann G, Ünal A, Cherif C. Spacer fabrics from hybrid yarn with fabric structures as spacer. ICCM Int Conf Compos Mater. 2007;1–5.

[34] Dou R, Qiu S, Ju Y, Hu Y. Simulation of compression behaviour and strain-rate effect for aluminium foam sandwich panels. Comput Mater Sci. 2016 Feb 1; 112:205–9.