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Effect of foil thickness and cell size of honeycomb on energy absorption of aluminium honeycomb sandwich composite (Charpy Test)

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Sandwich composites are special class of materials because of peculiar properties such as lightweight, high energy absorbing capacity, and high damping, etc. These properties make them suitable for their use in aerospace and marine industry. Generally, metal or FRP sheets are used as skin/face sheet and honeycomb, foam and balsa wood, etc. are used as core materials. The elastic properties of the honeycomb are the function of foil thickness and cell size. In the present study, the effect of parameters (Foil thickness and Cell size) of the honeycomb on the energy absorption capacity of the sandwich composite was investigated through experimental and numerical studies. Experiments were carried out on four sandwich composites having a variable combination of foil thickness, and cell size by using the Charpy ASTM E-23 machine. Further, numerical analyses were carried out using finite element (FE) software Abaqus. The experimental and numerical results were found to be in good agreement. The results show that energy absorption to mass ratio increases with the increase in foil thickness and with the decrease in cell size. For the improvement of energy absorption to mass ratio, the effect of change in the foil thickness is significant compared to that of change in cell size. Failure mechanism was discussed through numerical study. The impact force resisted by the sandwich composites was presented by using the impulse-momentum equation.

Keywords: Cell size, Charpy test, Foil thickness, Honeycomb, Sandwich composite

1 Introduction

The conventionally used materials in the shipbuilding industry are wood, FRP, and steel. Some of the problems associated with these materials are water absorption, manufacturing process, use of polymers (matrix) for GRP, and corrosion in steel, etc. The aluminum is light in weight and eco-friendly material. Aluminium honeycomb sandwich panels are light in weight and have high energy absorption capacity, bending stiffness, and damping along with no water absorption. These properties make them suitable for use in shipbuilding, aerospace, and automobile industry. The use of honeycomb structures, commonly used for mezzanines and movable car decks is a better solution for applications within the naval field as they facilitate lightweight. These can also be used on high-speed vessels as separating divisions or other secondary structures, where their excellent rigidity to weight ratio can be properly exploited[1]. Moreover, the aluminum products fulfill international maritime organization (IMO) requirements in terms of toxicity, smoke generation, and low flame spread. The face sheet and core of sandwich structures can encompass a myriad of materials, both composite and metallic. They can be used as per the requirements. Carbon fibre reinforced plastic face sheet and nomex or fiberglass honeycomb core are ubiquitous on airplanes and are frequently used as flight control surfaces, such as rudder skin panels, spoilers, elevator trims and for making engine nacelles. Sandwiches of glass fibre-reinforced plastic face sheet and honeycomb core are widely used as fairings and floorboards. Metallic sandwich structures, especially aluminium facesheet over aluminium honeycomb are widely used as slat wedge, trailing edge, and ailerons on aircraft. Mixed composite and metallic sandwiches, including CFRP skin and aluminium honeycomb, have found space applications, and foam-cored sandwich structures are used in helicopter blades and boat building.

Various theories have been proposed for the finite element analysis of sandwich composites. Ferreira *et al.*[2] have presented three-layer sandwich element formulation for linear static analysis with a numerical example. When it comes to the material characteristics of honeycomb, the elastic properties of honeycomb were established based on analytical and numerical approaches[3-6]. Sorohan *et al.*[7] estimated the out of plane shear modulus for the honeycomb core by using

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the finite element approach. It was stated that the elastic properties of the honeycomb structures are the function of foil thickness and cell size. Soliman and Kapania[8-9] have calculated the elastic properties of different shapes of honeycomb by applying nodal displacements in finite element models of different unit cells. The failure modes of sandwich composites have been discussed by several authors. The different forms of failure modes are face yielding, face wrinkling, core shear, core indentation, and delamination[10-11]. Crupi *et al.*[12] have investigated the different collapse mode of the aluminum honeycomb sandwich panel under bending and impact loading.

Levent ugur *et al.*[13] investigated the impact force on aluminium honeycomb sandwich composite by experiment and finite element analysis. Crupi *et al.*[14] compared the static and low-velocity impact response of two aluminium sandwich typologies with the core as honeycomb and foam. It was observed that the aluminum foam sandwich composite absorbs more energy than aluminum honeycomb sandwich composites. Srivastava[15] conducted experiments on the sandwich composite made of GFRP skin and core of polyurethane foam by using test methods of Izod, Charpy, and Drop weight and compared the energy absorbed by the sandwich panels. The experimental results show that the Charpy impactor yields high dynamic fracture toughness compared to that from the tests of Izod and Drop Weight. There is always need to enhance the strengths of the materials. Crupi *et al.*[16] proposed a prediction model for enhancing the impact response of aluminium honeycomb/foam by reinforcing glass fibre into aluminium foam and honeycomb sandwich composite.

Many researchers have worked on various aspects of the honeycomb sandwich composites; there is a limited study on the energy absorption to mass ratio with regards to the effect of the honeycomb parameters such as foil thickness and cell size. There is always an ardent need to employ tougher materials to bear high impact loads. When it comes to the selection of honeycomb parameter to enhance SEA of honeycomb sandwich composites. This study may help the designers to design the sandwich panels. The energy absorption to mass ratio is an important parameter to design any type of structure. In this present work, the effect of these parameters on the energy absorption to mass ratio has been studied by performing experiments and numerical analyses. This study may help to designers for designing the honeycomb sandwich structures.

2 Sandwich composite and honeycomb

Sandwich composites are fabricated by attaching two thin and stiff face sheets/skins to a lightweight thick core. The cellular solids are special class of materials having useful properties such as lightweight, high energy absorbing capacity, etc. A typical diagram of the sandwich structure is shown in Fig. 1.

A sandwich structure can be idealized as an I-Section. Therefore approximate and actual bending and shear stress distributions are shown in Fig. 2. A typical honeycomb structure and unit cell are shown in Fig. 3.

From the unit cell analysis of honeycomb[5], the elastic properties are found to be the function of foil thickness and cell size.

$$Elastic\ Properties = f\left(\frac{t}{l}\right) \qquad \ldots(1)$$

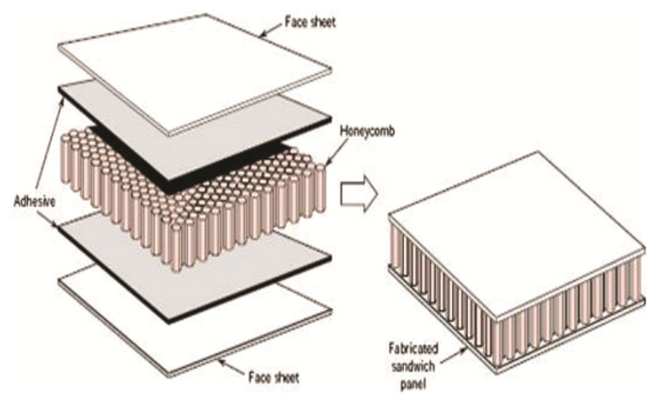

Fig. 1 — A typical sandwich composite.

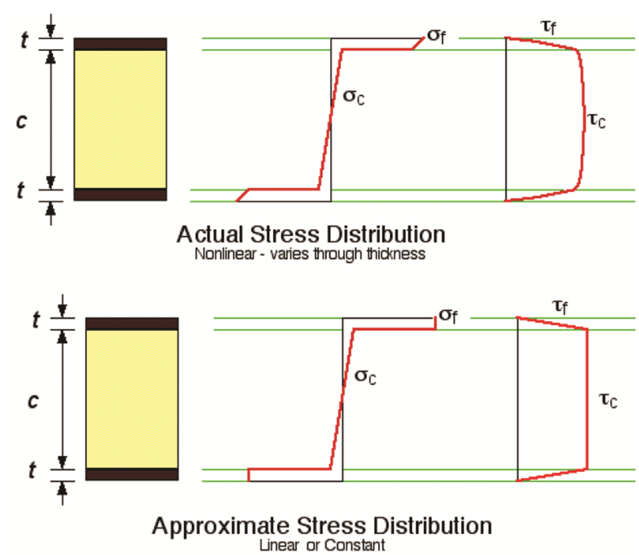

Fig. 2 — Bending and shear stress distribution for sandwich composites.

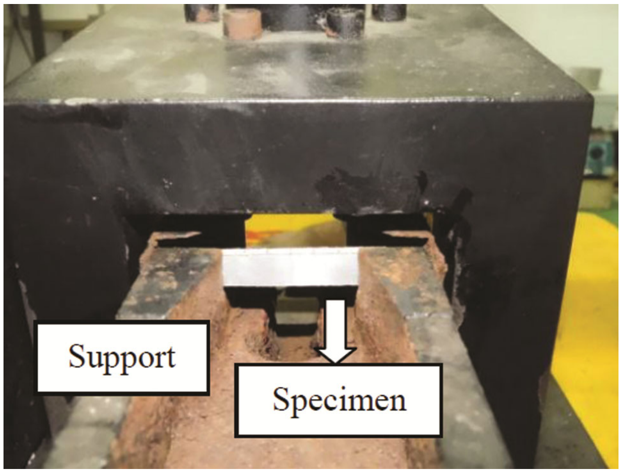

Fig. 5 — Sandwich specimen on supports of ASTM E-23 charpy test machine.

Table 4 — Energy absorption (J) for the four panels.

Panel	Sample 1	Sample 2	Sample 3	Sample 4	Mean	Standard deviation
Panel-1	2.5	2.2	2.1	2.8	2.40	0.2738
Panel-2	3.0	3.2	3.0	3.4	3.15	0.1658
Panel-3	1.2	1.5	2.0	1.5	1.55	0.2872
Panel-4	1.8	1.7	1.5	1.8	1.70	0.1225

Table 5 — Energy absorption to mass ratio (J/g).

Panel	Energy(J)	Mass(g)	Energy to mass ratio(J/g)
Panel-1	2.40	2.32	1.03
Panel-2	3.15	2.35	1.34
Panel-3	1.55	2.25	0.69
Panel-4	1.70	2.28	0.75

based on the standards of the Charpy test ASTM E-23 machine. For each of the panel, four specimens were tested and the mean of the values of the attained results was used in the study for accuracy. The test specimens were mounted horizontally on the supports to ensure that impact took place. The pendulum was then raised and secured in the release mechanism and the energy indicator on the measuring scale was adjusted to zero. The pendulum was then released from its release mechanism to impact the specimen. The energy with which the impact hammer strikes the specimen was about 407 J, corresponding to 30.24 kg mass of the hammer with a velocity of 5.19 m/s. The dial scale records the breaking energy. In deformed sandwich composites, fully crushed honeycombs and small cracking were observed on the upper layer of few specimens.

Table 4 and Table 5 presents the energy absorption and energy absorption to mass ratio of the panels.

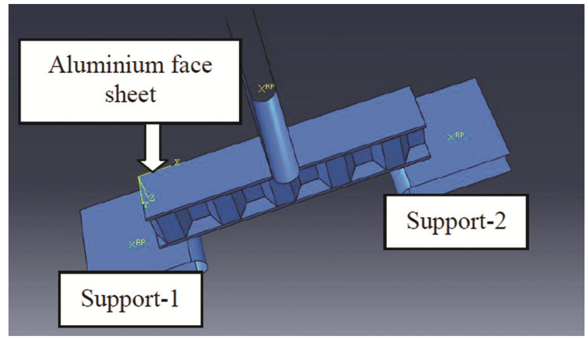

Fig. 6 — Charpy test assembly in abaqus .

4 Numerical investigation

The numerical simulations were carried out using commercially available finite element (FE) software Abaqus for assessing the numerical predictions and compared against the experimental results. 3-D FE based dynamic impact analysis was performed for estimating the energy absorption from each of the panels. The FE modeling and analysis details are discussed in the following sections.

The FE model includes the modeling of the hammer, specimen, and the supports using suitable elements available in Abaqus. The impact hammer and supports were modeled as a rigid body and the specimen of the sandwich composite was modeled as assembly of layers. The assembly is shown in Fig. 6.

The upper and lower layers of the sandwich specimen comprise the dimensions 55x10x0.7 (Length x Breadth x Thickness in mm) and modeled with the material characteristics of aluminium-3003 H-18 (shown in Fig. 6). These were modeled with Abaqus FE element hex C3D8R which is an 8-node brick element having the features of the reduced integration and hourglass control. Similarly, the honeycomb was modeled with a shell element named quad S4R which is a 4-node element having similar features of the reduced integration and hourglass control. The impactor and supports were modeled as the rigid body using the bilinear quadrilateral shell element naming quad R3D4[18,20]. During analysis 3-elements were taken for the skin along the thickness and 16-elements were taken for the honeycomb along the edge length.

All the supports were fixed and the translational motion of the hammer was permitted in only z-direction i.e. along the direction perpendicular to the face of the specimen and the rest of the degree of freedom were constrained. Tie constraints were assigned for bonding of the layers. The impactor was given a velocity of 5.19 m/s and was located at a

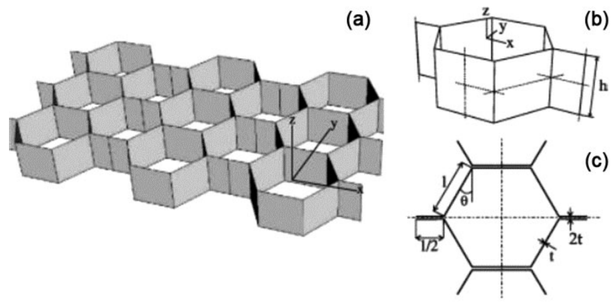

Fig. 3 — (a) Honeycomb and (b & c) A unit cell of honeycomb.

Table 1 — Specifications for honeycomb core.

Description	Cell size(mm.)	Foil thickness (micron)	Honeycomb height(mm.)
Panel-1	6.4	50	8
Panel-2	6.4	60	8
Panel-3	9.5	50	8
Panel-4	9.5	60	8

where, t and l denotes the foil thickness and edge length of honeycomb respectively.

The total energy is the sum of energy due to bending, shear and indentation i.e.

$$E = E_b + E_c + E_i \quad ...(2)$$

where, E, E_b, E_c, and E_i are the total energy, energy due to bending, energy due to shear, and energy due to indentation respectively.

Therefore,

$$E = g\left(\frac{t}{l}\right) \quad ...(3)$$

Accordingly, the total energy absorbed by the honeycomb is a function of foil thickness to cell size.

3 Materials

For the present work, four different types of aluminium honeycomb sandwich panels with skin and honeycomb core of aluminium-3003 H-18 alloy were selected. The geometry dimensions of the honeycomb core and skin of sandwich composites are specified in Table 1. The length and breadth of sandwich specimens are 55 mm and 10 mm respectively. The properties of aluminium and steel are given in Table 2 and Table 3[17] respectively. Figure 4 presents the typical aluminium honeycomb and aluminium honeycomb sandwich specimen.

The section presents the experimental procedure and discusses the respective results of the sandwich panels. Charpy testing is generally used for the measurement of toughness (Energy absorption capacity) of materials subjected to impact loads. Experiments were carried out in this study using the ASTM E-23 Charpy test machine. Figure 5 shows the specimen on the supports of the Charpy ASTM E-23 machine.

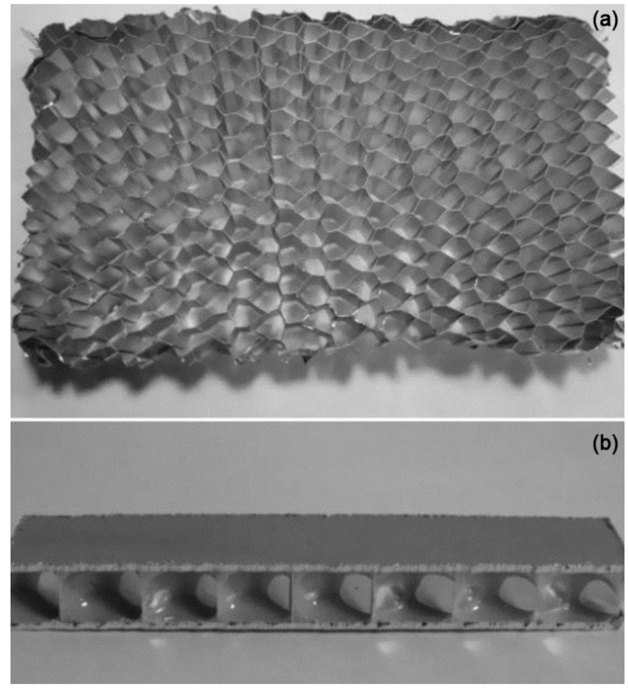

Fig. 4 — (a) Aluminium honeycomb and (b) Aluminium honeycomb sandwich specimen 4 Experimental investigation.

Table 2 — Properties of aluminium-3003 H-18 alloy.

Property	Value
Density	2700kg/m^3
Elastic Modulus	70GPa
Poisson's Ratio	0.33
Shear Modulus	27GPa
Yield Strength	180MPa
Ultimate Tensile Strength	210MPa
Elongation at Break	4.5%

Table 3 — Properties of steel.

Property	Value
Density	7800kg/m^3
Elastic Modulus	210GPa
Poisson's Ratio	0.3

As mentioned before, experiments were carried out on the four selected sandwich composite panels of the same length and width with a variable combination of foil thickness and cell size. The specimen length and width are 55 mm and 10 mm respectively, which are distance of about 0.5 mm from the upper layer of the specimen. Each of the analyses was carried out for a time period of 0.01s. The results from the analyses are discussed in the subsequent sections.

The numerical analysis was carried out on all the panels considered in the experimental study. The energy absorption was obtained from the analysis and the results are discussed in the following sections. Here, maximum principal stress criterion was chosen for the failure of aluminium. But suitable criterion are maximum shear stress and distortion energy theory. Since the plastic regime was considered during analysis, therefore, the maximum principal stresses have been compared with ultimate stress rather than the yield stress of the aluminum. The stresses were extracted at the time step where the specimen detached from the supports. The maximum principal stresses are listed in Table 6.

Table 6 — Maximum principal stresses in layers of sandwich panels.

	Upper Layer (Pa)	Core Layer(Pa)	Lower Layer (Pa)
Panel-1	2.36E8/4.83E7	2.43E8/0	2.34E8/5.72E7
Failure	Fail	Fail	Fail
Panel-2	2.19E8/1.31E8	2.43E8/0	2.23E8/5.54E7
Failure	Fail	Fail	Fail
Panel-3	2.38E8/9.38E7	2.43E8/0	2.04E8/3.92E7
Failure	Fail	Fail	-
Panel-4	2.33E8/9.37E7	2.43E8/0	2.09E8/8.247E7
Failure	Fail	Fail	-

Table 7 — Energy absorption for sandwich panels.

Panel	Time step(s)	Energy absorption(J)
Panel-1	0.00575	2.62
Panel-2	0.0057	3.17
Panel-3	0.00475	1.57
Panel-4	0.005	1.90

4.1 Energy and energy absorption to mass ratio

The energy absorbed by the sandwich panels was extracted at the time steps where specimen detached from the supports. The energy absorbed by sandwich panels is listed in Table 7. The internal energy is the sum of the elastic strain energy, plastic dissipation energy, and artificial strain energy. The internal energy, strain energy, plastic dissipation energy, and artificial strain energy for all the sandwich composites are shown in Fig. 7. The artificial strain energy is a parameter to check the mesh quality. If artificial energy is very less compared to the internal energy that means mesh quality is good[19,20]. In our case, artificial energies are very less.

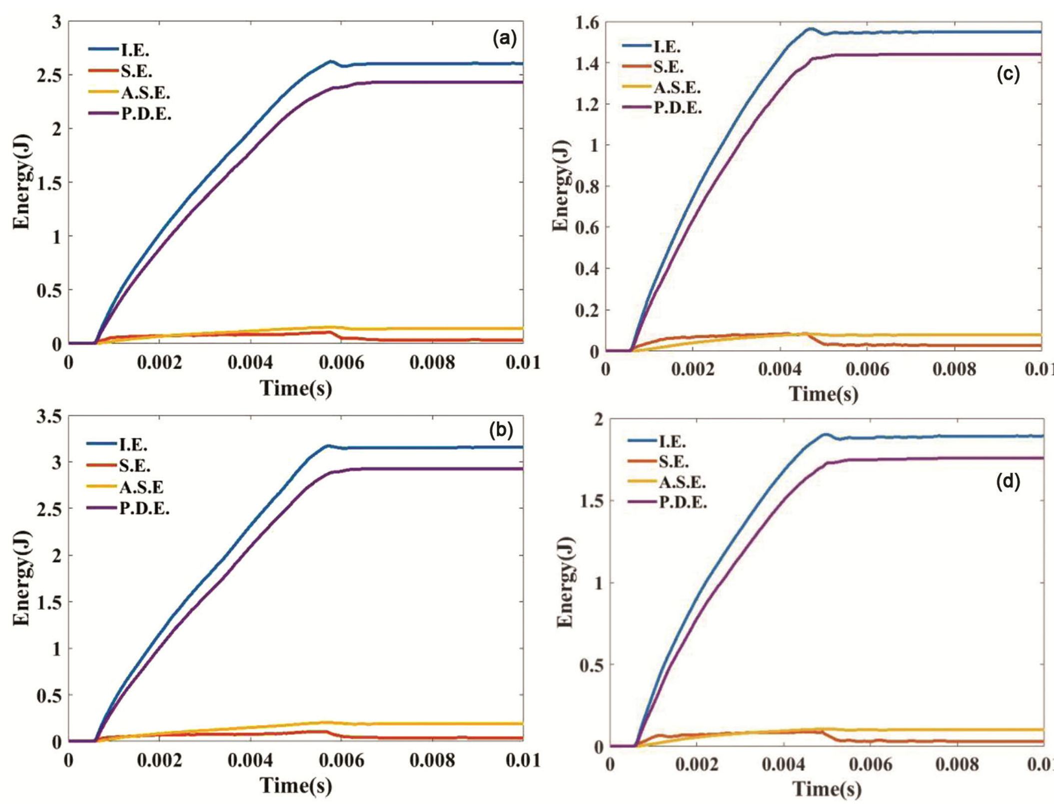

Fig. 7 — Energy variation (a) Panel-1, (b) Panel-2, (c) Panel-3 and (d) Panel-4.

The effect of honeycomb parameters (Foil thickness and Cell size) on energy absorption is shown in Table 8.

The energy to mass ratio is an important parameter which decides its applicability in various applications. Here in this study, the energy to mass ratio for the considered panels was calculated and presented in Table 9.

The density of the honeycomb was calculated by the empirical relation given by L. J. Gibson *et al.*[5].

$$\frac{\rho}{\rho_{al}} = \left(\frac{2}{\sqrt{3}}\right).\left(\frac{t}{l}\right) \quad \ldots(4)$$

where, ρ and ρ_{al} are the densities of honeycomb and aluminium respectively.

The mass of the sandwich panels was calculated by using the relationship

$$M = 2.(\rho_s.V_s) + \rho.V_H \quad \ldots(5)$$

where, M is the total mass of sandwich specimen. ρ_s, V_s, and V_H are the density of face sheet, volume of face sheet and volume of honeycomb respectively.

It is evident panel-2 has higher energy absorption to mass ratio whereas, the panel-3 has the least energy absorption to mass ratio.

4.2 Impact force

The velocity of the hammer after the impact can be obtained from the expression given below

Energy Absorbed by specimen = (Initial Energy-Final Energy) of the hammer

$$Total\ Energy\ Absorbed = \frac{1}{2}.m.v_1^2 - \frac{1}{2}.m.v_2^2 \quad \ldots(6)$$

Table 8 — Effect of honeycomb parameters.

	(%)Increment in mass(g)	(%)Increment in energy absorption(J)	(%)Increment in energy absorption/ Increment in mass(J/g)
Panel-1 and Panel-2	1.27	17.35	13.66
Panel-3 and Panel-4	1.31	17.77	13.56
Panel-1 and Panel-3	3.01	40.27	13.37
Panel-2 and Panel-4	2.97	39.96	13.45

Table 9 — SEA (Specific energy absorption).

	Energy(J)	Mass(g)	Energy absorption to mass ratio(J/g)
Panel-1	2.62	2.32	1.13
Panel-2	3.17	2.35	1.35
Panel-3	1.57	2.25	0.70
Panel-4	1.90	2.28	0.84

The final velocity can be calculated as

$$v_2 = \sqrt{\frac{2}{m}.\left(\frac{1}{2}.m.v_1^2 - Total\ Energy\ Absorbed\right)} \quad \ldots(7)$$

Then from Impulse-Momentum relation

$$F.dt = m(v_1 - v_2) \quad \ldots(8)$$

where, m is the mass of hammer. v_1 and v_2 are the initial anf final velocities of hammer. F and dt are the impact force and contact time between hammer and specimen.

The value of dt was attained from the numerical simulation and was taken as the time period between the instants where the impactor touched the specimen and specimen detached from the supports.

The estimated impact force on the specimen is listed in Table 10.

5 Comparison (Experimental versus numerical)

The comparison of energy absorption capacity (Experimental vs. Numerical) is shown in Table 11. The deformation pattern is similar to the experiments. The impactor touched the specimen at the time step about 6E-4s then the upper and lower layer bends and honeycomb edges buckles (localized) followed by the rupture in the honeycomb. The foil thickness to core height ratio is very less (long column) therefore, initial buckling in the edges of honeycomb takes place. The deformation pattern of sandwich composite and honeycomb are shown in Fig. 8.

The variation in the experimental and numerical results may be due to the following reasons,

1 The layers in sandwich composites were bonded by adhesives, whereas in finite element analysis tie constraints were chosen to bond the layers.
2 Finishing errors during cutting the samples.
3 Experimental and manual errors.

Table 10 — Impact force.

Panel	Final velocity of hammer(m/s)	Impact force(N)
Panel-1	5.1733	98.18
Panel-2	5.1698	119.99
Panel-3	5.1800	58.61
Panel-4	5.1779	88.46

Table 11 — Comparison of energy absorptions (Experimental versus numerical).

	Experimental(J)	Numerical(J)
Panel-1	2.40	2.62
Panel-2	3.15	3.17
Panel-3	1.55	1.57
Panel-4	1.70	1.90

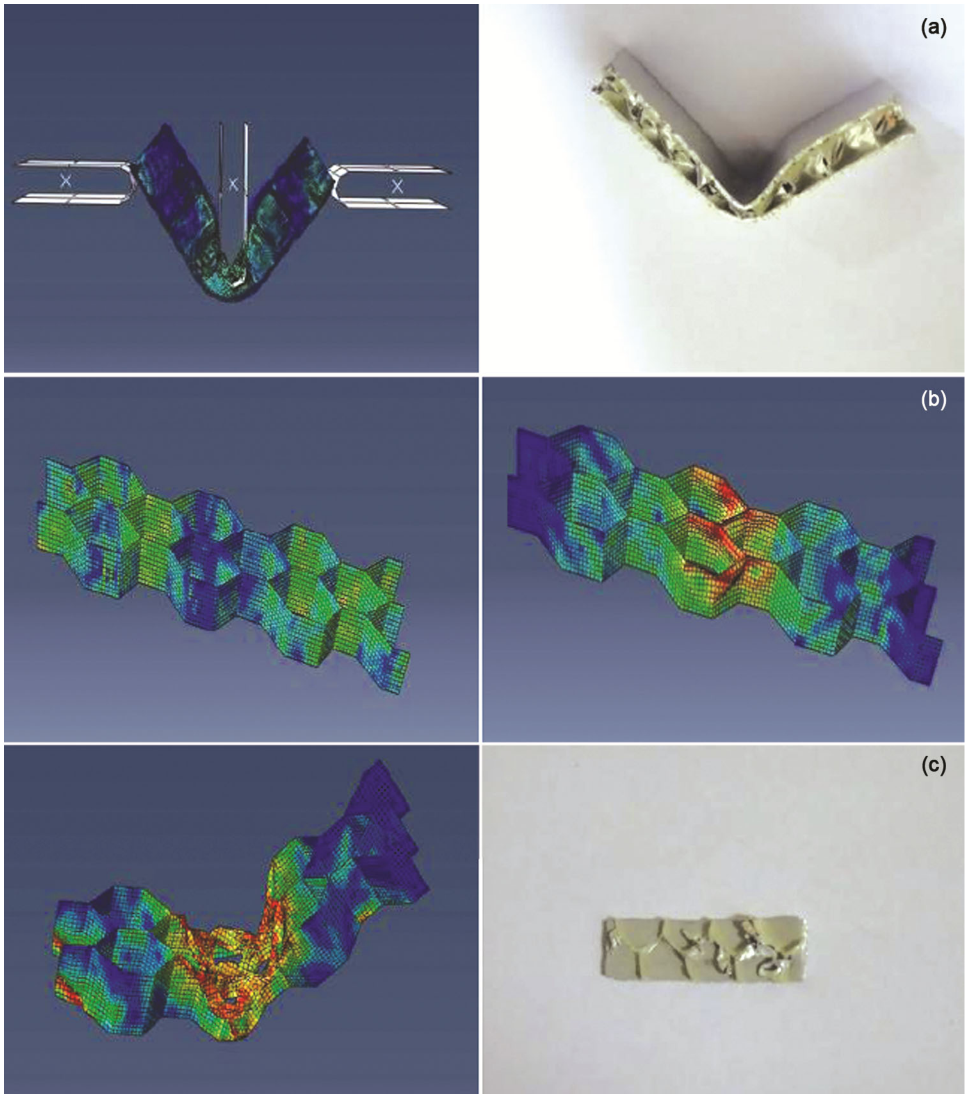

Fig. 8 — Comparison of deformation pattern (a) sandwich specimen, (b) two stages of honeycomb (between buckling to crushing) and (c) crushed honeycomb.

4 Standard properties were used for the analysis from literature.
5 Approximation errors.

6 Conclusions

The experimental and numerical investigation was carried out to find the energy absorption capacity of the aluminum honeycomb sandwich composites. Four panels were chosen for the study with a different combination of foil thickness, and cell size. The Experiments were carried out on standard Charpy ASTM E-23 test machine and numerical simulations were carried out using finite element tool Abaqus. The influence of foil thickness and cell size on the energy absorption to mass ratio was discussed. It was observed that energy absorption and energy absorption to mass ratio increases with increase in foil thickness and with decrease in cell size. Further, it was found that increase in foil thickness is more effective than decrease in cell size in terms of energy absorption to mass ratio. The maximum impact force resisted by the sandwich composites was estimated by using the impulse-momentum equation and found the impact force increases with increase in foil thickness and decrease in cell size. The layers are bonded by adhesives. Increase in foil thickness and decrease in cell size results in strong bonding between layers.

The energy absorption to mass ratio is an important parameter to design any type of structure also the thickness of aerospace and marine structures are less therefore it is recommended to increase in foil thickness rather than decrease in cell size for enhancing energy absorption to mass ratio. The aluminium honeycomb sandwich composites can be better alternatives to polymer composites because of lightweight, high energy absorption capacity, eco-friendly and recyclability, etc. This study is a step toward the application of aluminium honeycomb sandwich composites in various industries such as aerospace, marine, and automobiles.

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