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Ballistic impact response of reinforced honeycomb sandwich panels

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Ballistic impact response of reinforced honeycomb sandwich panels

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Abstract. Honeycomb sandwich panels are extensively adopted in a wide range of structures including aircraft, ships, automobiles, and infrastructure for being lightweight and occupying high out-of-plane compression and out-of-plane shear properties. They are evenly popular for their attractive energy absorption capability and resistance to ballistic impacts. Reinforcement of the hexagonal honeycomb panels is an efficient way to improve the impact resistance. However, a detailed study on the reinforcement types against ballistic impacts has not yet been reported. Therefore, the current research investigates the improvement of total energy absorption, ballistic limit velocity, and specific energy absorption (SEA) of three different reinforced hexagonal honeycombs, namely, triangular, circular, and hexagonal reinforcements against high-velocity blunt impacts. A parallel study is also carried out without any reinforcement and only thickening the cell wall of the non-reinforced hexagonal honeycomb panel. A numerical approach is adopted with commercial finite element code Ansys Explicit to analyze the virtual impact cases. The plate of the honeycomb panel is assumed as aluminum alloy Al-7075-T6, while the honeycomb core is made of Al-5083-H116. For both the alloy variants, Johnson-Cook flow stress parameters are utilized. For the projectile, a blunt cylindrical-shaped structural steel bullet is considered. It is found that, for the current investigations, triangular and circular reinforcements can significantly improve the overall ballistic performance of the sandwich panels with a penalty of weight increment. However, thickening the cell wall of the hexagonal core without any reinforcement exhibits the best ballistic performance.

1. Introduction

Inspired by the natural bee honeycomb structure, the man-made honeycomb sandwich panel has successfully found its application to a wide range of industries including aerospace, marine, automobile, and infrastructure due to their excellent flexural rigidity and bending strength in contrast to the low weight ratio. The sandwich panel is manufactured by adhering two thin faceplates with honeycomb cores, where the plate material generally possesses higher stiffness and strength in comparison to core material [1]. The core follows the natural hexagonal shape during production, as shown in Figure 1 [2], which can be structurally reinforced to meet the specific application requirements, as shown in Figure 2 [3]. Moreover, filling the hollow core spaces with different foam materials [4] and varying the thickness and material of faceplates and core walls can also contribute to achieving the desired performance of the honeycomb sandwich panels [5].

2. State of The Art

In recent times, a significant amount of research is conducted to investigate and improve the ballistic impact response of sandwich panels. Yang et al. [6] compared the ballistic resistance of two different sandwich panels with aluminum foam and auxetic honeycomb cores. They found that the energy absorption of auxetic honeycomb cores decreases with increased impact velocity. An experimental and numerical study conducted by Aryal et al. [7] on the composite honeycomb sandwich panel concluded that the numerical model can provide a good correlation with experiments despite having a complex failure mechanism of composite materials. Later on, an Abaqus VUMAT subroutine based on Hashin failure criteria and Matzenmiller-Lubliner-Taylor (MLT) material degradation model is adopted for composite skin by Khodaei et al. [8] to accurately capture the ballistic impact phenomena of a composite honeycomb sandwich panel. After a thorough comparison with available experimental data from the literature, they found that the developed subroutine can correctly predict the energy absorption and damage of the composite panels. Rahimijonoush and Bayat [9] conducted experimental and numerical investigations of ballistic response on the sandwich panel with titanium face plates and aluminum hexagonal core. Their study revealed that the cell wall thickness plays a crucial role to enhance the ballistic limit velocity and energy absorption of the panel. Zhang et al. [10] studied the impact response of three different projectiles, namely, flat, hemispherical, and conical on the sandwich panel with honeycomb cores. They concluded that the sandwich panel absorbs maximum energy when the impactor is conical.

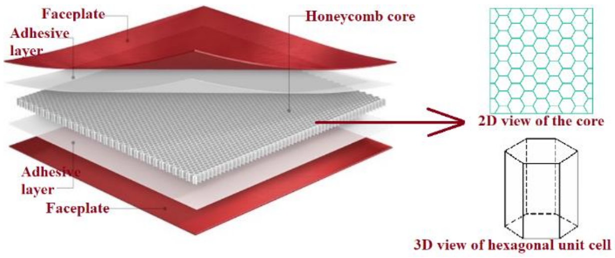


Figure 1. Basic honeycomb design [2]

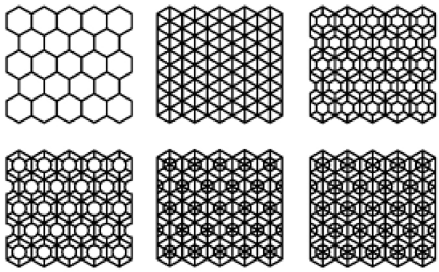


Figure 2. Various types of reinforcement [3]

To improve the ballistic performance of the honeycomb sandwich panel, Roudbeneh et al. [11] investigated the honeycomb cell filled with foam material and found that the specific energy absorption can be maximized by 23% in contrast to the unfilled one. A similar study of honeycomb cells filled with reactive powder concrete prisms suggests a significant improvement of energy absorption during ballistic impact [12]. Another study of sandwich composite panels filled with silica-based shear thickening fluid (STF) revealed that the filler core can improve the energy absorption by 67.4% in contrast to the hollow core [13].

Furthermore, Khaire and Tiwari [14] studied four different hemispherical sandwich shells with different cell sizing of 3.2 mm, 5.0 mm, 7.0 mm, and 9.0 mm. Their study suggested that the energy absorption of the sandwich panel can be enhanced by increasing the thickness of the face sheet and cell wall, whereas, it decreases with the increase of cell size. Wang et al. [15] examined five different honeycomb structures, namely, hexagonal, reentrant, square, triangular, circular (in square and hexagonal arrangement), and suggested that circular honeycomb structure with square and hexagonal arrangement can improve the ballistic limit velocity by 15.2% and 25% respectively, in contrast to the hexagonal honeycomb panel. Gunes et al. [16] studied a honeycomb sandwich structure with three different composite faceplates made of ceramic and aluminum-based functionally graded material against 0.30 caliber fragment simulating projectile. Three different enrichments are adopted, to be specific, n = 0.1 (metal-rich), 1.0 (linear) and 10.0 (ceramic-rich). They concluded that when the faceplate is ceramic-rich (n=10.0), the ballistic velocity limit can reach the maximum value. A similar experimentation suggests that the projectile retains 37% kinetic energy when the faceplate is metal-rich, in contrast to the ceramic-rich faceplates when 97.4% kinetic energy is absorbed successfully [17]. More recently, Zhao et al. [18] investigated the potentiality of an injection-molded composite sandwich bulletproof system and concluded that the ballistic resistance can be improved greatly in contrast to the non-injection molded system.

In summary, it can be concluded that the ongoing effort of improving the ballistic response of honeycomb sandwich panels will be facilitated in the upcoming future along with the emergent of current manufacturing technology. In an attempt to enhance the ballistic performance of the honeycomb sandwich panel, it is crucial to understand the effect of different reinforcements in honeycomb cell structure. Therefore, in this current research, the ballistic performance of three different reinforcement types inside of a hexagonal core, namely, (i) triangular reinforcement, (ii) circular reinforcement, and (iii) hexagonal reinforcement are compared with (iv) hexagonal honeycomb – I (cell wall thickness 0.16 mm) without any reinforcement, and (v) hexagonal honeycomb – II with thickened cell wall (cell wall thickness 0.32 mm) based on residual velocity, ballistic limit velocity, total energy absorption and specific energy absorption (SEA) of the panels.

3. Finite Element Modelling

3.1 Honeycomb cell design

To design the honeycomb sandwich panels, Ansys Design Modeler is adopted. The three-dimensional model of the panel consists of two faceplates with a thickness of 0.5 mm each and a honeycomb core of 18.5 mm, along with the panel height and width of 60 mm is shown in Figure 3 (a). The unit cell dimension of the hexagonal core is given in Figure 3 (c) while triangular, circular, and hexagonal reinforcements can be found in Figure 3 (d-f). For all cases, the cell wall thickness is kept as 0.16 mm while for the increased wall thickness case, the value is doubled.

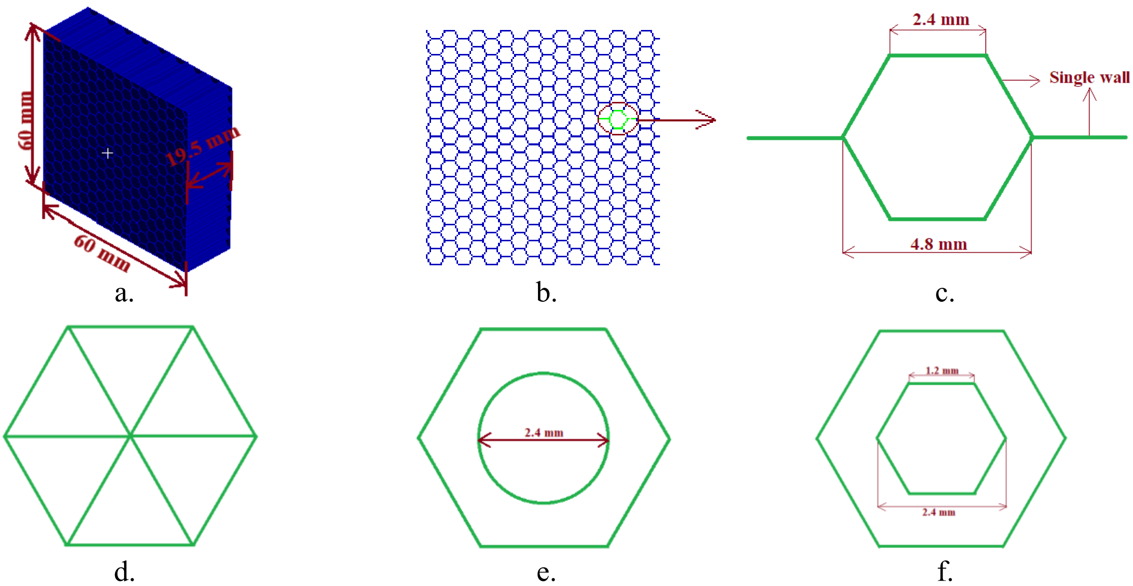


Figure 3. Honeycomb cell modeling a) 3-D Honeycomb sandwich panel, b) 2-D Honeycomb hexagonal cells, c) Unit cell, d) Triangular reinforcement, e) Circular reinforcement, f) Hexagonal reinforcement.

3.2 Honeycomb Material Modelling

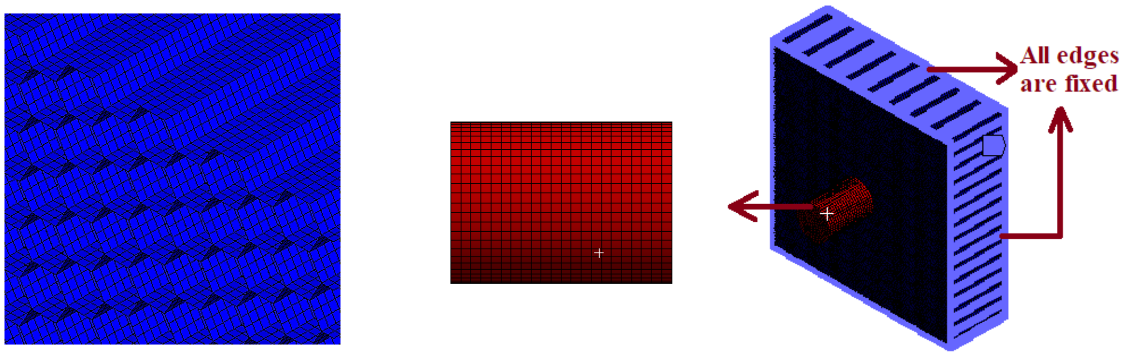
The faceplate of the honeycomb sandwich panel is made of Aluminum Alloy 2024-T3, while the core material is selected from aluminum 5000 series alloy, to be specific, Aluminum Alloy 5754-H11, which is widely adopted as sandwich core material. Since the stress-strain relationship of aluminum alloys vary significantly at different strain rates, therefore, Johnson-Cook flow stress parameters are selected for the present study which is expressed as $\sigma = (A + B\varepsilon^n)(1 + C\ln\dot{\varepsilon}^*)(1 - T^{*m})$, where σ, ε, A denotes as the equivalent stress, equivalent plastic strain, and yield stress of the material respectively. Other remaining constants, namely, $B, n, C,$ and m denotes to strain hardening modulus, strain hardening exponent, strain rate constant, and thermal softening exponent (in case of considerable heat generation) [19]. The material parameters are taken from the literature [20], which is given in Table 1.

Table 1. Johnson-Cook material parameters of Aluminum alloys [20]

Parameters	Aluminum - 2024 - T3	Aluminum - 5754 - H11
Density, ρ (kgm^{-3})	2700	2700
Poisson's ratio, υ	0.3	0.3
Young's modulus, E (GPa)	70	68
Yield stress, A (MPa)	352	28.13
Strain hardening modulus, B (MPa)	440	278.67
Strain hardening exponent, n	0.42	0.183
Reference strain rate, $\dot{\varepsilon}_0$ (s^{-1})	3.3×10^{-4}	0.1
Strain rate coefficient, C	0.0083	0.000439
Thermal softening exponent, m	1.7	2.527
Reference temperature, T_0 (°K)	293	293
Melting temperature, T_{melt} (°K)	775	873
Specific heat (J/kg-°K)	900	900

3.3 Impactor Modelling, Mesh Generation and Boundary Setup

A blunt impactor is modeled with a length of 15 mm and a radius of 5.5 mm. The body is considered as rigid during the impact with a material property of Structural Steel having Young's Modulus, E = 200 GPa, and Poisson's ratio, υ = 0.3. Furthermore, the impactor is meshed with hexagonal brick solid elements, as shown in Figure 4 (b). For faceplates and honeycomb sandwich core, quadrilateral shell elements are selected, as shown in Figure 4 (a). A mesh convergence study presented in table 2 confirms the optimal element size for the meshed bodies at an impact velocity of 165 m/s. The selected velocity is chosen such that the projectile cannot penetrate through the back faceplate and is trapped inside the core with permanent deformation of the back faceplate. Since the maximum deformation results of the back faceplate do not vary significantly with the element sizing from 0.9 mm to 0.7 mm, therefore, a value of 0.7 mm is selected for the present study. Please note that the same element size is also adopted for the reinforced honeycomb panels. Finally, the edges of the sandwich panels are set fixed as the boundary condition, Figure 4 (c).



a. b. c.

Figure 4. Meshed Bodies a) Honeycomb core shell elements b) Blunt impactor solid elements c) Fixed Edges.

Table 2. Mesh Convergence Study (Impact velocity = 165 m/s)

Element Sizing : Plates and Cores, mm	Element Sizing: Bullet, mm	Maximum Deformation of the back faceplate, mm

0.90	0.90	3.13
0.85	0.85	3.45
0.80	0.80	3.50
0.75	0.75	3.46
0.70	0.70	3.28

4. Results and Discussions

4.1 Residual Velocity and Total Energy Absorption

At first, the velocity history of the projectile at an initial impact velocity of 245 m/s is shown for all the five investigated cases, Figure 5. From the illustration, it is apparent that the residual velocity of the projectile is minimum for hexagonal honeycomb – II, to be specific, 48.7 m/s, followed by the triangular reinforcement with a value of 79.3 m/s. In addition, for hexagonal honeycomb – II, the projectile reaches the residual velocity at 0.0003 s which suggests that the panel restricts the blunt projectile to complete penetration at a longer period of time compared to other cases. In contrast, the hexagonal honeycomb – I and hexagonal reinforcement provide little restrictions to the projectile, while the projectile still owns a residual velocity of 140.3 m/s after penetration.

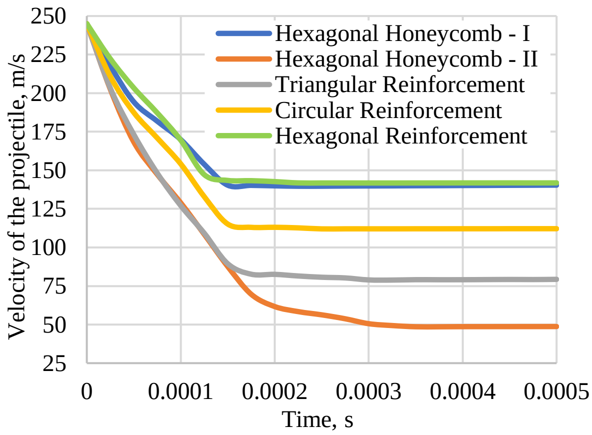


Figure 5. Velocity history of the blunt projectile at 245 m/s

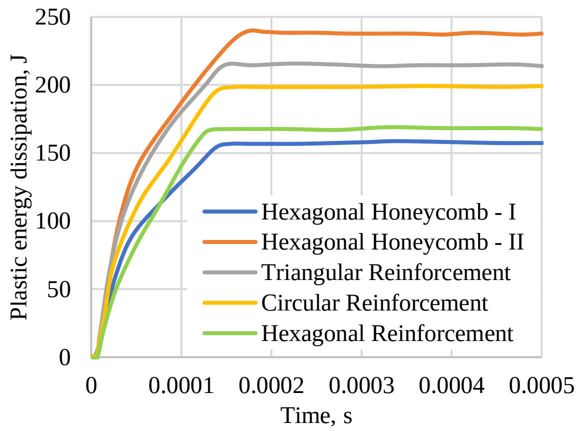
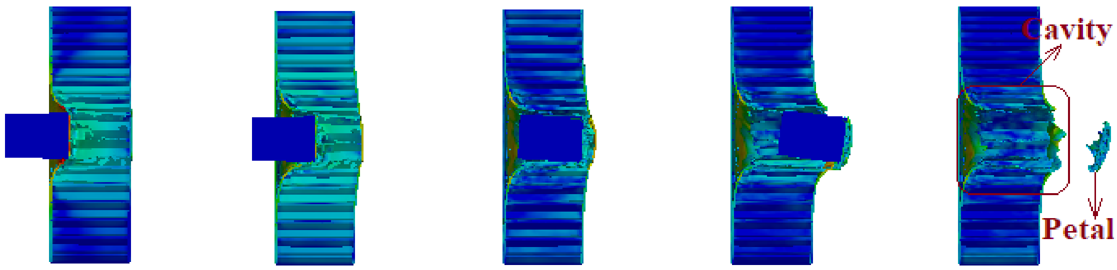


Figure 6. Plastic energy dissipation history of the blunt projectile at 245 m/s

Next, the plastic energy dissipation of the sandwich panels during the blunt impact is illustrated in Figure 6. Among all the cases, the maximum amount of energy, 239.6 J is dissipated by hexagonal honeycomb – II, followed by triangular reinforcement with an amount of 215 J. This finding also suggests that since the maximum kinetic energy is dissipated by the hexagonal honeycomb – II and triangular reinforcement, therefore, the projectile loses most of its impact velocity, around 80.4% and 67.7% during the impact with hexagonal honeycomb – II and triangular reinforcement respectively (See Figure 5). Finally, despite being reinforced, the hexagonal reinforcement dissipates only 168.9 J kinetic energy which is 34.1% less than the hexagonal honeycomb – II and only 6% higher than the hexagonal panel without any reinforcement (Hexagonal Honeycomb –I).

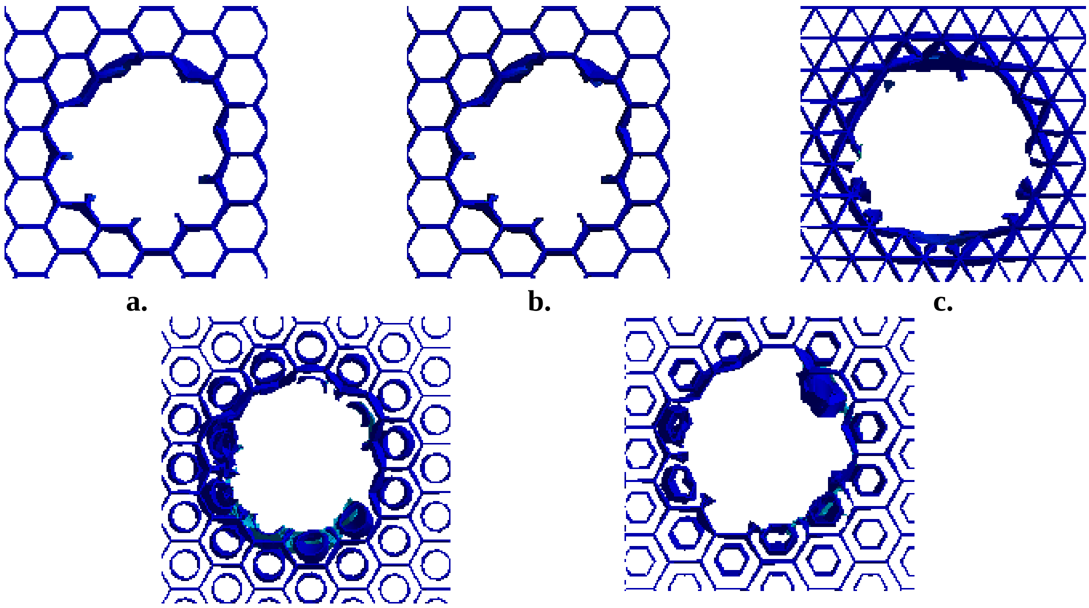
4.2 Damage Initiation

The complete damage initiation procedure of a sandwich panel during the projectile impact velocity of 245 m/s is illustrated in Figure 7. Due to the complete penetration of the panel, petals are identified which are generated from the front faceplate, sandwich core, and back faceplate [Figure 7(e)]. Therefore, a permanent cavity is developed inside the sandwich cores as shown in Figure 8. For all five cases, the central damaged area is mainly utilized to resist the impact while the cell walls outside the holes have a negligible deformation.



a. b. c. d. e.

Figure 7. Damage initiation (side view), Impact at a) 0.00002 s , b) 0.00005 s, c) 0.0001 s, d) 0.00016 s, e) 0.0002 s.



a. **b.** **c.** **d.** **e.**

Figure 8. Damaged area after the penetration of the projectile (front view) a) Hexagonal honeycomb – I , b) Hexagonal honeycomb – II, c) Triangular reinforcement, d) Circular reinforcement, e) Hexagonal reinforcement

4.3 Ballistic Limit Velocities and Specific Energy Absorption (SEA)

Finally, the ballistic limit velocities and specific energy absorption of the sandwich panels are shown in figures 9 and 10 respectively. Ballistic limit velocity defines the velocity at which the sandwich panel is fully penetrated and the projectile comes out with a negligible velocity [6].A simplified way to calculate the ballistic limit velocity is the average between the maximum velocity of the projectile at which the panel is not fully penetrated and the minimum velocity at which the panel is fully penetrated [21]. From Figure 9, it is apparent that certain reinforcement types have definite advantages over the non-reinforced honeycomb panel – I. Both triangular and circular reinforcement have improved the ballistic limit velocity of the honeycomb panels by 8.4% and 17.88% respectively. However, similar to the previous case studies, it is found that thickening the cell wall (hexagonal honeycomb – II) provides the best ballistic limit velocity among all the cases, to be specific 236 m/s. Finally, despite being reinforced with hexagonal cores, the hexagonal reinforcement exhibits a similar performance to honeycomb panel – I.

Since reinforcement or thickening of the cell wall increases the overall weight of the sandwich panel, therefore, SEA can be an important factor that does not depend on the weight of the structure. From the SEA illustration (Figure 10), it is evident that the hexagonal panel – I absorbs maximum energy per gram, to be specific, 4.92 J compared to other honeycomb panels; while the triangular reinforcement has the least energy absorption value of 3.73 J/g. In addition, thickening the cell wall (honeycomb panel – II) can also provide excellent energy absorption than reinforcing the sandwich panels.

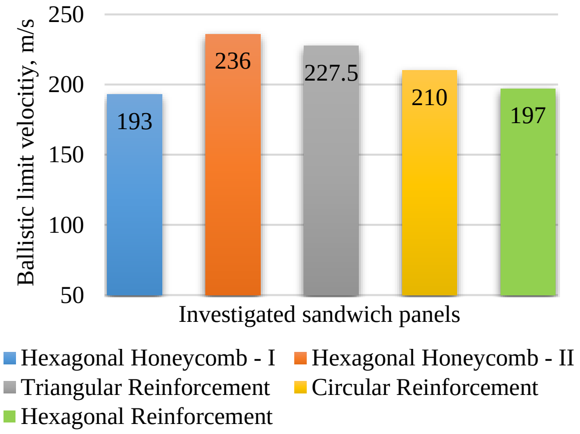


Figure 9. Ballistic limit velocity of the investigated panels

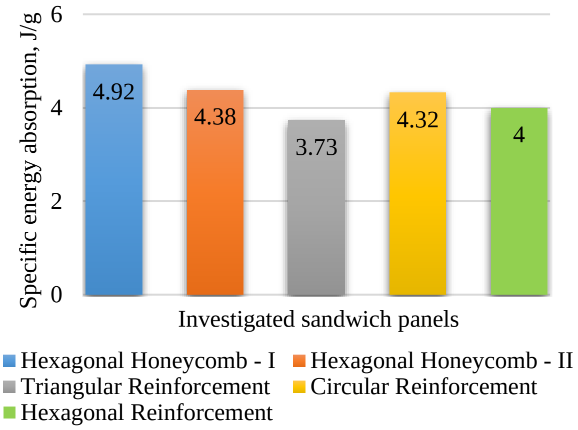


Figure 10. Specific energy absorption of the investigated panels

5. Conclusions

In this present study, a detailed comparison is made among the honeycomb sandwich panels to investigate the effect of three different reinforcements and cell wall thickening against the impact of a blunt projectile. Numerical impact tests are carried out with the commercial software code Ansys. After investigating the in-detailed ballistic response of the honeycomb sandwich panels, the following conclusions are drawn:

1. Certain reinforcement types (triangular and circular) can improve the overall ballistic response of honeycomb sandwich panels. However, for the current investigation, hexagonal reinforcement failed to provide any visible improvement.
2. In terms of energy absorption, both circular and triangular reinforcement exhibit around 36% and 26% energy increments for projectile impacts compared to non-reinforced hexagonal honeycomb panels. On the other hand, the ballistic limit velocity is increased by 8.4% and 17.88% respectively.
3. Cell wall thickening is proved to be more efficient than reinforcing the honeycomb panels to improve the ballistic response of the sandwich honeycomb panels. For total energy absorption, ballistic limit velocity, and SEA, honeycomb panel – II with thickening wall provides approximately 11%, 4%, and 17% improved performance than triangular reinforcement.

In summary, the present study reveals the potentiality of reinforcing the hexagonal cell panels against ballistic impacts. As a future step, other possible reinforced designs will be considered for mass optimization and better ballistic performance.

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