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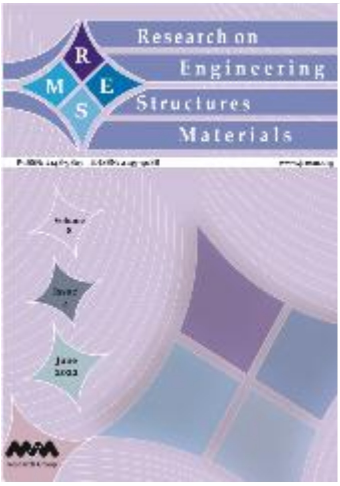

Air blast response of sandwich structures with auxetic cores under in-plane and axial loadings

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Research Article

Air blast response of sandwich structures with auxetic cores under in-plane and axial loadings

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Abstract

Blast loading due to an explosion nearby may generate severe damages on the target. Therefore, engineering structures need to be designed by considering blast loads due to terrorist attacks, accidental explosions or natural disasters. Sandwich structures are good candidates for blast loading applications and core section of these panels are very important to absorb blast loads. This study focused on blast resistance of sandwich structures with lattice core designs. Sandwich panels with honeycomb cores and re-entrant and double arrowhead auxetic cores, which are common and easy to produce in comparison to other type of lattice structures, were used to investigate the impact of core design on front and back face sheet thicknesses, total absorbed energy and maximum stress under in-plane and axial loading due to an explosion. Results revealed that sandwich structures absorb more energy when loaded along axial direction than in-plane direction. According to the simulation results, double arrowhead core outperformed by showing the lowest stress, front and back face displacement and the highest total energy absorption.

1. Introduction

Military vehicles, marine structures and buildings undergo very high loads with very high strain rates due to the detonation of an explosive nearby. When an explosive is detonated, a shock wave with a high velocity and pressure is released from the explosive and moves towards the target. This shock wave or blast loading may generate severe damages on the target. Therefore, these structures need to be designed by considering these loads, or specifically blast loads [1].

To increase the blast resistance of engineering applications, different studies have been performed on blast analysis of different types of structures and materials in literature. Sandwich structures with crushable cores (Fig. 1) are good candidates for blast loading applications since cores between front and back face sheets can dissipate a very large amount of energy in a blast scenario and weakens the transmitted shockwave to back face sheets and therefore protects the vital structures from failure [2]. Core design and core type selection is very important for air blast loading applications of sandwich structures. In literature, different types of sandwich structures with different types of cores have been investigated in terms of their blast performance [3-6]. One of the core types used in sandwich structures to increase blast resistance is auxetic core. When a material or structure is subjected to tensile loading, it extends in longitudinal direction and contracts in lateral direction. The negative value of the ratio of contraction strain to extension strain is called Poisson's ratio which is close to 1/3 for most materials but in rubbery materials it approaches to 1/2. Apart from these materials, some materials show negative Poisson's ratio characteristics [7]. Negative Poisson's ratio, or auxetic, materials expand laterally

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when stretched and contract laterally when compressed [8]. Auxetic structures have unique mechanical, indentation, deformation and viscoelastic behaviors [9]. As stated by Prawoto, auxetic materials find their usage in different industrial applications where specific applications need negative Poisson's ratio, large shear resistance, higher hardness, lower fatigue crack propagation, large toughness and modulus resilience and / or vibration absorption characteristics [10]. For instance, auxetic structures have been used effectively in crashworthiness tubes in automotive and aerospace applications to increase energy absorption capability and without increasing the total weight considerably. Studies showed that auxetic foam filled tubes had 41.3% and 14.3% higher energy absorption capability than empty tubes and tubes with conventional foam filled, respectively [11]. In another study, it was stated that specific energy absorption of anti-tetrachiral and re-entrant lattices filled tubes were 28.5% and 20.6% higher than empty tube, respectively [12]. It was also stated that tubes with auxetic foam filled had better progressive collapse compared to empty tubes and tubes with conventional foam filled [13].

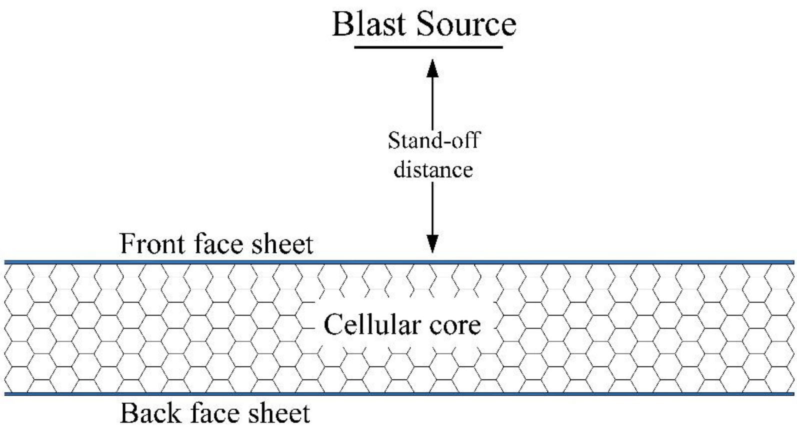

Fig. 1 Blast mitigation concept using a sandwich panel

In a blast loading, auxetic structures move towards impacted area due to their unique negative Poisson's ratio characteristics causing more densification and larger energy absorption at impacted area [14]. Due to these unique characteristics, different types of auxetic structures have been used as core structure in sandwich structures for blast loading applications. For instance, reentrant auxetic structures have been used for blast loading applications in literature [15, 16]. Qi et al. investigated ballistic response of honeycomb sandwich structures with aluminum face sheets and aluminum regular, rectangular-shaped, and re-entrant hexagons cores. They stated that sandwich structures with re-entrant hexagons cores showed the highest blast resistance due to negative Poisson's ratio characteristics [17]. Jin et al. investigated the blast resistance of sandwich structures with graded and cross-arranged auxetic re-entrant cell honeycomb cores. They stated that, compared to ungraded and regular-arranged cores, these structures showed higher resistance against blast loads and the highest blast resistance was observed in structures where cross-arranged graded honeycomb cores with higher density of the upper layer were used [18]. Imbalzano et al. investigated blast performance of sandwich structures with re-entrant auxetic core and stated that re-entrant auxetic core increased the plastic energy dissipation by 50% and decreased back face sheet displacement by 30% when compared with equivalent monolithic steel plates [2]. Qi et al. evaluated blast performance of sandwich panels with honeycomb core and re-entrant hexagonal cells both numerically and experimentally. They stated that these structures showed higher blast resistance than conventional honeycomb structures of the same size, areal density and material [19]. Wang et al. stated that sandwich structures with three-dimensional double V auxetic core showed higher blast resistance and less back face deflection than solid plate [20]. Yang et al. stated that sandwich structures with auxetic core showed better blast performance than traditional panels and this performance can be increased by increasing the number of layers and Poisson's ratio of core [21]. Imbalzano et al. investigated blast resistance of auxetic composite sandwich structures and equivalent honeycomb structures. They stated that in both structures, core and front face sheets completely absorbed the impact energy, but auxetic composite sandwich structures resulted in less stress on back face sheets. Energy dissipation increased and stress on back face sheet reduced when number of layers increased in auxetic composite sandwich structures [22]. Hajmohammad et al. investigated blast response of sandwich structures with nanocomposite face sheets reinforced by carbon nanotubes and auxetic honeycombs core. Their results revealed that reinforcing face sheets with 0.1% carbon nanotubes decreased the maximum dynamic deflection by 59% [23]. Xiao et al investigated the high velocity impact response of sandwich beams with auxetic re-entrant hexagonal aluminum honeycomb core experimentally and numerically. They stated that during impact, local indentation with negative Poisson's ratio deformation and then global deformation were observed and when re-entrant wall thickness increased, negative Poisson's ratio deformation characteristics decreased [24]. Lan et al. investigated the blast resistance of cylindrical sandwich structures with three different cores: aluminum foam core, hexagonal honeycomb core, and auxetic honeycomb core. They stated that structures with auxetic honeycomb cores showed higher blast resistance than that with aluminum foam cores and hexagonal honeycomb cores. Their numerical results revealed that blast performance of structures with all types of cores increased with an increase in curvature and face sheet thickness. Increasing back face sheet thickness was more effective than increasing front face sheet thickness in panels with auxetic honeycomb cores in terms of blast resistance. This result came out to be opposite for the other two core configuration [25]. Novak et al. investigated blast resistance of sandwich composite structures with 3D chiral auxetic core. Experimental results revealed that sandwich composite structures with chiral auxetic core resulted in higher specific energy absorption than a core with a positive Poisson's ratio materials of the same porosity and mass [14]. Lan et al. investigated the blast response of a curved structure with three-dimensional double arrow auxetic core [26]. Luo et al. investigated blast resistance of sandwich structures with composite face sheets and re-entrant and honeycomb cores. Their results revealed that structures with honeycomb cores showed less stress at back face sheet. On the other hand, panels with re-entrant cores showed the best anti-explosion performance at front face sheet. Panel deformation from blast loading was due to crushable cells with auxetic behavior for panels with re-entrant cores and to whole panel bending for panels with honeycomb cores [27].

The studies in literature cover the mechanical and blast performance of sandwich structures with different cores in single lattice structure orientation. However, to the best of authors' knowledge, no study has so far focused on the blast resistance of sandwich structures with different type of auxetic cores under in-plane and axial loadings. To fill the gap of showing efficiency of lattice structure orientation, in this study, blast resistance of sandwich structures with AISI 4340 steel front and back face sheets and different types of AA5083-H116 aluminum alloy auxetic structures as core geometries were investigated by using CONWEP (conventional weapons effects program) blast loading model. Honeycomb cores and re-entrant and double arrowhead auxetic cores were used as design variables and front and back face sheet thicknesses, total absorbed energy and maximum stress under in-plane and axial loadings were evaluated as design outputs. The contribution focuses only on through numerical investigations since experimental studies are not practical in view of the special loading regime. However, the employed CONWEP framework which is already based on experimental investigation partially fills this gap. A similar approach was used by Walkowiak et al. [28] where they investigated different core topologies in sandwich panels subjected to air blast loading. However, the distinguishing feature of the present study is the analysis of different loading regimes in terms of in-plane and axial loading directions. The rest of the paper is organized as follows: Section 2 describes the numerical method details used for blast loading analysis, Section 3 reveals the analysis results and relations between core type and design outputs, and finally the paper is concluded with a Conclusion section which lists main findings from the study.

2. Materials and Methods

In the present study, AISI 4340 steel front and back face sheets with 1.25x640x640 mm dimensions and AA5083-H116 aluminum alloy auxetic cores with 50x640x640 mm dimensions were used. The highest dimensions for the sandwich structure were selected in accordance with the computational efficiency and the current study in literature. The material properties of AISI 4340 steel and AA5083-H116 aluminum alloy are shown in Table 1. AISI 4340 steel material is characterized by its high yield stress and low ductility, on the other hand, AA5083-H116 aluminum alloy is characterized by its high specific energy absorption [22].

Table 1. Material properties of AISI 4340 steel and AA5083-H116 aluminum alloy [2]

	AISI 4340	AA5083-H116
Density (kg/m3)	7850	2750
Elastic modulus (GPa)	210	70
Poisson's ratio	0.3	0.3
Melting temperature (K)	1800	893
Yield stress (MPa)	792	215
Stress hardening (MPa)	510	280

Three different core geometries were used: honeycomb core and re-entrant and double arrowhead auxetic cores. The geometries were modelled by using Siemens NX 12 software. The dimensions of each unit cells for each core geometries are shown in Fig. 2.

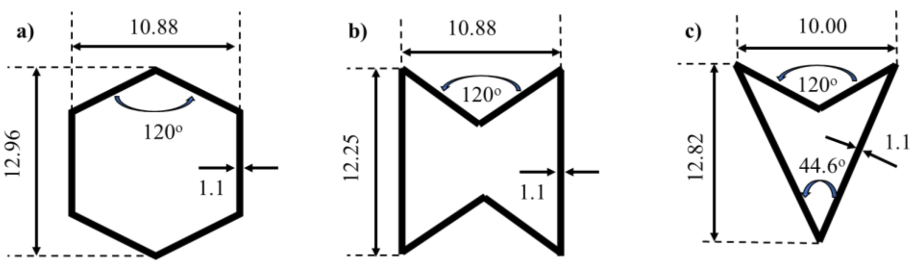

Fig. 2 Dimensions of unit cell geometries: a) honeycomb, b) re-entrant, c) double arrowhead

By using unit cell topologies, sandwich structure core geometries were modelled. The dimension of the unit cell topologies is selected in terms of obtaining the equal core thickness in different designs. These sandwich structures were intended to be loaded in axial and in-plane directions. The in-plane direction is the direction where the orientation of the cell walls is as much parallel as to the bonding axis [29]. The loading directions for each core geometry and related sandwich structures are shown in Fig. 3 and 4, respectively.

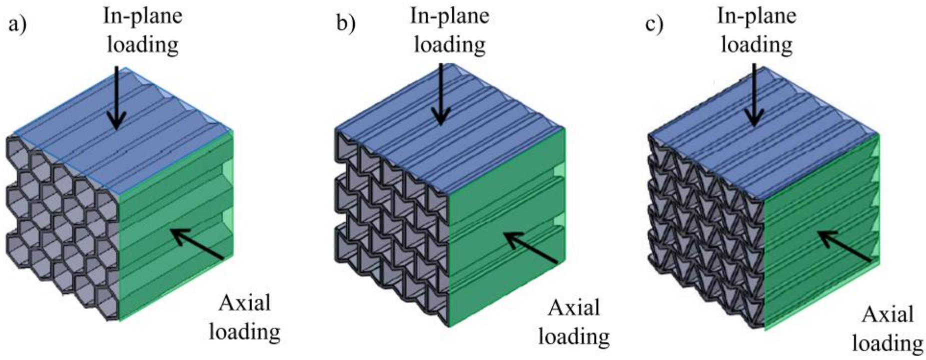

Fig. 3 Loading directions for: a) honeycomb, b) re-entrant, c) double arrowhead lattice structure cores

Blast loading applications were performed by using CONWEP (conventional weapons effects program) blast loading model in Abaqus 6.14. In CONWEP, the blast originated from the source creates pressure and it decays with time, as expressed below:

$$P(\mathrm{t}) = \mathrm{P_{so}}\left[1-\frac{\mathrm{t}-\mathrm{T_a}}{\mathrm{T_0}}\right]\exp\left[\frac{-\mathrm{Ax}(\mathrm{t}-\mathrm{T_a})}{\mathrm{T_0}}\right] \tag{1}$$

in which P(t) – MPa is the pressure at the time t - sec, P_{so} – MPa is the peak incident pressure, T_o – ms is the positive phase duration, A is the decay coefficient, and T_a - ms is the arrival time of the shock wave. The explosive mass (1 kg TNT) was placed at the center of sandwich structure and 100 mm away from the front face. The mass of the explosive is determined as a result of different amount of explosive mass trials in order to define the optimum emerged blast that the sandwich structures are able to mitigate. In order to apply boundary conditions, all the edges of the sandwich structures are clamped, and a quarter model is constituted with symmetric boundary conditions to reduce the computational time as seen in Fig. 5. Johnson Cook material parameters and model are utilized in the simulations to describe the rate-dependent behavior of metallic alloys used in the simulations.

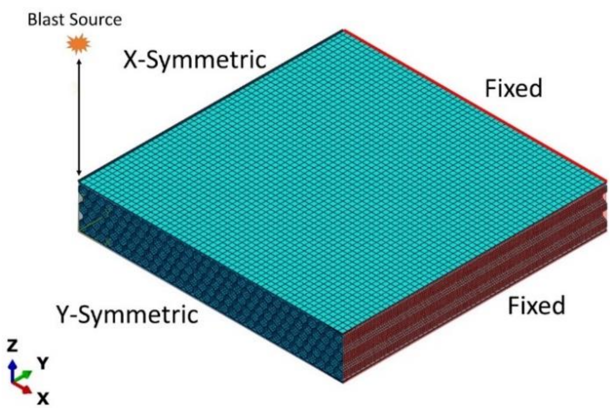

Fig. 5 A quarter sandwich structure model meshed with 5 mm shell elements (S4R) and boundary conditions

The general contact algorithm of shell elements is incorporated using hard contact formulation, while the tangential behavior is described with a penalty friction formulation with a friction coefficient of 0.3. For the discretization, 5 mm thick shell elements (S4R) were used for both core topologies and front and back face sheets (Figure 5) as a result of convergence study with compromising the computational time [22]. Front and back face displacements and total energy absorption values were calculated at 1.5 ms after the blast takes place.

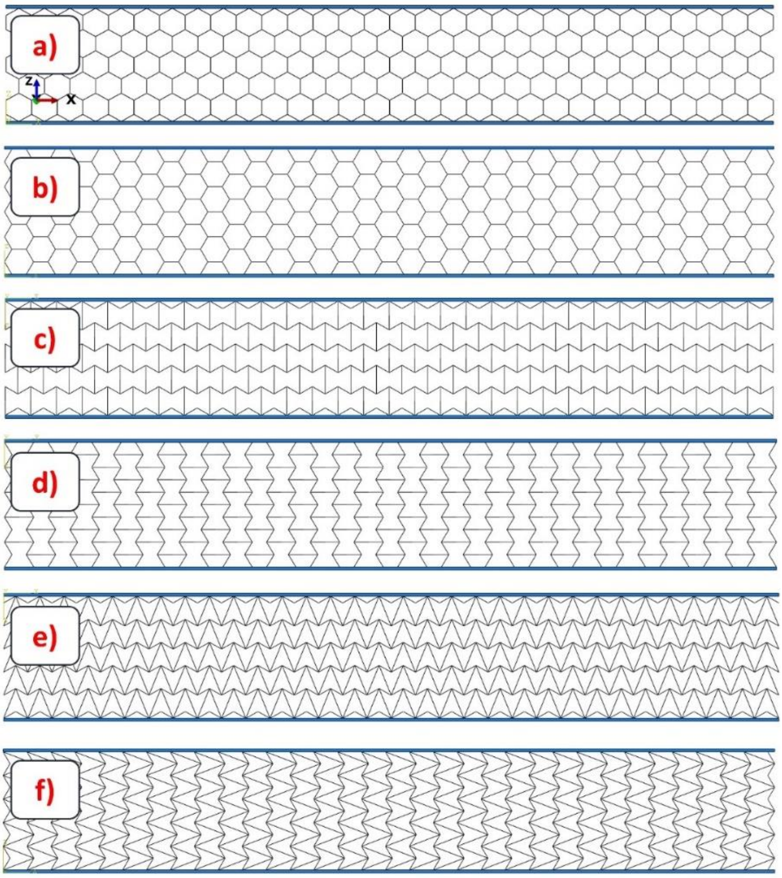

Fig. 4 Sandwich structures with: a) in-plane honeycomb core , b) axial honeycomb core, c) in-plane re-entrant core, d) axial re-entrant core, c) in-plane double arrowhead core, d) axial double arrowhead core

3. Results and Discussions

3.1. Von Misses Stresses

Von Misses stress distribution on the sandwich structures with honeycomb core under in-plane and axial loading conditions are shown in Fig. 6a and 6b, respectively. When explosive mass is detonated, an air blast shock wave propagates towards the sandwich panel. After the first interaction between shock wave and sandwich structure, the front face sheet is deformed elastically and plastically, and the shock wave is redistributed on the core. When the back face sheet deflection is maximized, the sandwich panels rebound, and some amount of both the front and the back face sheet deflections are recovered [25].

As shown in Fig. 6, the honeycomb core shows bending-dominated behavior meaning that expansion and deformation of the core from center of the sandwich structure to the sides are present [22]. It can also be stated that the blast energy is dissipated in the core through three mechanisms: breakage of honeycomb cell walls, honeycomb core compaction and plastic deformation [30]. It was observed that in-plane loading resulted in higher stresses than axial loading (1257 MPa vs 1160 MPa).

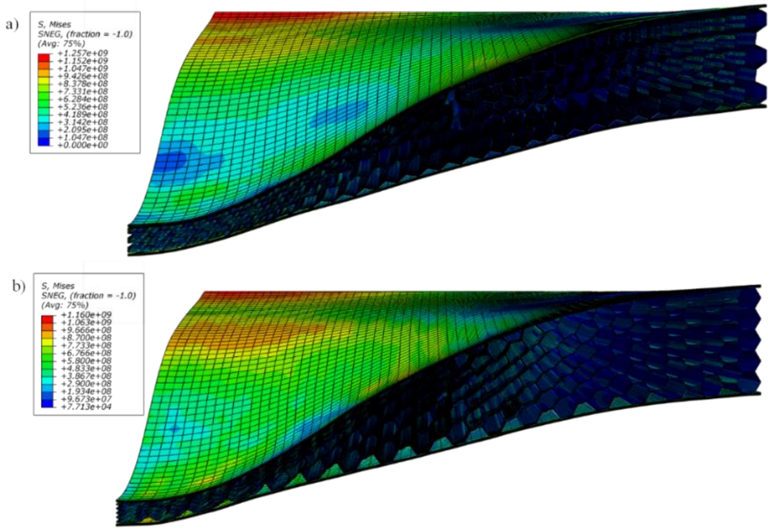

Fig. 6 Stress distribution on quarter sandwich structures with honeycomb core under: a) in-plane loading, b) axial loading

Von Misses stress distribution on the sandwich structures with re-entrant core under in-plane and axial loading conditions are shown in Fig. 7a and 7b, respectively. Contrary to the sandwich structures with honeycomb core, the maximum stress on the sandwich structure with re-entrant core is higher when loaded in axial direction compared to the in-plane loading (1297 MPa vs 1198 MPa). Similar results (1090 MPa vs 1049 MPa) were also observed in sandwich structures with double arrowhead core as shown in Fig. 8. For the three different core topologies, the maximum and the minimum stress values were observed on sandwich structure with re-entrant core under axial loading and that with double arrowhead core under in-plane loading, respectively.

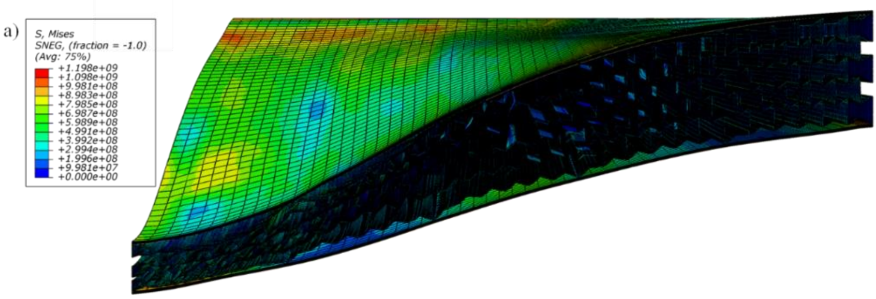

Fig. 7 Stress distribution on quarter sandwich structures with re-entrant core under: a) in-plane loading

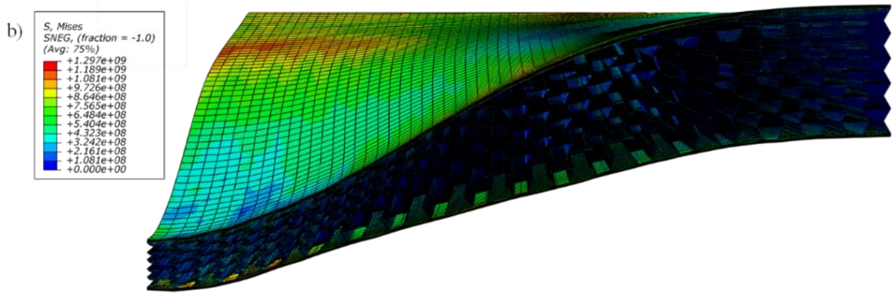

Fig. 7(cont) Stress distribution on quarter sandwich structures with re-entrant core under: b) axial loading

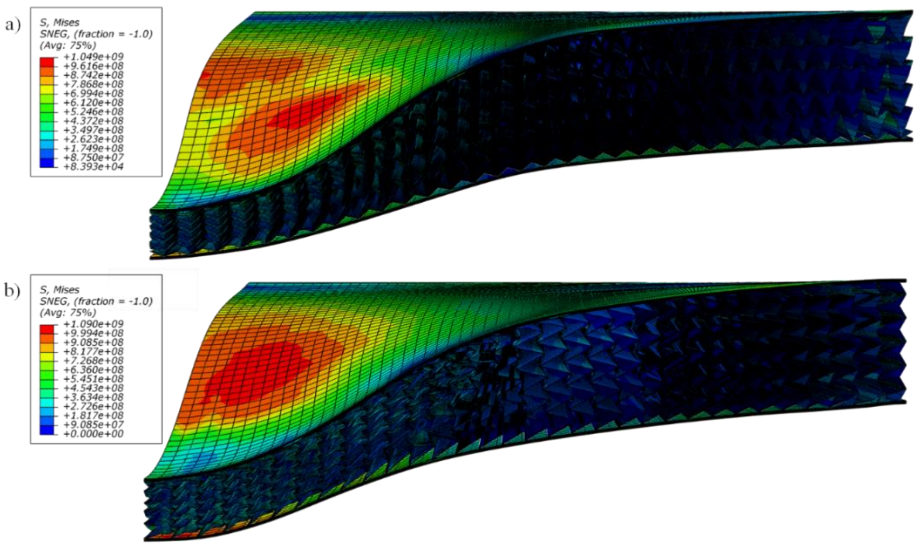

Fig. 8 Stress distribution on quarter sandwich structures with double arrowhead core under: a) in-plane loading, b) axial loading

3.2. Front Face Displacements

Fig. 9 shows the front face displacements for different core topologies under in-plane and axial loading conditions. For all core topologies, it is clear that front face progressively deforms up to its maximum displacement at a certain time, then due to the auxetic effect and redistribution of the load on the entire core, the displacement decreases and the front face tries to get back its original shape [31]. In Table 2, the maximum front face displacement, maximum displacement times and deviations comparing to honeycomb lattice structures response in in-plane direction are displayed. For sandwich structures with honeycomb core, the maximum displacements were observed at 0.80 ms with a value of 117.6 mm and 0.78 ms with a value of 116.4 mm for in-plane and axial loading conditions, respectively. For the in-plane and axial loading of sandwich structures with re-entrant and double arrowhead core topologies, the maximum displacements were observed at 0.88 ms with a value of 107.2 mm, at 0.80 ms with a value of 106.1 mm, at 0.70 ms with a value of 89.0 mm and at 0.74 ms with a value of 90.2 mm, respectively. The highest displacement was observed with honeycomb core topology under in-plane loading condition. On the other hand, the lowest displacement was observed with double arrowhead core topology under in-plane loading condition. Loading along axial direction resulted in lower maximum front face displacement for sandwich structures with honeycomb and re-entrant cores, but the situation is opposite for sandwich structures with double arrowhead core.

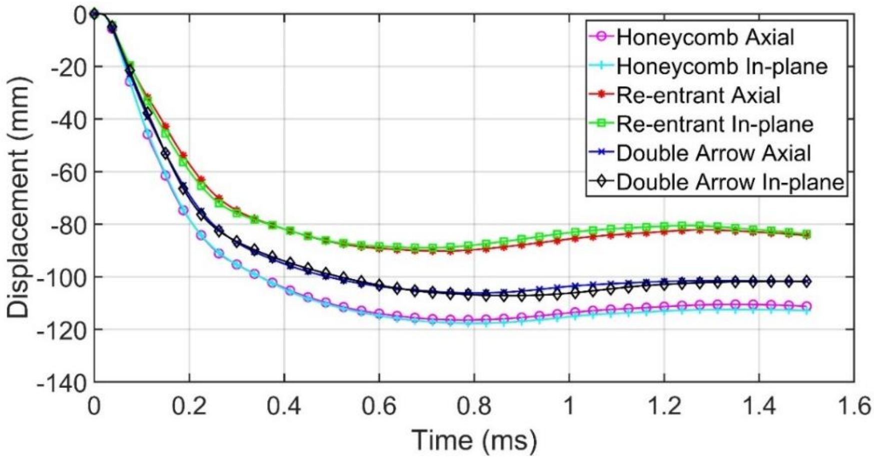

Fig. 9 Front face displacements

Table 2. Maximum front face sheet displacements, maximum displacement times and deviations comparing to honeycomb lattice structures response in in-plane direction

	Orientation	Time (ms)	Maximum Displacement (mm)	Deviation (%)
Honeycomb	Axial	0.780	116.393	-1.04
	In-plane	0.803	117.621	-
Re-entrant	Axial	0.803	106.136	-9.76
	In-plane	0.878	107.156	-8.90
Double	Axial	0.735	90.147	-23.36
Arrowhead	In-plane	0.698	88.983	-24.35

Table 3. Front face displacements at 1.5 ms and deviations comparing to honeycomb lattice structures response in in-plane direction

	Orientation	Displacement (mm)	Deviation (%)
Honeycomb	Axial	111.22	-1.41
	In-plane	112.82	-
Re-entrant	Axial	101.66	-9.89
	In-plane	101.77	-9.79
Double Arrowhead	Axial	84.28	-25.30
	In-plane	83.75	-25.77

The final front face displacements at 1.5 ms for all topologies are shown in Table 3. Axial loading resulted in slightly less final front face displacement than in-plane loading for honeycomb cores. However, the loading direction has insignificant effect on final front face displacement for re-entrant and double arrowhead cores. Honeycomb cores showed higher final front face displacements than re-entrant and double arrowhead cores. It can be concluded that sandwich structures with double arrowhead core outperformed in terms of front face displacement.

3.3. Back Face Displacements

Fig. 10 shows the back face displacements for different core topologies under in-plane and axial loading conditions. For all core topologies, similar displacement behavior was observed compared to front face displacement. The maximum displacement values, times and deviations in comparison to honeycomb lattice structure's response to the blast load in in-plane direction of back sheets for all lattice structures are shown in Table 4. For sandwich structures with honeycomb core, the maximum displacements were observed at 0.80 ms with a value of 80.7 mm and 0.77 ms with a value of 73.0 mm for in-plane and axial loading conditions, respectively. For the in-plane and axial loading of sandwich structures with re-entrant and double arrowhead core topologies, the maximum displacements were observed at 0.87 ms with a value of 78.8 mm, at 0.80 ms with a value of 70.6 mm, at 0.70 ms with a value of 54.9 mm and at 0.73 ms with a value of 63.8 mm, respectively. Similar to the front face displacement, the highest displacement was observed with honeycomb core topology under in-plane loading condition. On the other hand, the lowest displacement was observed with double arrowhead core topology under in-plane loading condition. Loading along axial direction resulted in lower maximum back face displacement for sandwich structures with honeycomb and re-entrant cores, but the situation is opposite for sandwich structures with double arrowhead core.

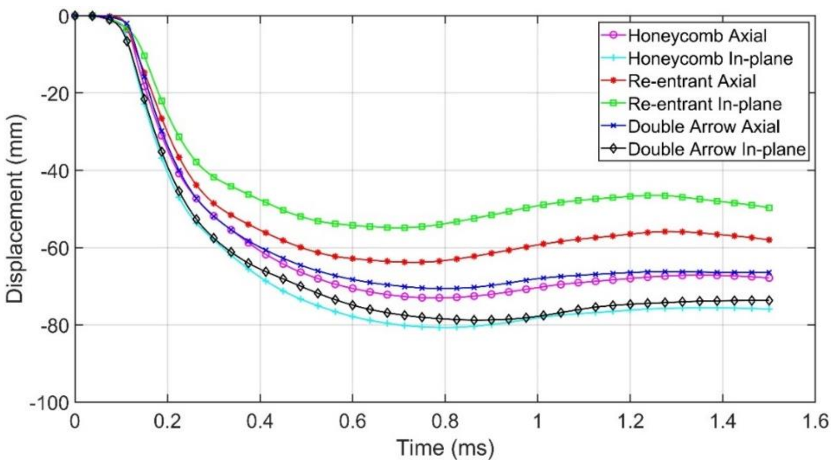

Fig. 10 Back face displacements

The final back face displacements at 1.5 ms for all topologies are shown in Table 5. Axial loading resulted in less final back face displacement than in-plane loading for honeycomb and re-entrant cores. However, the situation is opposite for sandwich structures with double arrowhead core. For both in-plane and axial loading, honeycomb cores showed higher final back face displacements than re-entrant and double arrowhead cores. Similar to the front face displacement, sandwich structures with double arrowhead core outperformed in terms of back face displacement. A comparison between back and front face displacements can reveal that back face displacements are lower than front face displacements indicating that sandwich structure core dissipated some of the energy transmitted from the front face to the back face. This can reduce the structural damages behind the sandwich structure due to air blast loading [20].

Table 4. Maximum back face sheet displacements, maximum displacement times and deviations comparing to honeycomb lattice structures response in in-plane direction

	Orientation	Time (ms)	Maximum Displacement (mm)	Deviation (%)
Honeycomb	Axial	0.77	73.01	-9.50
	In-plane	0.80	80.68	-
Re-entrant	Axial	0.80	70.60	-12.49
	In-plane	0.87	78.79	-2.34
Double	Axial	0.73	63.81	-20.91
Arrowhead	In-plane	0.70	54.89	-31.97

Table 5. Back face displacements at 1.5 ms and deviations comparing to honeycomb lattice structures response in in-plane direction

	Orientation	Displacement (mm)	Deviation (%)
Honeycomb	Axial	67.8	-10.62
	In-plane	75.94	-
Re-entrant	Axial	66.45	-12.50
	In-plane	73.70	-2.95
Double Arrowhead	Axial	58.02	-23.61
	In-plane	49.71	-34.54

3.4. Total Energy Absorption

Total energy absorption of sandwich structures with different core topologies are shown in Table 6. It is clear that sandwich structures absorbed more energy when loaded along axial direction than in-plane direction. The highest and the lowest total energy absorption were observed with double arrowhead core under axial loading and honeycomb core under in-plane loading, respectively.

Table 6. Total energy absorption and deviations comparing to honeycomb lattice structures response in in-plane direction

	Orientation	Absorbed energy (kJ)	Deviation (%)
Honeycomb	Axial	167.67	1.27
	In-plane	165.56	-
Re-entrant	Axial	192.26	16.13
	In-plane	191.24	75.90
Double Arrowhead	Axial	198.24	19.73
	In-plane	181.31	9.51

This can be attributed to the fact that in re-entrant and double arrow core topologies, cells are stretched towards the center of the panel where first interaction between the air blast wave and sandwich structure takes place which increases its energy absorption. On the other hand, in honeycomb core topology, cells at the middle are nearly fully compacted and the other cells are partially compacted [32]. As stated earlier, due to the expansion and deformation of the honeycomb core from center of the sandwich structure to the sides [22], the center of the sandwich structure weakens and smaller magnitude of blast loading can deform the core when compared to re-entrant and double arrowhead cores where the center of the sandwich structure is densified with the application of blast load due to the auxetic behavior of the cells and higher magnitude of blast loading is necessary to further deform the panel. Therefore, more energy is absorbed by re-entrant and double arrowhead core when compared with honeycomb core.

5. Conclusions

In the present study, the effectiveness of different core topologies in sandwich structures under air blast loading was studied. Different loading conditions (in-plane and axial loadings) were also investigated to understand the core topology behavior. The key findings can be summarized as follows:

- Double arrowhead core showed the lowest stress, front and back face displacement under in-plane loading. It showed the highest total energy absorption under axial loading.
- Honeycomb core showed the highest front and back face displacement and the lowest total energy absorption under in-plane loading condition.
- Re-entrant core showed the highest stress under axial loading.
- Sandwich structures absorbed more energy when loaded along axial direction than in-plane direction.
- In-plane and axial loading have different effects on front and back face displacements, stress and total energy absorption of different core topologies. For instance, axial loading resulted in higher stresses than in-plane loading for re-entrant and double arrowhead core. However, the opposite situation was observed for honeycomb core. Axial loading resulted in lower maximum front and back face displacement and less final back face displacement for sandwich structures with honeycomb and re-entrant cores, but the opposite situation was observed for double arrowhead core. Finally, it was observed that a slight or insignificant effect of loading direction on final front face displacement was revealed for all core topologies.

Reducing the effect of air blast loading due to an explosion nearby on the target (especially military applications) is one of the important design criteria. This study showed that by using sandwich panels with honeycomb cores or auxetic cores, the damage due to an explosion on the application can be significantly mitigated due to the energy absorbed by the core geometry. As a future study, experimental verification of numerical studies will be performed and optimum core and loading conditions will be proposed to prevent the any structural application from damages due to air blast loading.

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