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Numerical Investigation of Dynamic Response of Honeycomb Sandwich Panels Filled with Circular Tubes Under Low Velocity Impact in the In-Plane Direction

Honeycomb sandwich structures, composed of many regularly arranged hexagonal cores and two skins, show excellent impact performance due to strong energy absorption capability under impact loads. In this paper, a numerical study of low velocity impact on honeycomb sandwich panels filled with circular tubes in the in-plane direction was performed. To calibrate the numerical model, simulation results in the out-of-plane direction are compared with the experimental ones. The numerical modelling of the drop weight test was carried out using the nonlinear explicit finite element code Abaqus/Explicit. The impact responses are presented as the contact force between the impactor and the panel versus the time. It was concluded that the filled honeycomb panel absorbs the same amount of impact energy in a shorter time than an empty one. In addition, the deflections of the front and back facesheets are investigated. The panel degradation and the stress distribution during the crushing are also discussed.

Keywords: *Aluminium honeycomb, Finite element analysis, Low velocity impact, Tube reinforced honeycomb.*

1. INTRODUCTION

A honeycomb sandwich is a structure that consists of two relatively thin facesheets bonded to a relatively thick lightweight honeycomb core [1]. The addition of a lightweight core between facesheets increases the moment of inertia with a slight increase in weight generating an effective bending- and buckling-resistant composite structure. For this reason, these sandwich panels are very common in structural uses for a wide range of applications in the aerospace and automotive industry that require low weight, high bending strength and high energy absorption capability [2-9]. However, impact scenarios affecting these structures range from low velocity impacts (tool drop, hail on ground) over intermediate velocity impacts (runway debris, tire fragments) to high velocity impacts (bird strike, hail in flight, engine parts). Hence, extensive research was conducted on the honeycomb sandwich structure for studying their mechanical behaviour under quasi-static as well as dynamic loading [10-18].

The dynamic response of the honeycomb sandwich panels under impact loading in the out-of-plane direction has strongly investigated since the structure in this loading direction is stiffer and more effective in energy absorption compared to the in-plane loading direction [19-30]. Zhang et al. [20] investigated the dynamic response of the tube-reinforced honeycomb sandwich structure exposed to drop weight impact. It was concluded that the filled tubes strongly increase the stiffness of the panel allowing absorb impact energy more quickly than the empty one. Low-speed impact response of sandwich panel with tube filled honeycomb core was numerically investigated in [21]. Liu et al. founded that the honeycomb filled with circular tube configuration promote the local impact resistance and significantly improved the global flexural rigidity of the thin sandwich panel. Low-velocity impact failure of aluminium honeycomb sandwich panels is discussed in [27]. Results showed that higher density cores have higher level of peak loads and experienced minor damage profiles in the core and front facesheet. Khodai et al. [30] numerically investigated high velocity impact on foam-filled honeycomb structures. Authors found that adding foam to honeycomb leads to an increase in energy absorption of the projectile in the form of plastic dissipation and frictional dissipation, which in turn increases the energy absorption by the target and increases ballistic limit velocity.

In some applications, such as using a honeycomb block as an energy absorption layer in aircraft against bird or debris collision, the crushing could occur along any direction of the honeycomb. Thus, the dynamic behaviour of honeycomb structure in the in-plane direction under impact loading is also needs to be investigated. This domain is not extensively studied, nonetheless, some articles are published on it [31-34]. The dynamic responses of aluminium honeycomb sandwich panels subjected to the in-plane high-velocity impact were numerically studied in [31]. Alam et al.

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[32] investigated the performance of sandwich struc–tured armour systems upon ballistic impact load. The model of the armour was in the form of sandwich structure with fiber reinforced polymers as the skin and aluminium alloy as the core. The core was filled with silicon carbide (SiC) and aluminium oxide (Al2O3). In [34], impact and close-in blast response of auxetic honeycomb-cored sandwich panels were inspected. Both field, blast and drop weight tests, were performed using the proposed sandwiches as a shield for concrete panels in combination with conventional steel protective plates. The combined shield was found to be effective in protecting reinforced concrete structures against severe impact and close-in blast loadings.

As it can be concluded from the aforementioned articles, new structural designs could be the suitable way of improving the loading capacity, impact resis–tance and energy absorption of sandwich structures. Creating hierarchical honeycombs, honeycomb-corru–gation hybrids, and grid reinforced honeycombs, as well as filling the honeycomb holes, are the approaches generally used to improve honeycomb structure strength.

In this article, honeycomb sandwich panels filled with circular tubes submitted to in-plane low velocity impact are numerically investigated using the finite element code Abaqus/Explicit. In order to validate the finite element (FE) model by comparing the simulation results with experimental values published by Zhang et al. in [20], the simulation of impact loading in the out-of-plane direction is carried out. The numerically obtained impact responses of the panel in the in-plane direction under different impact energies (5J, 10J, 20J and 30J) are analysed in detail. The deflections of the front and back facesheets of the empty and filled honeycomb core are explored. The panel degradation and the stress distribution during the crushing are also discussed.

2. FINITE ELEMENT MODEL

In order to investigate the response of the honeycomb sandwich panel in the in-plane direction under low velocity impact, the numerical modelling of the drop weight test was carried out using the nonlinear explicit finite element code Abaqus/Explicit. The impact in the out-of-plane honeycomb core direction is also modelled with the aim of validating the FE model. The configurations of the sandwich panels are presented in the Figure 1.

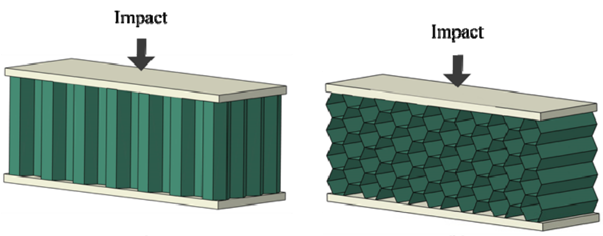

Figure 1. Schematic of honeycomb sandwich panel: (a) out-of-plane direction, (b) in-plane direction

2.1 Out-of-plane impact model (model validation)

To validate the FE model, the experimental test (EXP) of an empty honeycomb sandwich (EHS) panel under low velocity impact in the out-of-plane direction, realized in [20], was numerically modelled. The sandwich panel specimen consists of the front and back facesheets with dimensions of 150 mm × 100 mm × 1 mm, tied to the honeycomb core with dimensions of 150 mm × 100 mm × 20 mm. In addition, the back facesheet is bonded to the rigid support which had a 125 mm × 75 mm hole in the centre. The impact is simulated using a 16 mm diameter rigid hemispherical impactor with the total mass of the 10.637 kg, as shown in Figure 2a.

A unit cell of the honeycomb core is dimensioned as regular hexagonal with hexagon side length of 3 mm, single-wall and double-wall thicknesses of 0.05 mm and 0.1 mm, respectively, see Figure 2b. The cell wall material as well as the facesheet’s one is modelled as elastic-perfectly plastic aluminium alloy Al 3003 with the parameters defined in [20] and summarized in the Table 1. The general contact frictional coefficient of 0.2 is applied for the model. The strain rate effect of the sandwich panel was not considered because of the insensitivity of the aluminium alloy to the strain rate under low velocity impact load [20].

The honeycomb core is meshed using the 4-node, quadrilateral shell element, reduced integration with hourglass control (S4R) with element size of 0.8 mm. The element 8-node linear brick, reduced integration with hourglass control (C3D8R) and element size of 0.5 mm is used to mesh the facesheets. Besides, the 4-node three-dimensional bilinear rigid quadrilateral element (R3D4) is used to mesh the impactor and the rigid support with element size of 0.5 mm and 1 mm respectively. The mesh parameters are summarized in Table 2. The mass scaling technic has been adopted to reduce the computational effort while keeping good accuracy of results.

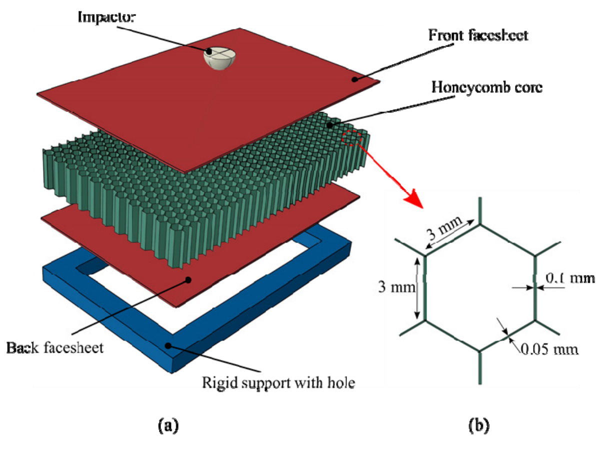

Figure 2. (a) FE model in the out-of-plane direction, (b) regular hexagonal cell geometric parameters

2.2 In-plane impact model

The EHS panel (Figure 3a) and the circular tubes filled honeycomb sandwich (CTFHS) panel (Figure 3b) are modelled to simulate the behaviour of these panels under low velocity impact in the in-plane direction. The EHS panel specimen consists of the front and back facesheets with the same dimensions as the ones in the out-of-plane model, tied to the same cell geometrical honeycomb core with dimensions of 150 mm × 100 mm × 20.8 mm but oriented in the in-plane direction Figure 3c.

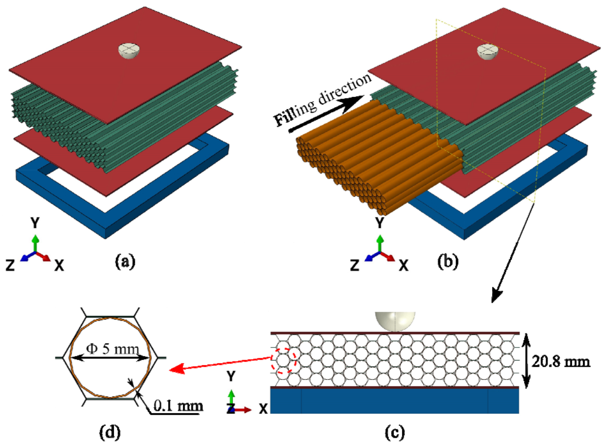

Figure 3. FE model in the in-plane impact direction: (a) EHS panel, (b) CTFHS panel, (c) cross-section of the CTFHS panel and (d) geometric parameters of the filling circular tubes

Furthermore, the CTFHS panel is designed as the honeycomb core filled with circular tube with 5 mm inner diameter and thickness of 0.1 mm, Figure 3d. It should be noted that there is no adhesive or weld connection between the honeycomb and tubes, the inside tubes are simply inserted into the hollow area of the honeycomb cells. The circular tubes are meshed using the 8-node linear brick, reduced integration with hourglass control (C3D8R) with element size of 0.8 mm, see Table 2.

Table 1. Material parameters of the aluminium alloys Al 3003 and Al 6061

	Al 3003	Al 6061
ρ (kg/m^3)	2730	2700
E (GPa)	69	69.5
ν	0.33	0.33
Yield stress (MPa)	175	200

Table 2. Finite element model mesh parameters

Component	Element size (mm)	Element type	Number of elements	Number of nodes
Out-of-plane				
Front facesheet	0.5	C3D8R	120000	181503
Back facesheet	0.5	C3D8R	120000	181503
Honeycomb core	0.8	S4R	193950	186160
Impactor	0.5	R3D4	1892	1894
Rigid support with hole	1	R3D4	22145	21954
In-plane				
Front facesheet	0.5	C3D8R	120000	181503
Back facesheet	0.5	C3D8R	120000	181503
Honeycomb core	0.8	S4R	208680	196182
Circular tube	0.8	C3D8R	3760	7560
Impactor	0.5	R3D4	1892	1894
Rigid support with hole	1	R3D4	22145	21954

In addition to the aluminium alloy Al 3003 used for the honeycomb and the facesheets, the aluminium alloy Al 6061 is modelled as elastic-perfectly plastic material and used for the tubes [20]. The material parameters are summarized in the Table 1.

The EHS and CTFHS panels in the out-of-plane and in the in-plane directions are subjected to four different impact energies; 5J, 10J, 20J and 30J which correspond to impact velocities of 970, 1370, 1940, and 2380 mm/s, respectively.

The duration of each analysis took around 3 hours with a computer equipped with 6 CPU cores of 2.20 GHz and memory of 16 GB.

3. RESULTS AND DISCUSSION

3.1 Model Validation

The FE analysis of EHS panel under different impact energies in the out-of-plane direction is carried out. The numerical and experimental results of the contact force versus time are presented and compared with each other. It should be noticed that the numerical results are in very good agreement with the experiment ones [20], as shown in Figure 4. Consequently, it is clearly con–firmed that the FE model is able to reproduce accurately the tests and can be used for further numerical analysis.

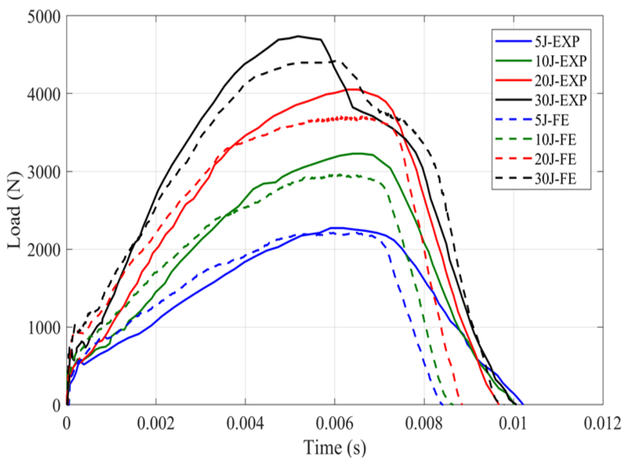

Figure 4. Load-time curves of FE and EXP impact in the out-of-plane direction

3.2 Impact Response

In order to analyse the impact response of the EHS and CTFHS panels under different impact energies, the evolution of the contact force between the impactor and the panel over time was drawn. Moreover, the velocity of the impactor was also drawn in the same figures.

The responses of the EHS panels show, for all impact energies, that the maximum values of the contact force were registered in the first 0.01s (Figure 5), which lead to absorb the major amount of the impact energy. This energy extremely crushes the panel and causes a detachment between the impactor and the panel. Hence, the contact force drops to zero. However, as can be seen from the velocity curves, the kinematic energy of the impactor was not entirely absorbed before this detac–hment. Thus, another impact occurs allowing the total absorption of the energy and the rebound of the impactor.

Nevertheless, it is noticeable that filling the honeycomb core with the tubes strongly increases the contact force, Figure 6. Compared to the EHS panels, the peak load of the CTFHS panels showed an increase of 65%, 64%, 61% and 60% when subjected to 5J, 10J, 20J and 30J impacts, respectively. Besides, the entire amount of the impact energy was absorbed during a shorter time. It should also be noticed that no detachment appears between the impactor and the panel until the rebound of the impactor, see Figure 6.

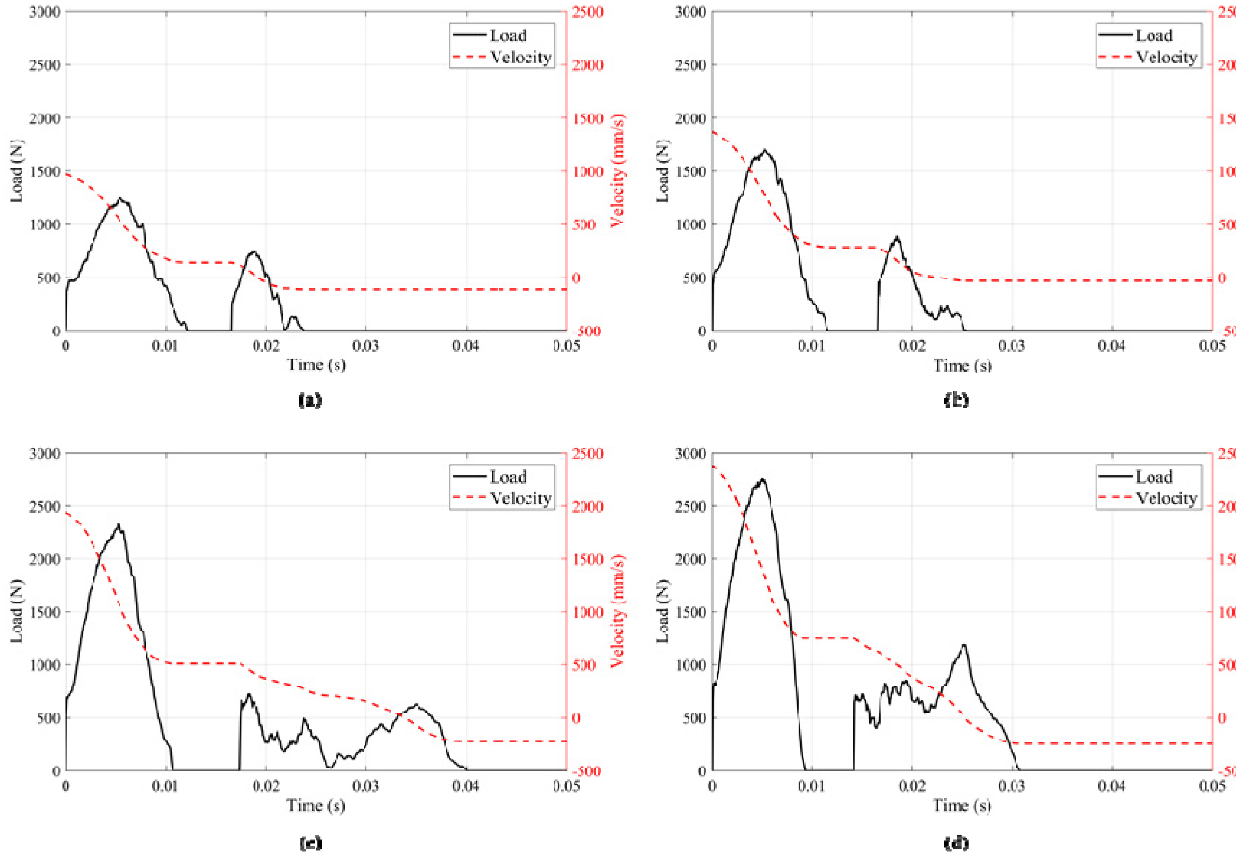

Figure 5. In-plane impact response of the EHS panel under the impact energies: (a) 5J, (b) 10J, (c) 20J and (d) 30J

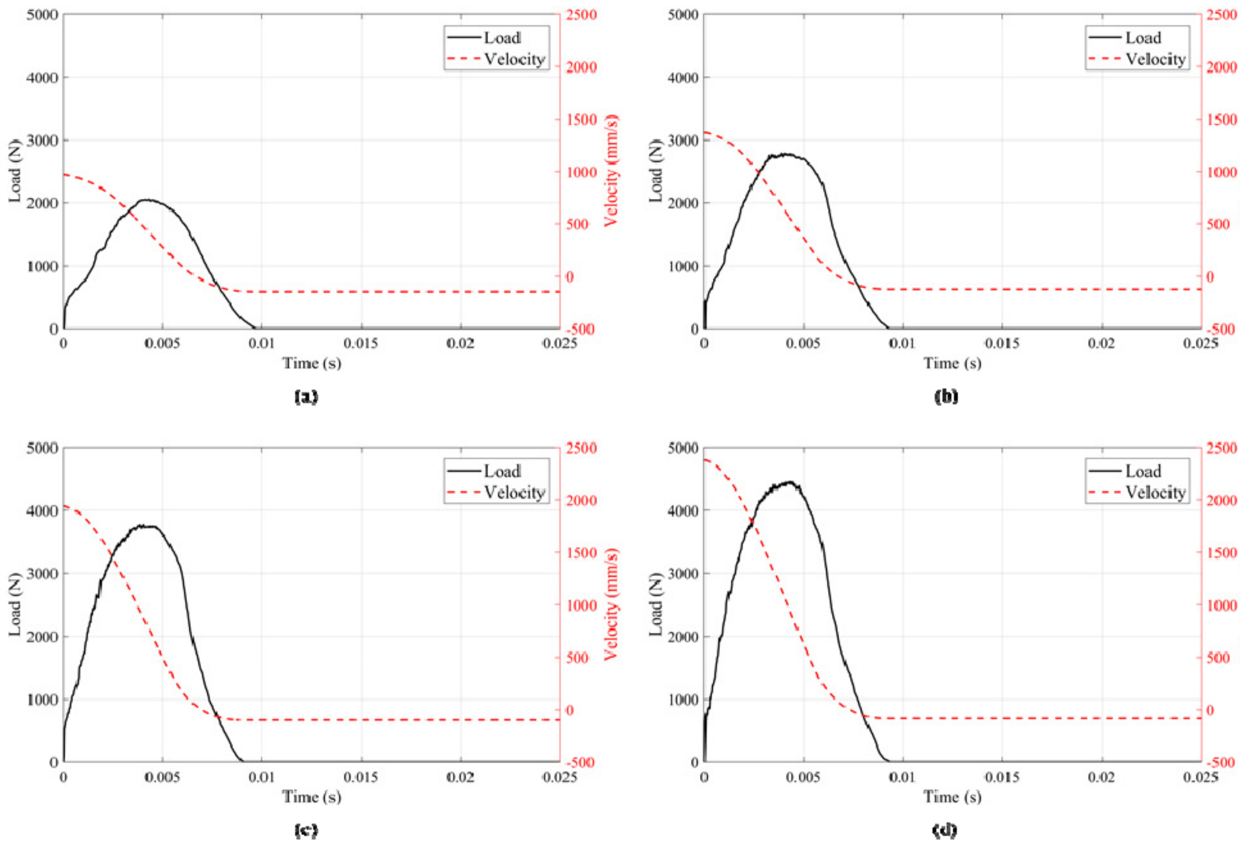

Figure 6. In-plane impact response of the CTFHS panel under the impact energies: (a) 5J, (b) 10J, (c) 20J and (d) 30J

3.3 Facesheet deformation

To explore the front and back facesheets deformation under different impact energies of the EHS and CTFHS panels, the displacement-time curves of the Node 1 and Node 2, which correspond respectively to the centre node of the front and back facesheet (Figure 7), are presented in Figures 8 and 9.

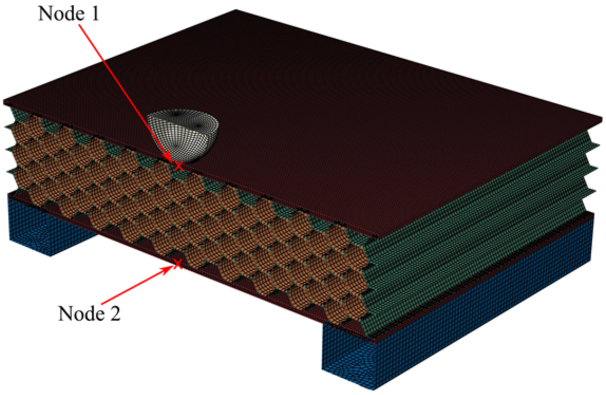

Figure 7. Cross-sectional view of the sandwich panel showing the position of the Node 1 and Node 2

As can be seen in the Figure 8, the deflection of the Node 1 increases with increasing the impact energy. However, the maximum deflection of the Node 1 in the CTFHS panel, compared to the EHS, decreased by 47%, 53%, 64% and 61% for the impact energies 5J, 10J, 20J and 30J, respectively. This decrease is caused by the presence of the tubes which provide higher resistance to the panel.

The displacements of the Node 2 of the EHS panels show a small oscillation, especially for 5J, 10J and 20J impact energies due to the strong attenuation of the stress wave absorbed during the global crushing of the honeycomb core, see Figure 9a. On the other hand, the CTFHS panel become stiffer by inserting the tubes and a significant deflection of the back facesheet were detected, as shown in Figure 9b.

3.4 Deformation analysis

In order to investigate the deformation of the EHS and CTFHS panels subjected to different impact energies, both the panel cross-sectional view and facesheet's frontal views at zero impactor velocity are shown in the Figure 10 and Figure 11, respectively. Moreover, the stress distribution is also presented in the same figures.

It can be observed from the Figure 10, that the deformation of the EHS panel shows, in addition to the local indentation, a global crushing of the honeycomb core because of its low resistance. In contrast, the local indentation was occurred in the CTFHS panel without global crushing owing to the high honeycomb core impact resistance increased by the tubes.

The stress distribution in the front facesheets of the CTFHS panels shows a stress concentration in the impact zone due to the local indentation. On the other side, the distribution range, in the front facesheet of the EHS panels, was relatively lower because of the dissipation of the energy in the crushing of the honeycomb core, see Figure 11a.

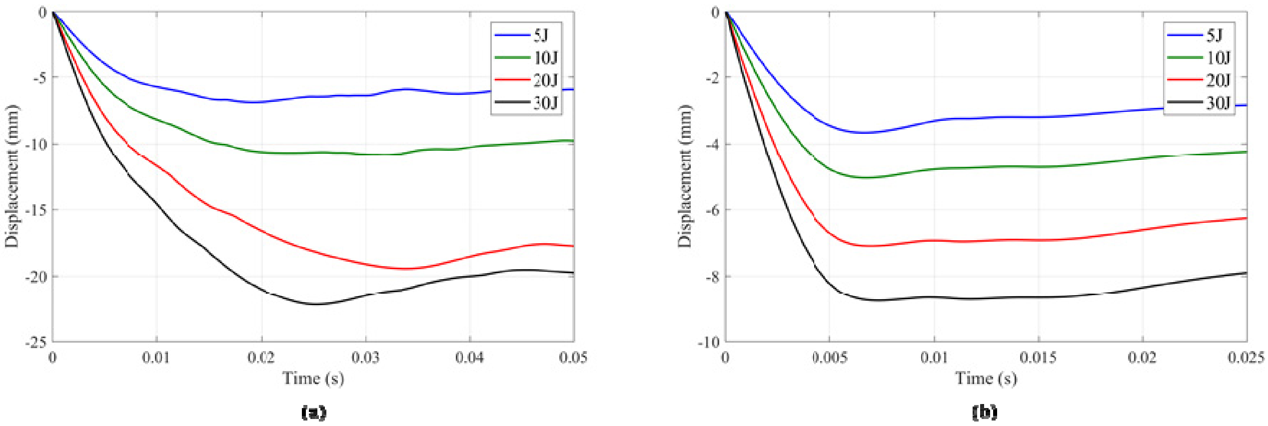

Figure 8. Node 1 deflection of (a) EHS panel and (b) CTFHS panel

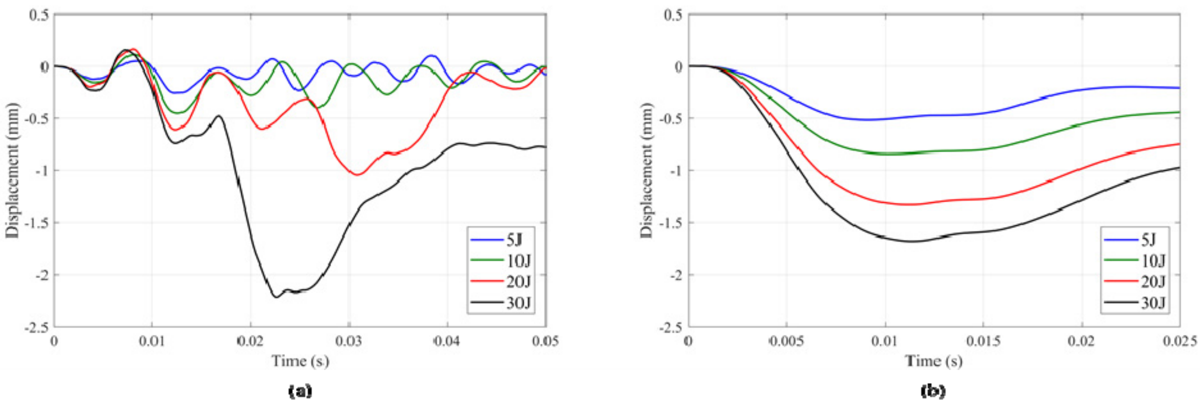

Figure 9. Node 2 deflection of (a) EHS panel and (b) CTFHS panel

As presented in the Figure 11b, the back facesheets of the EHS panels show a neglected stress distribution of those expected for the 20J and 30J impact energy due to the significant penetration of the impactor, see Figure 10c and Figure 10d. However, the CTFHS panels show a higher stress in its back facesheets which lead to the conclusion that, in this configuration, the back facesheet participate in the energy absorption process.

The damaged CTFHS panels may be repaired using the external patch repair method after removing the damaged area under the impactor. The EHS panels cannot be repaired using this method because of the significant damage occurred to the honeycomb core.

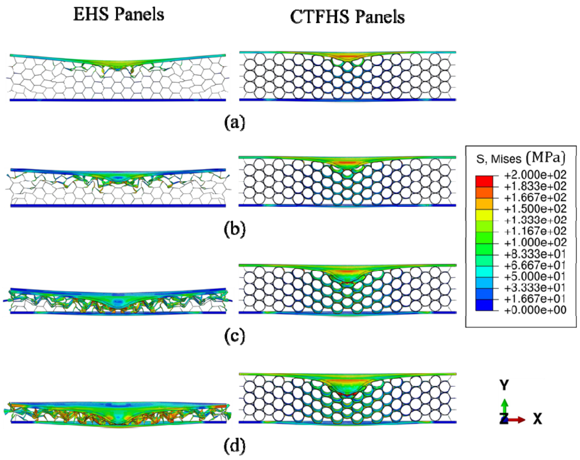

Figure 10. Cross-sectional view with stress distribution of the EHS and CTFHS panels under the impact energies: (a) 5J, (b) 10J, (c) 20J and (d) 30J

3.5 Energy absorption

The energy absorption is one of the most important characteristics when designing a lightweight honey–comb sandwich structure. To provide a better insight, the evolution of the impactor kinetic energy, the strain energy and the total energy are shown in the same figure for each impact energy, see Figure 12.

It is absolutely clear that the kinetic energy was rapidly absorbed and converted to the strain energy for the CTFHS panels compared to the EHS once.

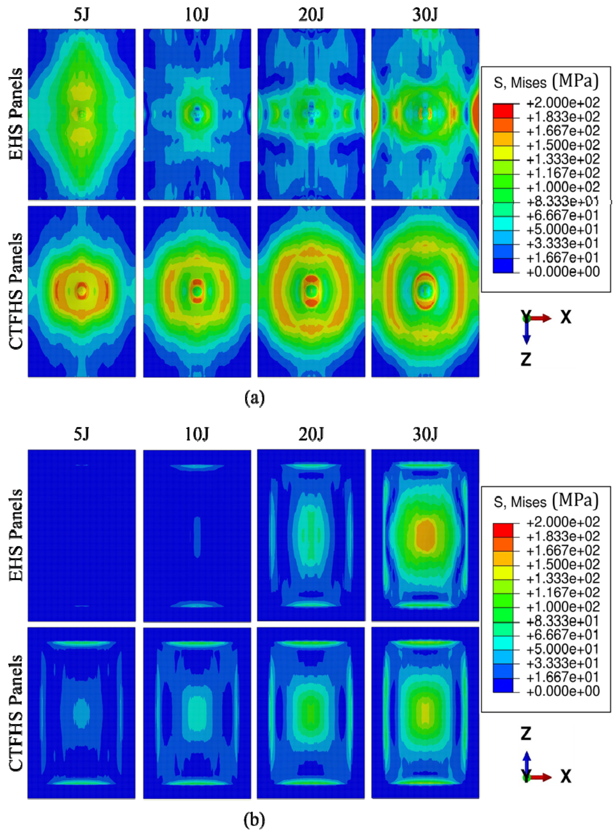

Figure 11. Frontal view with stress distribution of the EHS and CTFHS panels under the impact energies of 5J, 10J, 20J and 30J: (a) front facesheet and (b) back facesheet

The difference between the final absorbed energy of the EHS and CTFHS panels is a consequence of the con–si–derable frictional dissipated energy caused by the inter–action between the honeycomb core and the filled circular tubes.

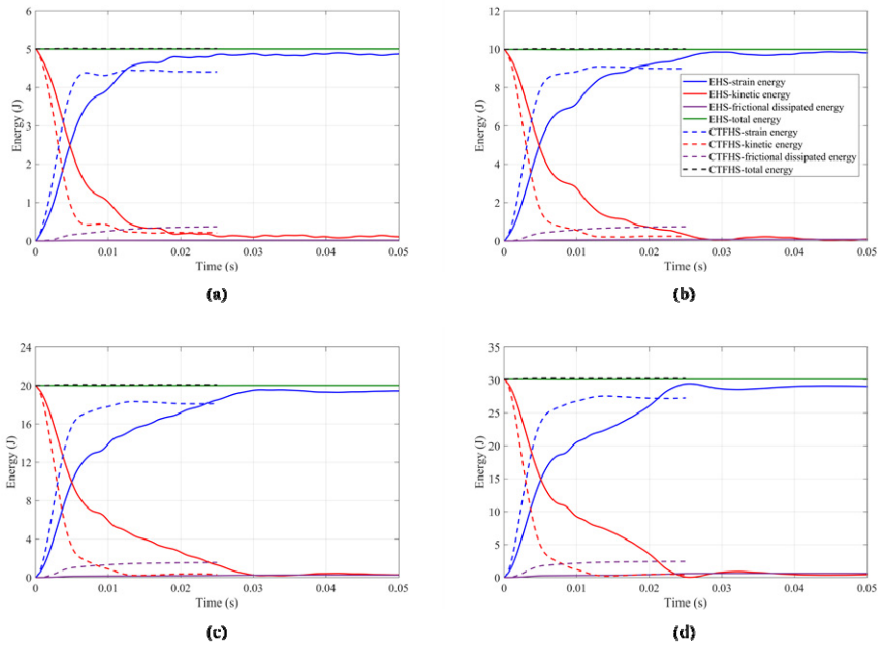

Figure 12. Energy evolution of the EHS and CTFHS panels under the impact energies: (a) 5J, (b) 10J, (c) 20J and (d) 30J

The specific energy absorption, defined as the ratio between the energy absorption to the mass of the structure, is very useful for comparing the energy absorption performance of structures with different geometries and masses. However, in this study, this parameter was not studied because of the fact that both EHS and CTFHS absorb the same amount of energy (conversion of the kinetic energy) and that the CTFHS is clearly the heaviest structure. Thus, the choice of the structure to use depends on the different requirements.

4. CONCLUSION

In this paper, the FE model was developed to investigate the dynamic response of the EHS and CTFHS panels subjected to low velocity impacts in the in-plane direction. In order to validate the numerical model, the EHS panel was simulated to impact tests in the out-of-plane direction. A very good agreement between the numerical and the experimental results [12] was found allowing validating the FE model. It was concluded that filling the empty honeycomb core with circular tubes increases the stiffness of the CTFHS panel and leads to absorb the entire impact energy more quickly than the EHS panel. Besides, the deflection of the front facesheet of the CTFHS panel, compared to the EHS panel, decreases by 47%, 53%, 64% and 61% when subjected to 5J, 10J, 20J and 30J impact energies, respectively. However, the back facesheet of the CTFHS panel shown a significant deflection compared to the EHS panel. It was also found that increasing the sandwich core resistance shows a deformation by local indentation of the impactor, whereas the EHS panel shows, in addition to the local indentation, a global crushing of its honeycomb core. Finally, it can be noted that inserting the tubes is very convenient to improve the crashworthiness of the honeycomb sandwich structure.

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НУМЕРИЧКА АНАЛИЗА ДИНАМИЧКОГ ПОНАШАЊА КОМПОЗИТНОГ САЋАСТОГ ПАНЕЛА ИСПУЊЕНОГ ЦЕВЧИЦАМА ПОД ДЕЈСТВОМ УДАРНОГ ОПТЕРЕЋЕЊА МАЛЕ БРЗИНЕ У РАВНИ ПАНЕЛА

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Композитне структуре, састављене од шестоугаоне саћасте испуне и горње и доње спољашне композитне плоче, се услед добрих апсорпционих карактеристика одликују изванредном отпорношћу на ударна оптерећења. У овом раду приказана је нумеричка анализа динамичког понашања композитног саћастог панела, код којег је унутар сваке ћелије саћа уметнута цевчица, под дејством ударног оптерећења мале брзине у равни панела. Калибрација дефинисаног нумеричког модела извршена је упоређивањем добијених нумеричких резултата са експерименталним резултатима за случај ударног оптерећења мале брзине у правцу управном на правац композитног панела. Нелинеарна анализа удара методом коначних елемената извршена је у софтверском пакету Abaqus/Explicit. Динамичко понашање панела графички је представљено временском променом интензитета силе контакта између импактора и композитног панела. На основу резултата нумеричке анализе утврђено је да исту количину енергије композитни сендвич панел код којег су унутар саћасте испуне уметнуте цевчице апсорбује у доста краћем временском интервалу него композитни панел са стандардном саћастом испуном. У раду је такође извршена и анализа напонско-деформационог стања саћасте испуне, као и горње и доње спољашње композитне плоче приликом дејства ударног оптерећења.