



Corrugated Sandwich Structure Modeling Under Low Velocity Impact

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1 Introduction

The CFRP composite materials are mostly used in several applications such as automobile, wind turbine, and rail transport industry. Sandwich structure consists of mainly face sheets and core material [1, 2]. In sandwich, we use different kind of materials for face sheets and core. There are different types of sandwich are available, for example metallic sandwich (both face sheet and core are of metallic structure), pure composite sandwich (both face sheet and core material are of composite), and hybrid sandwich (both face sheet and core of composite and metallic). The advantage of using the sandwich structure is that we get the higher stiffness and strength for the same weight of structures as compared to the solid structure [1–6]. The sandwich consists of CFRP face sheets and a lightweight core material aluminum used between the face sheets. The hybrid CFRP sandwich structure provides an excellent property such as high specific stiffness and strength and also excellent corrosive resistance properties, with it the core we are using, i.e., aluminum foam is lightweight and having excellent energy absorbing capacity [1–8].

Žmindák et al. [9] presented the perforation of steel and aluminum sandwich structure under impact load with using the eight layers of carbon reinforced with core aluminum. The Johnson–cook material model and Hashin damage were used to determine the failure behavior of the core aluminum and composite plate, respectively. It was observed that the ply orientation provided the significant effect of the sandwich structure under high velocity impact. Tang et al. [10] studied the CFRP sandwich panel behavior subjected to the high velocity impact to determine the residual velocity, impactor velocity, and energy absorption for the different impactor shape. Hua et al. [9] performed the LVI analysis of the sandwich panel to determine the ballistic limit of the sandwich structure using different shape of impactor. Force and displacement curves were showed the flat and conical shape impactor showed the higher and minimum energy, respectively. Zhu et al. [11] determined the numerical result of the circular sandwich structure subjected to the LVI. The contact force versus displacement showed that the different stage of failure behavior. Zhang et al. [12] performed the quasi-static and LVI test by experimental method on hybrid sandwich panel. By varying the thickness of the upper and lower face sheet but keeping the total thickness constant. In this work, they explained the various failure modes due to varying the thickness and how the impact load vary

with the deflection of various sandwich beam with varying thickness. He et al. [13] presented an extensive work on the sandwich panel with CFRP as it faces sheet and a corrugated Al sheet as its core member. In this work, they performed the LVI test of various energy levels by varying the thickness of the core member only and obtained the impact load and energy curve with respect to time. In this work, they also explained the failure mechanism in detailed. Shi et al. [14] studied the CFRP composite plate under LVI performs the experimental and numerical analysis to determine different modes of failure, displacement, various failure mechanism, and energy absorption.

The above literature showed that some literature available on the LVI response on composite panels but the limited work available on the different core design of the sandwich panels under LVI. So, in this paper, developed the different corrugated core's structure design such as trapezoidal, rectangular, and circular shape with the CFRP composite face sheet under LVI to determine the failure behavior of the sandwich structure, energy absorption, and force time history. Numerical simulation results validated with experimental results [13] for the trapezoidal core with CFRP composite faces under LVI. In this study, the progressive damage modeling is used for the CFRP composite plate under LVI to determine the composite failure such as fiber mode tensile and compressive, matrix modes tensile, and compression as well as delamination failure using the thickness of the various core structures are constants.

2 Numerical Simulation

The corrugated sandwich structure is made up of metal core structure and composite face plates. The aluminum core and composite face sheet damage modeling are used for the Johnson–Cook and Donaldson criteria, respectively. The Johnson–Cook ductile damage models are given in below.

2.1 Ductile Damage Initiation Model

The finite element analysis (FEA) is performed for the different shapes of core structure to predict the plastic deformation of the core structure using the ductile damage initiation and propagation model based on Johnson–Cook and tabular form criteria, respectively.

$$\omega_d = \int \frac{d\varepsilon_{pl}}{\dot{\varepsilon}_{pl}^d(\eta, \dot{\varepsilon}_{pl})} = 1 \quad (1)$$

Here, ω_d is state variable, $\dot{\varepsilon}_{pl}^d(\eta, \dot{\varepsilon}_{pl})$ equivalent plastic strain, η is the stress triaxiality, and $\dot{\varepsilon}_{pl}$ is the equivalent plastic strain-rate [13].

2.2 Damage Propagation Criteria for Metal

Damage propagation model is used for the plastic deformation of the structure to calculate the plastic deformation of the aluminum core. If the damage initiation criterion $\omega_d \geq 1$ is satisfied, then propagation-based failure model as shown in Eq. (2) is used to predict the plastic failure. The damage variables are calculated based on the relative plastic

displacement is specified by the tabular form plastic stress and strain curve. Ductile damage propagation is defined as

$$\dot{\bar{u}}_{pl} = L\dot{\bar{\epsilon}}_{pl} \tag{2}$$

Here, L is the characteristics length of the element, \bar{u}_{pl} is the effective plastic displacement. The damage variable directly based as a tabular function of equivalent plastic displacement, $d = d(\bar{u}_{pl})$ as shown in Fig. 1.

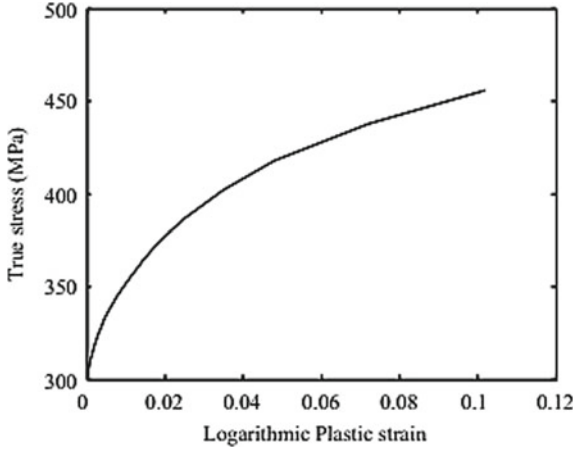


Fig. 1 Compression test curve of Al sheet [13]

2.3 Composite Damage Modeling:

The continuum damage modeling is included the damage initiation and the propagation-based model using the Hashin [14] and Donaldson criteria [14], respectively, to determine the different modes of failure for the composites structure such fiber failure, matrix failure, and delamination failure. Hashin-based damage initiation criteria are used for the matrix tension mode, fiber tension, and compression modes. The matrix compression-based criterion did not provide the accurate results for the prediction of the matrix cracking [3–6]. Hence, the Puck and Shurman-based matrix compression criterion is used for the present study to determine realistic failure behavior for the matrix compression.

3 Sandwich Structure Modeling under Impact Load

The sandwich structure is made up of the CFRP composite face sheets with aluminum core material. The Al core was modeled as shown in Fig. 2. Dimensions of core are taken as $L_1 = 7$ mm, $L_2 = 25$ mm, and $\omega = 55^\circ$. The composite top and bottom face sheets were modeled as the deformable solid having dimensions of $96 \times 96 \times 1$ mm (Fig. 3) with stacking sequence $[0/90/0/90]_s$. The impactor was modeled as the discrete rigid

cylindrical shell with hemispherical end, and the mass was assigned on the reference point. Impact tests were performed on the sandwich panels with a hemispherical shape of impactor having diameter of 12 mm and total weight of 13.2 kg. In boundary condition, the edges were fixed of the face sheets. The energy level of impactor was obtained by the initial velocity, i.e., for 10 J, the velocity was given as the 1.23 m/s. The panel was modeled 8-node quadrilateral (SC8R) in-plane general purpose continuum shell element. The element assigned to the impactor is R3D4 which is a 4-node-3D bilinear rigid quadrilateral. Mesh density of the impactor region was chosen dense as compared the other region. The impactor zone was divided into 50 elements by number, and the global size of the element was assigned as the 1 * 1 mm. The same impactor zone was also crated on the core part. The degradation parameter was set to 0.98–0.99 for panel, and the failed elements were removed from the FE model once the failure criterion was satisfied.

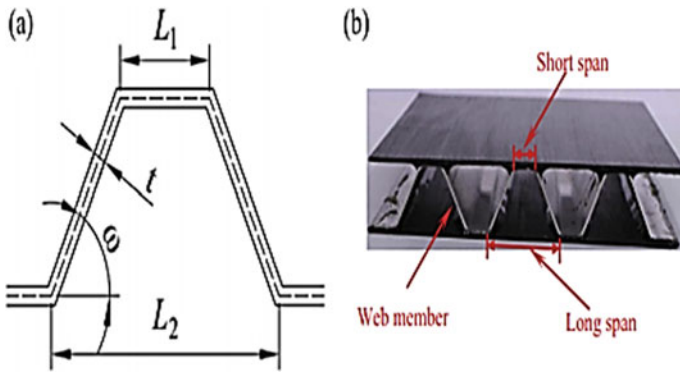


Fig. 2 Geometrical shape of trapezoidal core [13]

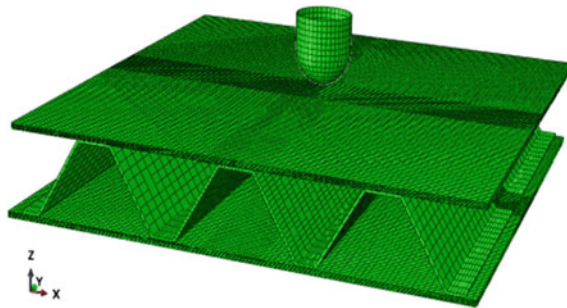


Fig. 3 Mesh model of sandwich panel

The different shapes of aluminum core structures are modeled using the ductile damage initiation and propagation model based on Johnson–Cook and tabular form criteria, respectively, to predict the plastic deformation of the core structure. The Hashin failure model was applied for the CFRP face sheets to determine the different model of

failure of composite faces. The property was used as the input for the ductile damage model and Hashin model in literature [13].

4 Hybrid Sandwich Structure Modeling of Different Cores

In the present study, the three different types of hybrid sandwich core structures modeling are performed using the FEA under the LVI.

4.1 Hybrid Sandwich Structure with Trapezoidal Core

Hybrid sandwich structure most commonly is used for the impact energy absorption. In this section, all the dimension of the trapezoidal core and top and bottom faces of the composites are considered the experimental literature [13]. The complete sandwich structure assembly and the FE mesh of the complete assembly is shown in Fig. 3. The trapezoidal sandwich structure subjected to the LVI considering the mass of impactor 13.2 kg and velocity impactor is 1.23 m/s (Fig. 4). The different modes of failure for the trapezoidal core structure and composite face sheet are shown in Figs. 5 and 6, respectively.

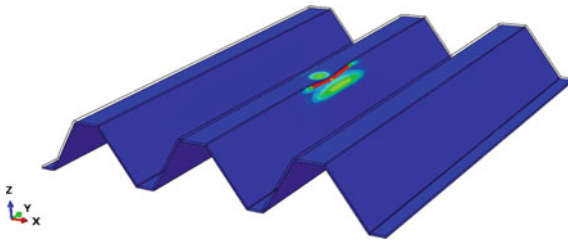


Fig. 4 Plastic deformation of the trapezoidal AL sheet core

4.2 Validation Study of the Hybrid Sandwich Structure with Trapezoidal Core

Hybrid sandwich structure with trapezoidal core numerical results is validated with the experimental result [13] for the same core structure with the CFRP face sheets. Numerical result for the impact load versus time and energy versus time is validated with the experimental published results [13]. The impact force versus time (Fig. 7) and energy versus time (Fig. 8) results showed the very close to experimental result. It is observed that the most of the energy are dissipated by the CFRP composite face sheets.

4.3 Rectangular Shell Core

The hybrid sandwich structure with rectangular core and CFRP face sheets are showed in Fig. 9 to determine the impact energy absorption. The rectangular core structure area is considered to be same as the trapezoidal section. The top and bottom faces are used for

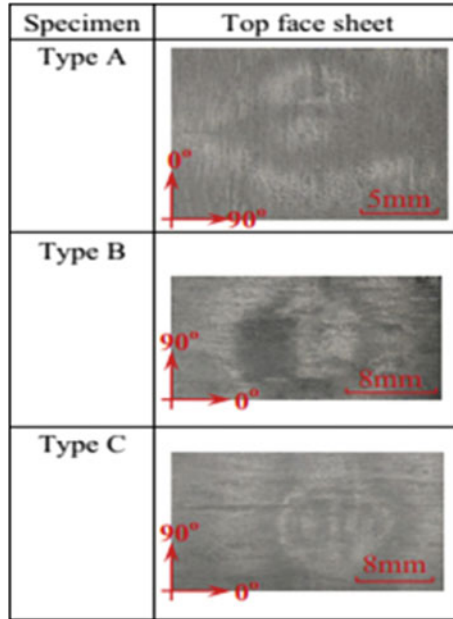


Fig. 5 Damage of top face sheet in testing [13]

the same as for the trapezoidal sandwich structure of the composites [13]. The complete sandwich structure assembly and the finite element mesh of the complete assembly are shown in Fig. 9. The rectangular sandwich structure subjected to the low velocity impact considering the mass of impactor 13.2 kg and velocity impactor is 1.23 m/s. We designed the rectangular shell member (Fig. 10) for core by choosing the dimension such that the thickness and the total volume of core remain constant as used in the previous corrugated core which is shown in the Fig. 2. The different modes of failure for the rectangular sandwich structure face sheets are the fiber failure in tension and compression, as well as matrix failure in tension and compression are shown in Figs. 11 and 12, respectively. The rectangular corrugated sandwich structure showed the impact force versus time and energy versus time Figs. 13 and 14, respectively.

4.4 Circular Shell Core

The hybrid sandwich structure with circular core and CFRP face sheets are showed in Fig. 15 to determine the impact energy absorption. The circular core structure volume and thickness are considered to be same as the trapezoidal section. The top and bottom faces are used for the same as the trapezoidal sandwich structure of the composites [13]. The complete sandwich structure assembly and the FE mesh of the complete assembly are shown in Fig. 15. The circular sandwich structure subjected to the LVI considering the mass of impactor 13.2 kg and velocity impactor is 1.23 m/s. The different modes of failure for the circular sandwich structure face sheets are the fiber failure in tension and

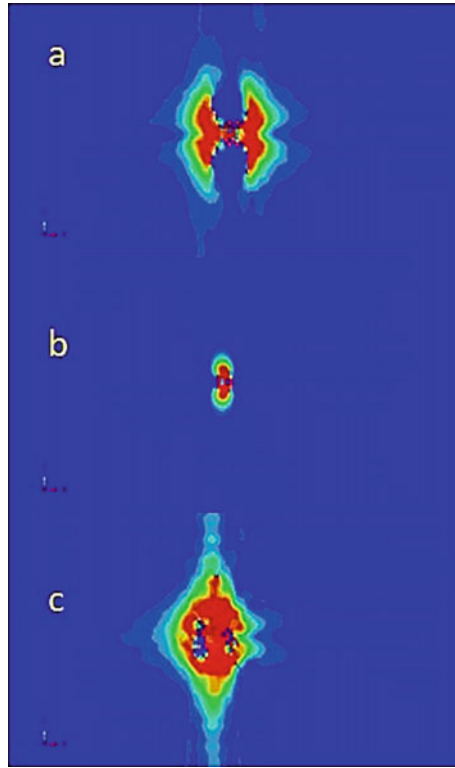


Fig. 6 Damage behavior of the trapezoidal corrugated structure (a) fiber tension (b) fiber compression (c) matrix tensile failure

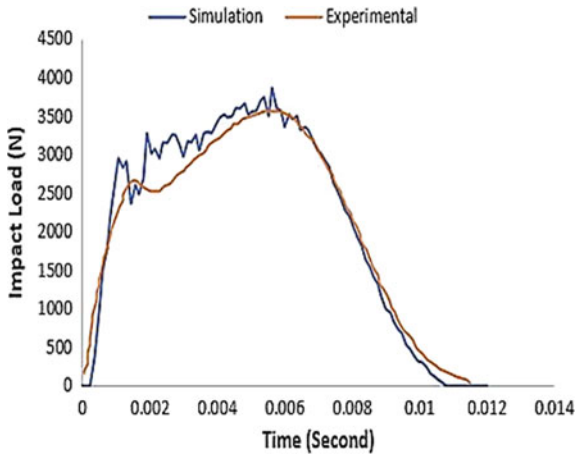


Fig. 7 Validation results of impact load versus time

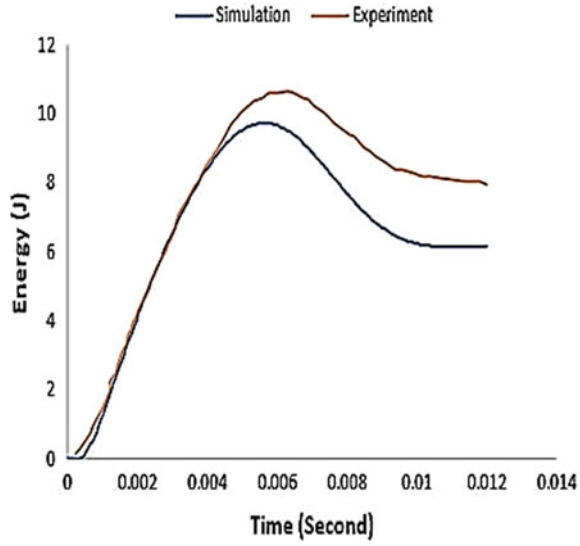


Fig. 8 Validation results of energy versus time

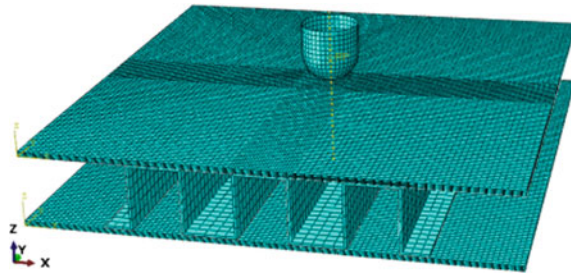


Fig. 9 FE mesh model of the rectangular corrugated structure

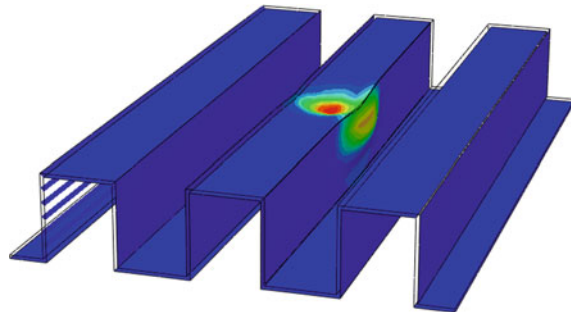


Fig. 10 Plastic deformation of the square AL sheet core

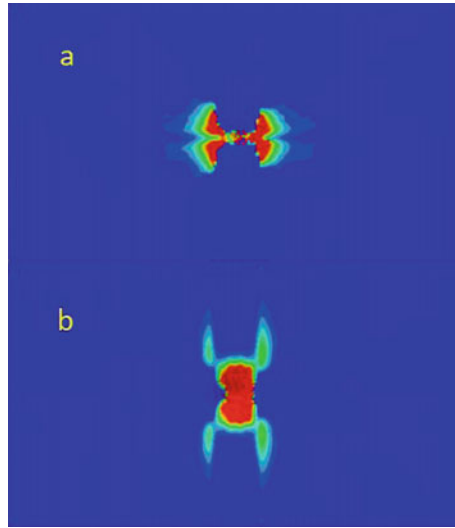


Fig. 11 Damage behavior of the rectangular corrugated structure (a) fiber tension (b) fiber compression

compression, matrix failure in tension and comparison are shown in Figs. 16, 17 and 18, respectively.

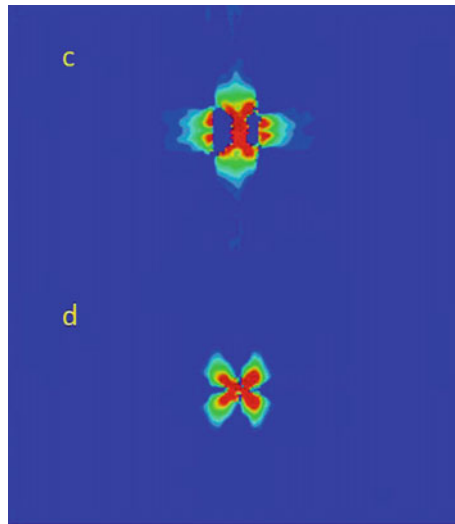


Fig. 12 Damage behavior of the rectangular corrugated structure (c) matrix tension (d) matrix compression failure

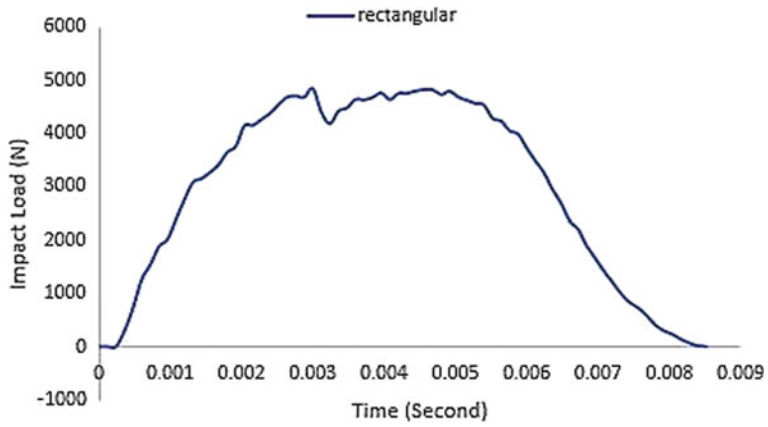


Fig. 13 Simulation results of impact load of rectangular core of 10 J impact energy level

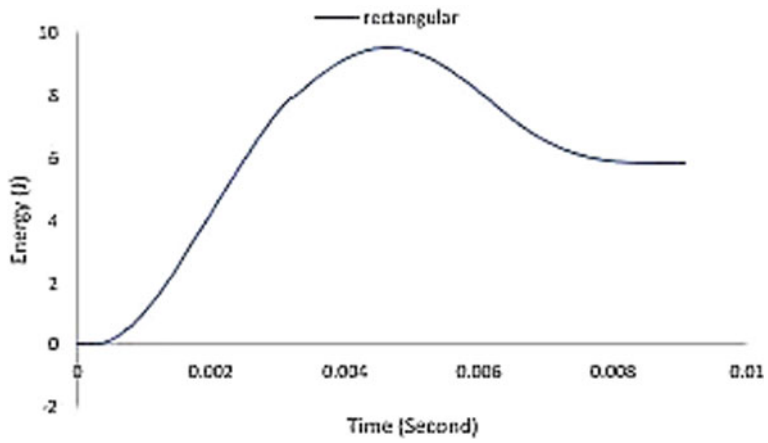


Fig. 14 Simulation results of impact energy absorption rectangular core for 10 J energy level

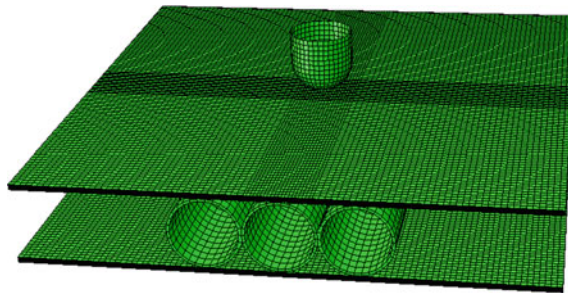


Fig. 15 FE mesh model of the circular corrugated structure

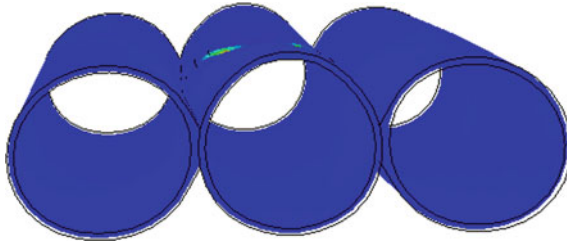


Fig. 16 Al damage of circular tube as core

5 Results and Discussion

In the current study, the three different types of corrugated cores such as trapezoidal, rectangular, and circular shapes are modeled using the FE analysis subjected to the LVI. The impactor transfers its kinetic energy to the panels. Initially, the impact load increases and reaches its first peak value. There is slight drop in the impact load for short time this is due to the fact that there may be little buckling occur in the core part and then increases the value of load again and reaches its maximum value. After reaching the maximum value, the load value again decreases as the impactor rebound back. The initial oscillation occurs in the impact load value due to the elastic vibration in the panel.

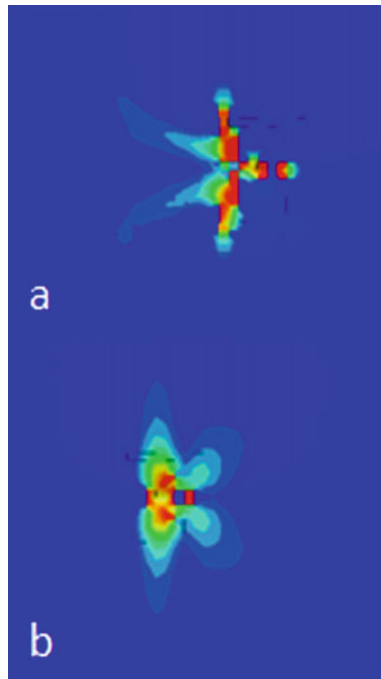


Fig. 17 Damage behavior of the circular corrugated structure (a) fiber tension (b) fiber compression failure

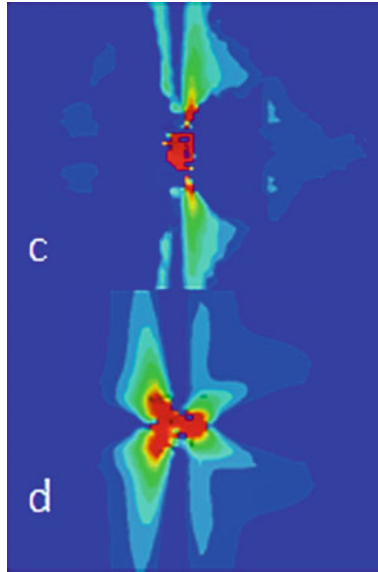


Fig. 18 Damage behavior of the circular corrugated structure (c) matrix tension (d) matrix compression failure

5.1 Contact Force Time History

As shown in the Fig. 7, initially, load increases with time and reaches the maximum value of 2.6 kN. Due to the very slight buckling of the core, the load values drop and increase again at the maximum value of 3.56 kN in the experiment. There is barely visible indentation occurs on the core surface. At this peak load, their damage initiation starts. However, during the unloading phase, the specimen returns to its original state more slowly and less completely. As shown in Fig. 8, the relation of impact energy and the time curve shows that as the impactor transfer its kinetic energy to the panel and the internal energy of the panel increases reaches its maximum absorption, i.e., near 10.6 J, and then during the unloading phase, it releases its elastic energy to the impactor. So, the energy drops to some value, i.e., near 6 J and then constant. Ideally, the whole elastic energy does not recovers because some part of energy losses due to the friction between the impactor and plate or damage of the fiber-matrix.

5.2 Comparison Study of Rectangular Shell Core and Circular Core Design

In this paper, studied the effect of impact loading and energy absorption by varying the core design and keeping all other same. Various simulations were performed on different core design, and the effect of impact on panel and results is shown in Figs. 3, 9, and 15 on various core geometries (i.e., rectangular shell and circular tubes). After impact on rectangular core, the initiation of damage take time as compared to the trapezoidal one and also the damage initiated at higher load, i.e., near 4.8 kN as against 2.6 kN. Also, the maximum energy absorption capacity in it is 9.4 J which is slightly less as

compared to trapezoidal but with it also recover faster than the trapezoidal core (Fig. 7). Overall comparing impact load, it was observed that the rectangular shell could wear the maximum load and also it returns to its original state fast as compared to other cores. In circular tubes of core, the initiation damage occurs at long as compared to the previous one but there is no buckling observed in the core. Also, the maximum energy absorption is same but its elastic recovery takes long time as compared to the previous trapezoidal core.

6 Conclusion

The continuum damage mechanics approach is developed and implemented the ABAQUS software to determine the realistic failure behavior. Impact force versus time and energy versus time were validated with experimental results, and it is showed the good agreements. The rectangular core sandwich structure investigated the initiation of damage take time as compared to the trapezoidal core structure. Rectangular core structure damage initiated at higher load, i.e., near 4.8 kN as against 2.6 kN in trapezoidal sandwich structure. The maximum energy absorption capacity in it is 9.4 J which is slightly less as compared to trapezoidal but with it also recover faster than the trapezoidal core. In next work, the effect of core geometry (rectangular, circular tubes) was studied on impact load and energy absorption capacity of sandwich panel and the result were compared. It was observed that the rectangular core has more impact wearing load capacity, i.e., nearly 20% and 25% greater than the trapezoidal and circular core, respectively. Similar behavior is also observed for the displacement and energy absorption for the rectangular and circular core structure. The rectangular corrugated sandwich structure showed the maximum energy absorption and maximum impact force as compared to the other core structure designs (trapezoidal and circular).

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