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LAWATY, Samy M., KHALAF, Haitham, ALDERSON, Andrew and ZIED, Khaled <<http://orcid.org/0009-0008-4850-9398>>

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Simulation and Analysis of Stiffened Auxetic Honeycombs Having Enhanced High Impact Velocity Response

Samy M. Lawaty¹ | Haitham Khalaf¹ | Andrew Alderson² | Khaled Zied^{1,3} 

¹Faculty of Engineering, Mataria, Capital University, Cairo, Egypt | ²Sheffield Hallam University, Sheffield, UK | ³College of Engineering at Yanbu, Taibah University, Yanbu, Saudi Arabia

Correspondence: Khaled Zied (kabozied@taibahu.edu.sa)

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ABSTRACT

This study investigates the ballistic performance of two aluminum-based re-entrant auxetic honeycomb configurations: classic and stiffened structures. Finite element analysis was conducted using ANSYS Explicit Dynamics to evaluate the in-plane response under high-velocity impact conditions. The effects of key geometric parameters, including horizontal cell wall length, wall thickness, and cell wall angle, were examined. The numerical model was validated against published data and showed good agreement. Simulations were performed for impacts in two orthogonal directions, revealing that the X-direction provides higher ballistic resistance. A total of 64 configurations were analyzed under a bullet impact velocity of 450 m/s and rotational speed of 11,771 rad/s. Results showed that increasing horizontal wall thickness significantly enhances ballistic resistance and energy absorption, while reducing wall length further improves impact performance. Cell wall angle exhibited minimal influence on ballistic time. Additionally, incorporating vertical and horizontal stiffening ribs significantly enhanced the ballistic performance, increasing the energy absorption efficiency by up to 119.45% and the projectile velocity reduction by up to 281.36% relative to the baseline specimen, that is, weakest unstiffened structure. The enhanced performance is attributed to structural reinforcement and auxetic-induced densification near the impact zone, which increases local resistance and energy dissipation.

1 | Introduction

Conceptually, auxetics has a phenomenon of Negative Poisson's Ratio (NPR) which exposes the opposite effect of regular material and structures. In tensile loading conditions, the auxetic material/structures expand laterally and vice versa for the compressive loading conditions, the laterally contraction occurs [1]. This advantage provides a superior performance through higher absorbed energy in different engineering applications; for example, auxetics plays important roles in electrical systems as well as textile and medical fields [2–4].

The reinforcement by the auxetic structure to the resin matrices with different resin types, for example, polyester,

vinyl-ester, and epoxy was investigated under quasi-static loading condition [5]. The energy absorption of the composite structures was increased by 21.7% as compared to the samples which were created from pure resin. Also, the increase in the specific energy absorption (SEA) reached 26%, which demonstrates better performance for these structures in energy absorption criteria. Lawaty et al. [6] proposed a new auxetic honeycomb structure which was created from a composite material. The study had a comparison between three structures (classical, splined, and stiffened); it was found that the stiffened structure has maximum two-directional moduli of elasticity as well as having the largest NPR in the axial direction and the lowest in the transverse direction.

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Fisher and colleagues studied the ballistic response for three structures: nonauxetic conventional hexagonal, reentrant, and doubled arrow structures under the same impact loading condition. They found that the transmitted force for the doubled arrow structure reduces by 44% compared to the hexagonal one. While, the maximum deformation was found in the doubled arrow structure with 17% above the conventional hexagonal structure value [7].

Basically, the identification of the auxetic structures' mechanical properties is verified by studying the cell geometrical parameters; Mohamed and colleagues derived expressions for the in-plane elastic moduli and Poisson's ratios in two directional loading conditions of a classical re-entrant honeycomb structure. They found that the negativity of the structure Poisson's Ratio has positive relationships with the rib length and angle, while it has a negative relationship with the rib thickness. On the other hand, the modulus of elasticity has a direct proportion with the rib angle and thickness and an inverse proportion with the cell rib length [8]. Another investigation of the curvature effect by applying a direct modification on the classical reentrant honeycomb structure was presented to verify the influence on the energy absorption as well as tensile behavior; the novel structure proved 83%, 73%, and 64% increasing in SEA, tensile energy absorption, and elastic modulus, respectively, compared to the arc-shaped reentrant honeycomb structure [9].

Many researchers focus on military applications which reflect the defense capabilities, where a composite structure is used in the ballistic protection application such as body armors [10]. In this attempt, the material was fabricated from a combination of high-performance para-aramid and polyamide fibers. The fibers were arranged in the form of auxetic structure shapes that impregnated with polyester and epoxy resin. Another investigation was performed by Shah et al. [11] for comparing the energy absorption amount between the monolithic and sandwich panel armors. According to their study, three material sandwich panel (aluminum alloy, UHMWPE, and silicon carbide for the face plate, sandwich core, and back plate, respectively) had a higher resistance of indentation with the same boundary conditions for the bullet compared to the conventional monolithic one. For the impact pads, De carried out a comprehensive study regarding to the selection of the best configuration and material from the proposed ones under high impact velocity [12]. He found that the re-entrant hexagon configuration, which was fabricated from polyvinyl chloride material, had the minimum deformation in the impact point and the best performance in higher velocity based on the fracture of the corresponding structure.

In many fields of research, the proposed design of the door panel of a helicopter was upgraded by additive manufacturing technique through increasing the auxetic structure's main characteristic, that is, NPR. The new technique participated in the optimization of the reentrant cell configuration and this improvement contributed to creating a lightweight structure as well as a better performance in high-impact response [13].

Recently, the upgrading of the classical re-entrant auxetic structure becomes an approach for creating a new lightweight

structure which can withstand severe loading conditions. New proposed structure, the arched re-entrant, has proved good results in different loading conditions, that is, static, dynamic, and harmonic. The structure has shown a 50% reduction in the deformation as compared to the regular re-entrant structure in dynamic loading conditions. It is also showed lower peak displacement and reaction force as well as a higher first natural frequency [14]. Not only upgrading the classical structures was performed, but also the merging between different auxetic structures was carried out; Hassan and colleagues proposed a comparison between three structures for high impact applications. The novel structure named "reentrant-star hybrid," which was created by a combination of two cell configurations, that is, reentrant and star shapes proved a superior energy absorption compared to the single-cell configuration structures. Also, they highlighted that the geometrical parameters have a significant role in optimizing structure response by conducting numerical analyses; the increasing in SEA reached 449% after applying an optimization for the two regular cell parameters, that is, inclination angle and strut thickness [15].

This study investigates the influence of unit cell geometric parameters of re-entrant honeycomb structures on their perforation resistance. The objective is to develop a cost-effective auxetic configuration with adequate performance under high-velocity impact conditions. Finite element simulations are performed to analyze the response of the structures subjected to high-velocity impact. Key geometric parameters, including horizontal cell wall length, cell wall angle, and cell wall thickness, are systematically varied. The residual velocity of the bullet is recorded for each case, and the corresponding ballistic limit velocity (V_b) is determined to quantify the ballistic resistance and energy absorption capacity based on deformation mechanism [16]. To further enhance structural performance, horizontal and vertical stiffeners are introduced to increase the postimpact stiffness [17].

2 | Numerical Model

In the present study, the ballistic impact response of auxetic honeycomb structures was investigated using finite element analysis (FEA). The simulations were carried out using ANSYS Explicit Dynamics, which is widely used for modeling high-velocity impact and highly nonlinear dynamic problems involving large deformation, material failure, and complex contact interactions.

Two types of auxetic cellular structures were investigated: a classic re-entrant honeycomb and a stiffened re-entrant honeycomb configuration, based on the geometric parameters including Horizontal cell wall length (h), Cell wall thickness (t), and Cell wall angle (Φ).

2.1 | Model Verification

To ensure the reliability of the numerical simulations, the developed finite element model was validated against previously published results [18]. A mesh convergence study was performed by varying the element size, as illustrated in Figure 1.

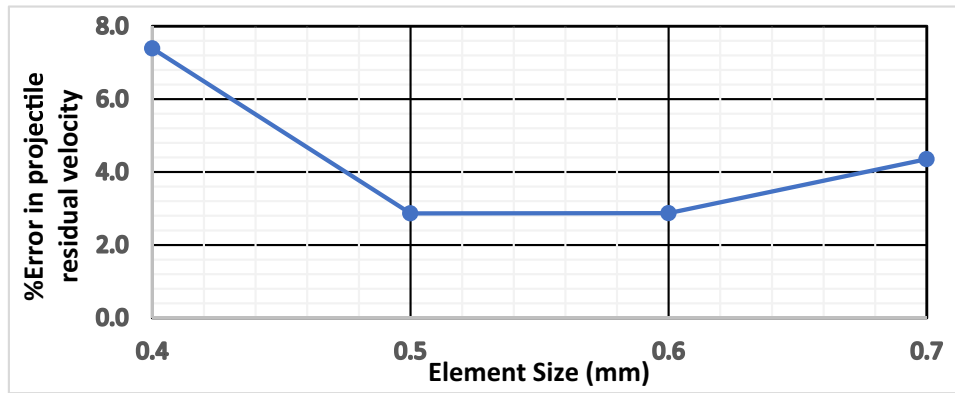


FIGURE 1 | Corresponding %error in residual velocity for different element sizes.

Both tetrahedral (SOLID187) and hexahedral (SOLID186) elements were employed to accurately represent the referenced geometry.

The results indicate that an element size of 0.5 mm provides the best agreement with the reference data, yielding an acceptable error margin of 2.9% in the projectile residual velocity for the same studied time. The predicted residual projectile velocity is 180.3 m/s, which compares well with the reported value of 186 m/s under the same initial impact velocity of 300 m/s and a ballistic time on the order of 2.6×10^{-4} s.

This validation confirms that the developed model is capable of accurately predicting the ballistic response of auxetic honeycomb structures under high-velocity impact conditions.

2.2 | Geometrical Modeling

3D model of auxetic re-entrant honeycomb structure and bullet was created using the Autodesk Inventor program. The i-logic parametric component feature is employed to create the geometry of the re-entrant honeycomb structure with varying dimensions.

The samples were designed with overall dimensions approximately $H \times W$ of 40×40 mm, while they remained constant during simulations, where H and W are the sample height and width, respectively. Table 1 lists 64 samples of re-entrant honeycomb structure generated by varying their main geometric parameters of the unit cell dimensions, including the horizontal cell wall length (h), the inclined cell wall length (l), the cell wall thickness (t), and the cell wall angle (Φ). Figure 2 shows the geometric dimensions of the bullet and re-entrant honeycomb structure geometric configuration along with their connection.

2.3 | Model Material Properties

The re-entrant honeycomb structures were considered to be manufactured from aluminum alloys AA60xx series which are widely used in lightweight structural and impact protection applications due to their favorable strength-to-weight ratio and good energy absorption capability. The material behavior was modeled using an elastic-plastic constitutive model that

accounts for strain hardening during the nonlinear plastic deformation.

The bullet with mass 0.005 Kg of structural steel was modeled as a rigid body to reduce computational cost while maintaining accuracy in the ballistic impact simulation. The material properties assigned to the bullet and the re-entrant honeycomb structure in the present simulations were obtained from the ANSYS material library and are summarized in Table 2.

2.4 | Boundary Conditions and Contact Definition

Appropriate boundary conditions were applied to represent realistic impact regimes. The top and the bottom surfaces of the auxetic structure that are parallel to the bullet direction were constrained to prevent rigid body motion during the simulation as shown in Figure 3. The bullet was positioned at an outer surface of the target structure and assigned an initial translational velocity of 450 m/s along the impact direction. Additionally, a rotational velocity of 11,771 rad/s was applied to simulate the spinning motion of the bullet.

Contact interaction between the bullet and the auxetic structure was defined using a nonlinear surface-to-surface contact algorithm, as illustrated in Figure 4. A friction coefficient of 0.47 was considered to represent the interfacial behavior between the steel bullet and the aluminum structure. This contact formulation allows accurate modeling of contact constraints including large deformation, sliding contact, and potential penetration between contacting bodies during the impact. Thereby ensuring realistic prediction of the interaction response between the contacting bodies.

2.5 | Mesh Generation

The finite element discretization of the bullet and the re-entrant honeycomb auxetic structures was performed using 3D hexahedral and tetrahedral solid186 & solid187 elements as shown in Figure 5. A mesh convergence study was performed with different element sizes as shown in Figure 6 which were applied in regions expected to experience severe deformation,

TABLE 1 | Structures' geometrical parameters.

Sample number	Horizontal cell length, h (mm)	Cell thickness, t (mm)	Cell angle, Φ (deg)	Sample number	Horizontal cell length, h (mm)	Cell thickness, t (mm)	Cell angle, Φ (deg)
S1	5	0.5	65	S33	10	2	75
S2			70	S34			80
S3			75	S35			85
S4			80	S36		2.5	70
S5			85	S37			75
S6		1	65	S38			80
S7			70	S39			85
S8			75	S40	15	0.5	65
S9			80	S41			70
S10			85	S42			75
S11		1.5	75	S43			80
S12			80	S44			85
S13			85	S45		1	65
S14		2	80	S46			70
S15			85	S47			75
S16	10	0.5	65	S48			80
S17			70	S49			85
S18			75	S50		1.5	65
S19			80	S51			70
S20			85	S52			75
S21		1	65	S53			80
S22			70	S54			85
S23			75	S55		2	65
S24			80	S56			70
S25			85	S57			75
S26		1.5	65	S58			80
S27			70	S59			85
S28			75	S60		2.5	65
S29			80	S61			70
S30			85	S62			75
S31		2	65	S63			80
S32			70	S64			85

particularly near the bullet impact zone and accurately capture the deformation of the thin cell walls to ensure that the numerical results were independent of the element size. As concluded from Table 3, the results indicate that an element size of 0.5 mm provides the optimal balance between accuracy and computational efficiency, yielding a minimum error of approximately 2%. Accordingly, this mesh size was adopted for subsequent simulations.

Due to the highly nonlinear nature of high-velocity impact analysis, further mesh refinement leads to increased computational cost and significantly longer simulation times, with only marginal improvement in accuracy. Therefore, the selected element size 0.5 mm represents a practical compromise between solution accuracy and numerical efficiency.

2.6 | Impact Simulation Setup

Ballistic impact simulations were performed in two different directions to evaluate the influence of impact direction on the structural response. The bullet was directed toward the auxetic panel along two orthogonal directions (X-axis and Y-axis). The simulation results were compared in order to determine the most critical impact orientation.

The explicit dynamic solver computes the transient response of the structure by integrating the equations of motion over very small-time increments. This approach enables accurate modeling of highly nonlinear phenomena such as large deformation, dynamic contact, and energy dissipation during the high-velocity impact process. According to Figure 7, the

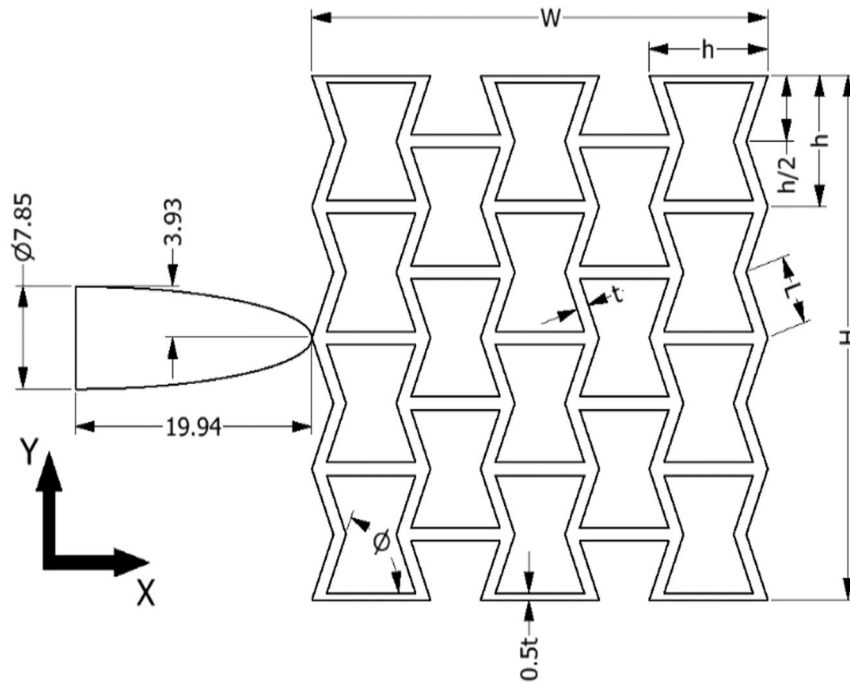


FIGURE 2 | Bullet and structure dimensions.

TABLE 2 | Material properties of bullet and structure components.

Component	Material	Elastic modulus	Poisson's ratio	Yield strength	Tangent modulus
Structure	Aluminum alloy	71 GPa	0.33	280 MPa	0.5 GPa
Bullet	Structural steel	200 GPa	0.3	250 MPa	1.45 GPa

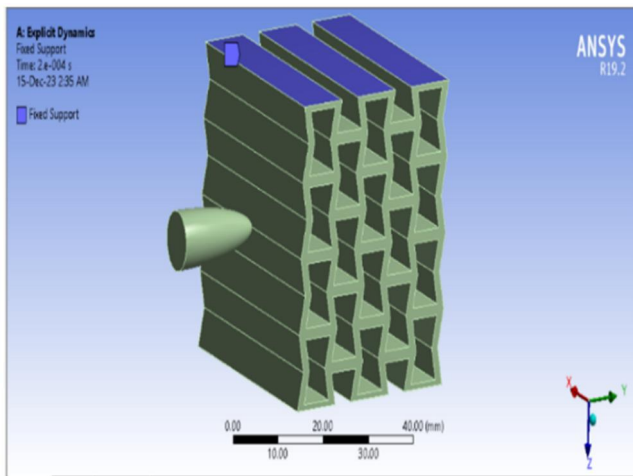


FIGURE 3 | Assembly fixed support constraint.

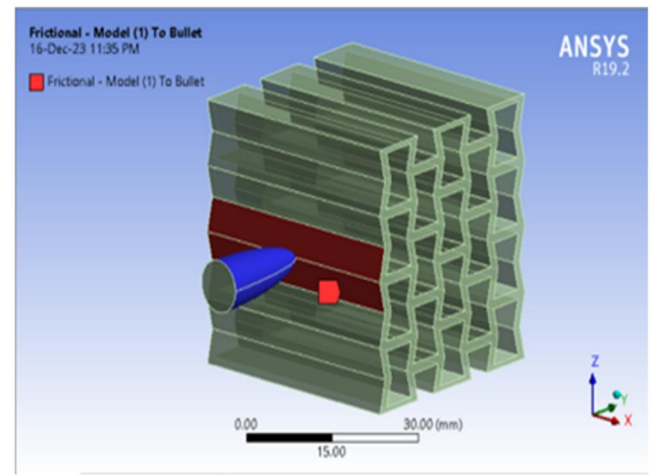


FIGURE 4 | Assembly contact details.

ballistic limit of the bullet in the X-direction is higher than the other direction which made it the interesting direction of study.

2.7 | Performance Evaluation Criteria

The ballistic performance of the auxetic structures was evaluated using several key parameters, including: ballistic time

(penetration time), estimated energy absorption capacity, structural deformation mechanism, and failure modes.

3 | Results and Discussion

3.1 | Determination of the Residual Velocity

The results demonstrate that the ballistic response of the structures is strongly dependent on their geometric parameters,

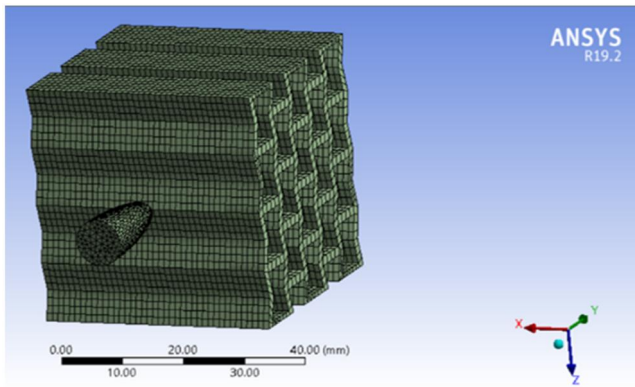


FIGURE 5 | 3D assembly meshing.

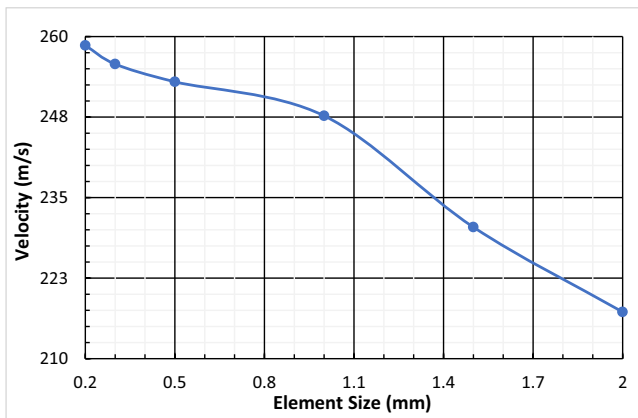


FIGURE 6 | Bullet velocity for different element sizes at ballistic time = 7.2×10^{-5} (s).

TABLE 3 | %Error in projectile velocity for different element size.

S. N.	Element size (mm)	%Error in bullet velocity
1	2	—
2	1.5	6.06%
3	1	7.5%
4	0.5	2.13%
5	0.3	1.09%
6	0.2	1.13%

horizontal cell wall length, cell wall angle, and cell wall thickness h , Φ , t , respectively. The ballistic limit is defined as the velocity of the bullet which it either comes to rest at the back side of the structure or perforates it with trivial residual velocity, varies with changes in h , Φ , and t . Similarly, the ballistic time is referred to the duration from the initial contact of the bullet with the front side of the structure to either its complete perforation or the instant at which the bullet velocity reaches to zero inside the structure shows noticeable variation among the tested configurations. The penetration energy corresponds to the total energy absorbed by the structure during the penetration process, whether partial or complete.

The velocity–time histories for all models illustrate the penetration duration for each configuration. At a constant initial impact velocity of $V_i = 450$ m/s, the velocity–time profiles as shown in Figures 8–21 reveal different penetration behaviors across the 64 models. Structures with specific geometric combinations (notably S16–S20 and S40–S49) exhibit full perforation as shown in Figures 12, 17, and 18, indicating relatively lower resistance to penetration, while the remaining models exhibit partial penetration, suggesting higher energy absorption capacity.

At an initial impact velocity of $V_i = 450$ m/s only models S16–S20 and S40–S49 exhibit full perforation as shown in Figure 22, while the remaining configurations successfully resist complete penetration as depicted in Figure 23. Overall, the results confirm that optimizing structural geometry can significantly improve ballistic resistance by increasing penetration energy absorption and prolonging ballistic time, thereby reducing the likelihood of complete perforation.

3.2 | The Influence of Geometric Parameters on Ballistic Response of Re-Entrant Structure

In this section, the influence of geometric parameters of the re-entrant honeycomb structure on its ballistic performance is presented. Specifically, the effects of horizontal cell wall length, cell wall thickness, and cell wall angle are investigated. Their impact on ballistic resistance, failure mechanisms, deformation behavior, and energy absorption (EA) characteristics is analyzed and discussed in detail.

3.2.1 | Influence of Horizontal Cell Wall Length

Figure 24 shows the relationship between the horizontal cell wall length and the ballistic time at similar cell wall thicknesses and cell wall angles. It is found that increasing horizontal cell wall length has a direct proportional effect on the ballistic time of the re-entrant honeycomb structure. Specifically, the ballistic time increases with increasing horizontal cell wall length, reflecting an extended duration of interaction between the bullet and the structure.

For instance, a sample S14 which has cell wall thickness and angle, $t = 2$ mm and $\Phi = 80^\circ$, the ballistic time is increased by 3.96×10^{-5} s and 1.026×10^{-5} s for the horizontal cell wall lengths 10 and 15 mm, respectively, corresponding to its value regarding to the horizontal cell wall length 5 mm. These increments correspond to increases of approximately 98% and 254% in ballistic time, respectively.

This behavior can be attributed to the increased deformation path and enhanced energy absorption capacity associated with longer horizontal ribs, which delay bullet deceleration and prolong the penetration process. As the rib length increases, the structure provides a larger interaction zone for the bullet, leading to a more gradual deceleration process.

Additionally, the re-entrant geometry enhances the deformation mechanisms, allowing for greater energy dissipation

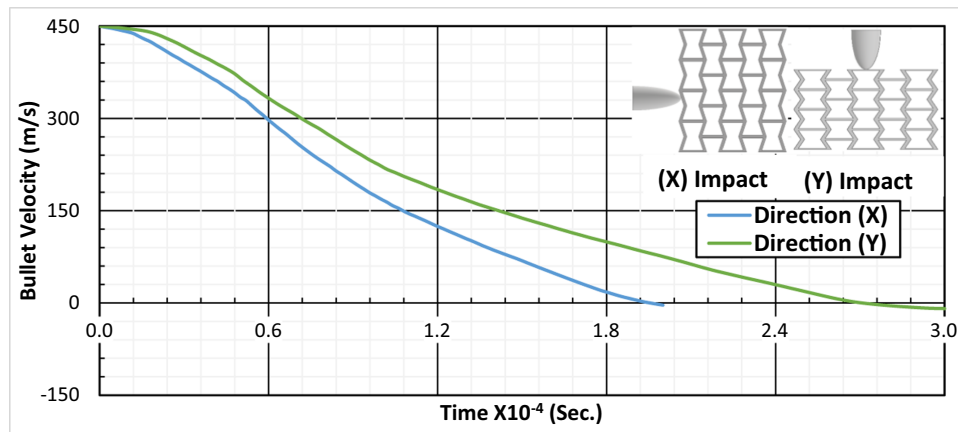


FIGURE 7 | Effect of impact bullet direction on ballistic time.

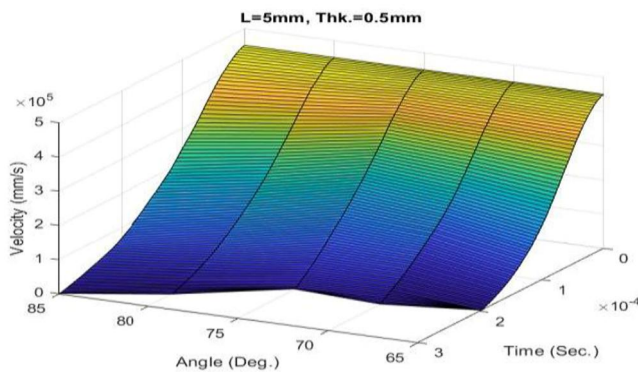


FIGURE 8 | Residual velocity for $h = 5$, $t = 0.5$ mm.

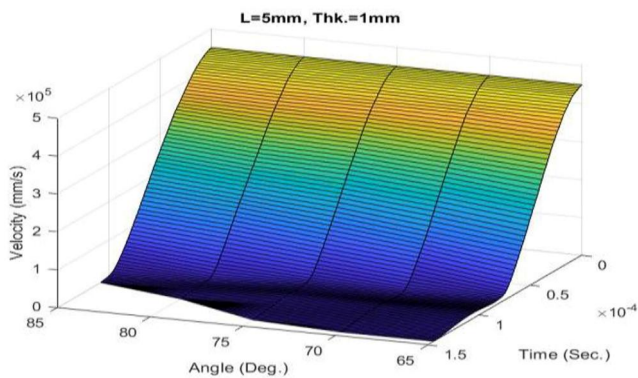


FIGURE 9 | Residual velocity for $h = 5$, $t = 1$ mm.

through bending and progressive cell collapse. Consequently, the bullet requires a longer time to either come to rest or perforate the structure, resulting in increased ballistic time.

According to Figure 25, the influence of the horizontal cell wall length on the failure mechanism is remarked. An increase in the horizontal cell wall length led to a higher tendency for buckling of the re-entrant honeycomb structure. At cell wall thickness and cell wall angle 1 mm and 70° respectively, the specimen with a horizontal cell wall length of 15 mm exhibits the highest degree of cell wall stretching, followed by 10 and 5 mm.

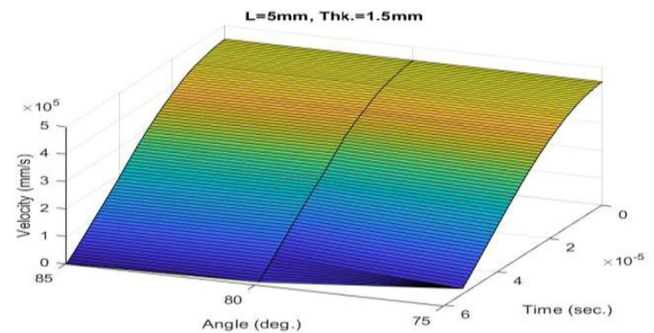


FIGURE 10 | Residual velocity for $h = 5$, $t = 1.5$ mm.

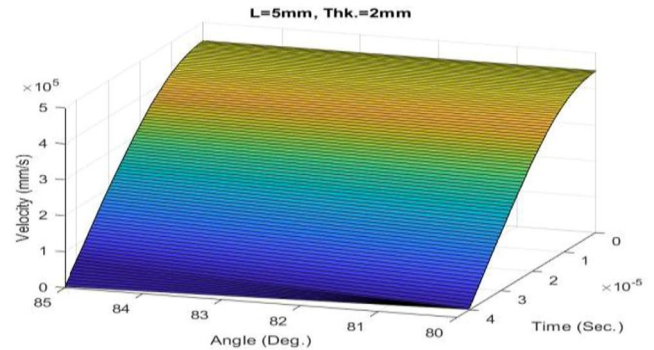


FIGURE 11 | Residual velocity for $h = 5$, $t = 2$ mm.

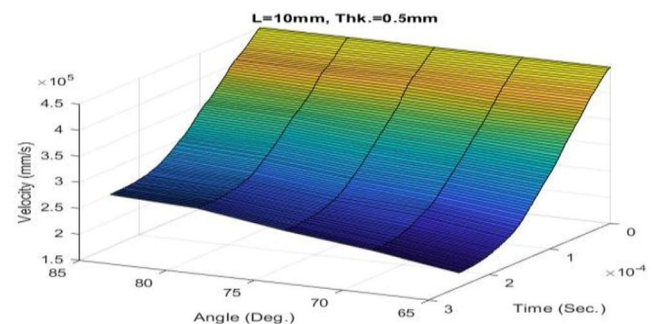


FIGURE 12 | Residual velocity for $h = 10$, $t = 0.5$ mm.

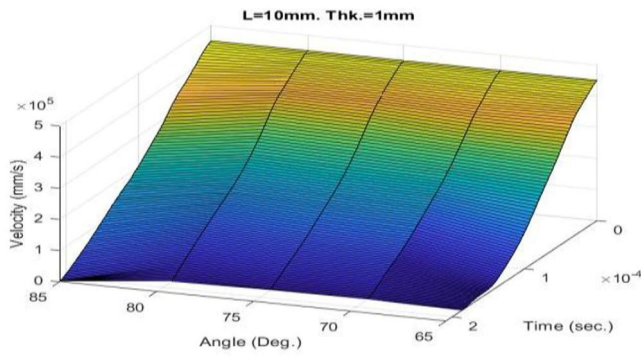


FIGURE 13 | Residual velocity for $h = 10$, $t = 1$ mm.

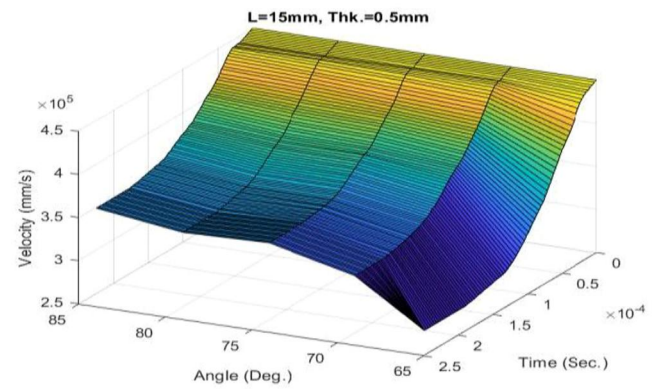


FIGURE 17 | Residual velocity for $h = 15$, $t = 0.5$ mm.

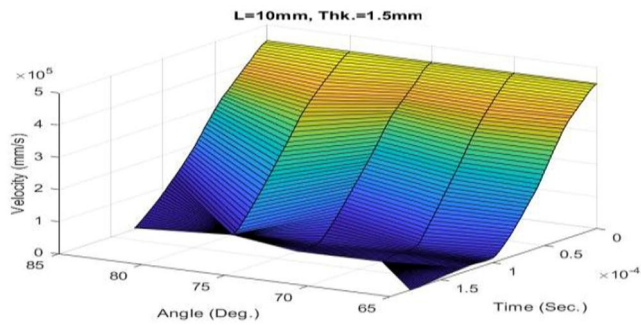


FIGURE 14 | Residual velocity for $h = 10$, $t = 1.5$ mm.

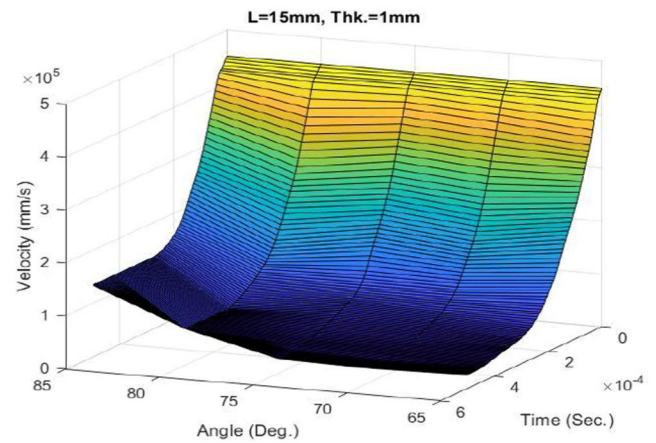


FIGURE 18 | Residual velocity for $h = 15$, $t = 1$ mm.

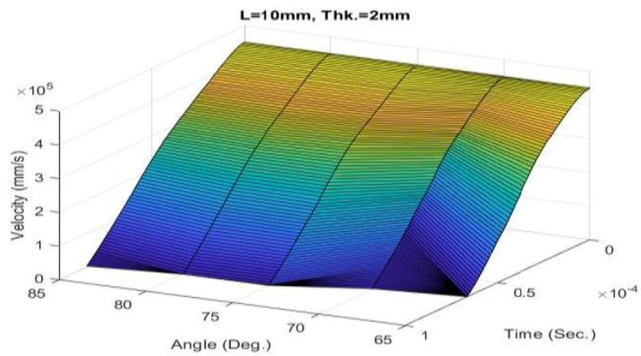


FIGURE 15 | Residual velocity for $h = 10$, $t = 2$ mm.

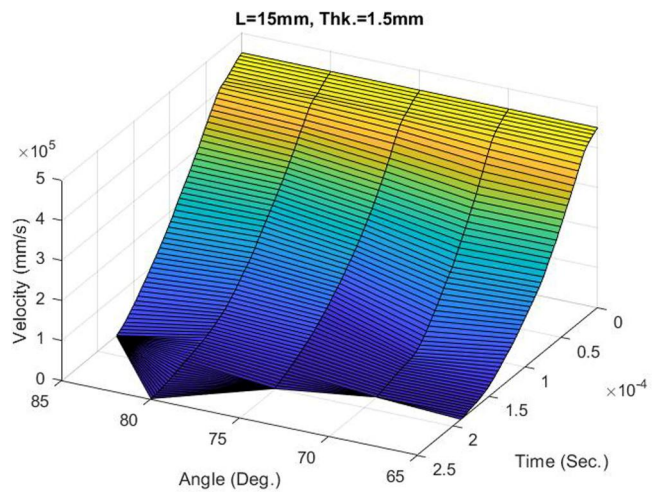


FIGURE 19 | Residual velocity for $h = 15$, $t = 1.5$ mm.

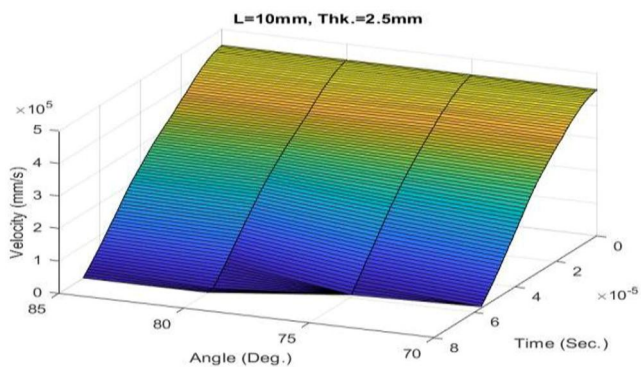


FIGURE 16 | Residual velocity for $h = 10$, $t = 2.5$ mm.

As the horizontal cell wall length increases, the number of unit cells within the structure decreases, resulting in reduced overall stiffness. Consequently, the structure becomes more susceptible to full perforation by the bullet. In contrast, shorter horizontal rib lengths increase the number of unit cells, enhancing the structural resistance against bullet penetration.

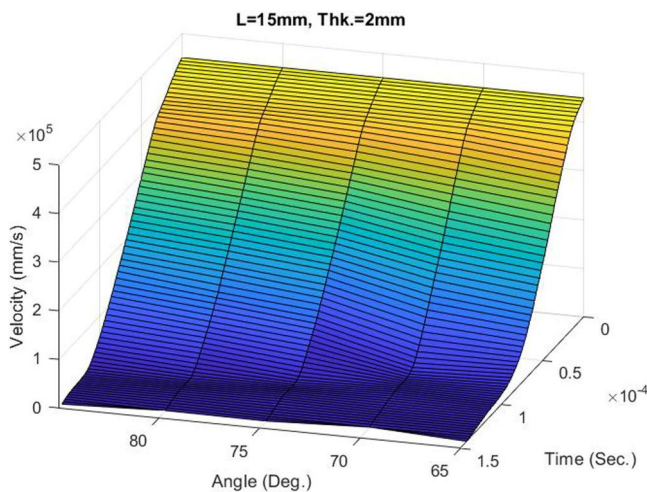


FIGURE 20 | Residual velocity for $h = 15$, $t = 2$ mm.

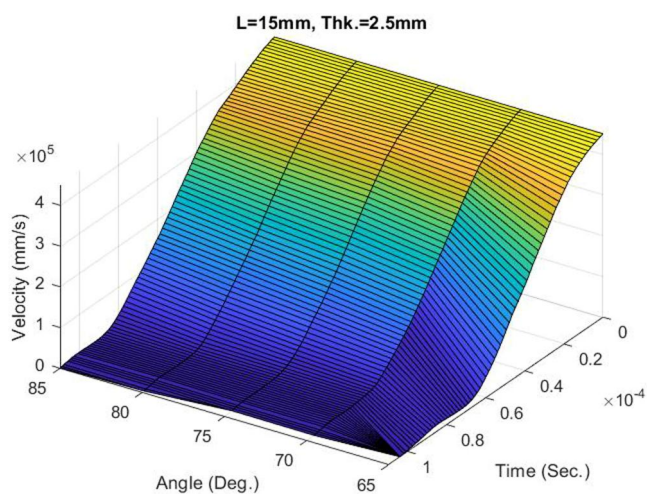


FIGURE 21 | Residual velocity for $h = 15$, $t = 2.5$ mm.

This behavior can be attributed to the auxetic effect of the re-entrant geometry, which promotes material densification around the bullet path. Additionally, shorter rib lengths provide more varied surface areas, increasing frictional resistance during penetration. As a result, the bullet experiences a greater and more rapid reduction in velocity when passing through structures with shorter horizontal cell walls.

It is also observed that the dominant failure mechanism in the honeycomb structure is highly localized. Cells adjacent or parallel to the bullet path do not have sufficient time to deform or contribute significantly to energy absorption before the bullet fully penetrates the structure.

3.2.2 | Effect of Cell Wall Thickness

The cell wall thickness of the re-entrant honeycomb structure is varied as 0.5, 1.0, 1.5, 2.0, and 2.5 mm. Figure 26 illustrates the influence of cell wall thickness on the ballistic time of the re-entrant honeycomb structure. It is clear that the cell rib thickness has a negative influence on the ballistic time, indicating an inverse relationship between ballistic time and cell wall thickness. For example, at constant cell geometric parameters, where

the horizontal cell wall length and cell wall angle are 5 mm and 85° , respectively, the ballistic time decreases from 1.09×10^{-4} , 6.01×10^{-5} , and 4.42×10^{-5} as the cell wall thickness increases from 1, 1.5, and 2 mm. Furthermore, a significant reduction approximately by 85.3% in the ballistic time is observed when the cell wall thickness increases from 0.5 to 2 mm for the same geometric configuration.

Likewise, the deformation of the re-entrant honeycomb structure is plotted for the different cell wall thicknesses which are shown in Figure 27. It is observed that the increase in the cell wall thickness causes a reduction in stretching, flexing or any deformation type of ribs. This behavior is attributed to increase in structure stiffness with greater cell wall thickness. Consequently, higher cell wall thickness enhances the overall stiffness of the re-entrant honeycomb structure, leading to reduced deformation and a corresponding decrease in ballistic time.

3.2.3 | Influence of Cell Wall Angles

Figure 28 presents the bullet ballistic time after impact on auxetic re-entrant honeycomb structures with varying cell wall angles. At a constant initial impact velocity, both ballistic time and residual velocity exhibit slight variations with changes in the cell wall angle. However, the influence of the cell wall angle on ballistic time is generally limited, with no clear or consistent trend observed over the range of 65° – 85° .

The limited effect of the cell wall angle on the ballistic response of the auxetic structure under high-velocity impact can be attributed to the dominance of dynamic deformation mechanisms over geometric re-entrant effects. During ballistic impact, the projectile transfers a large amount of kinetic energy within a very short time, producing highly localized deformation at the impact zone as shown in Figure 29. the response of an auxetic structure is therefore governed primarily by inertia effects, progressive cell crushing, rapid plastic collapse stress-wave propagation, whereas the kinematic lateral expansion associated with different cell wall orientations plays a comparatively minor role. Consequently, variations in the cell wall angle within the investigated range have only a limited influence on the overall ballistic performance.

Also, the numerical modeling assumptions may also contribute to the reduced sensitivity of the ballistic response to the cell wall angle. In the present simulations, the projectile motion was constrained to a prescribed impact direction without allowing rotational or lateral deviation after contact. This assumption suppresses possible trajectory changes and asymmetric interactions that could otherwise amplify the influence of cell wall orientation on the impact response. As a result, the predicted ballistic performance is governed predominantly by the local crushing resistance of the cellular structure rather than by directional effects associated with the auxetic geometry. Nevertheless, because this influence has not been evaluated through a dedicated sensitivity analysis, it should be regarded as a potential limitation of the current numerical model rather than an established cause.

For example, in sample S60 with horizontal cell wall length and cell wall thickness of $h = 15$ mm and $t = 2.5$ mm, respectively,

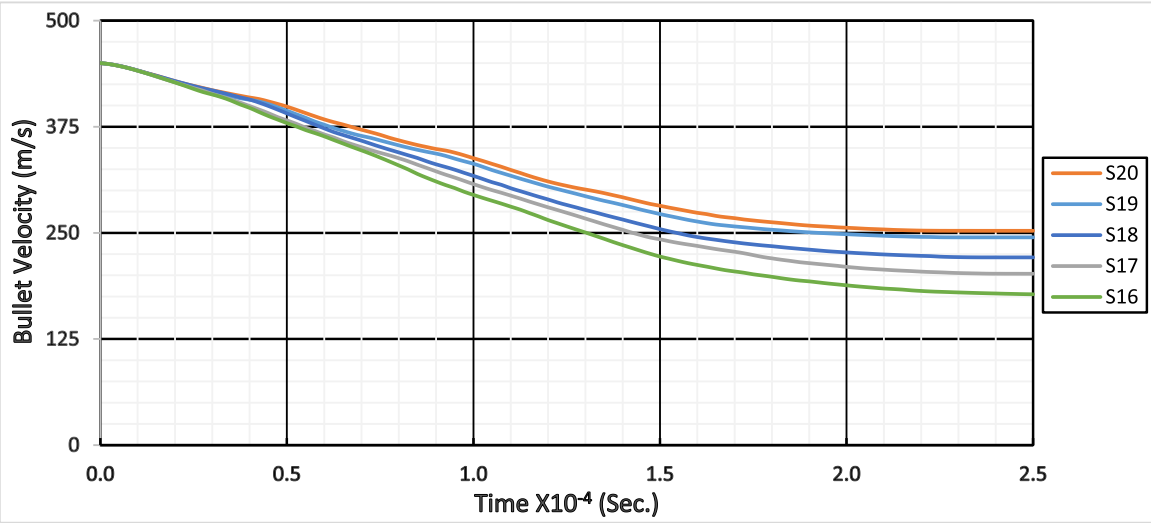


FIGURE 22 | Bullet residual velocity for fully penetrated samples.

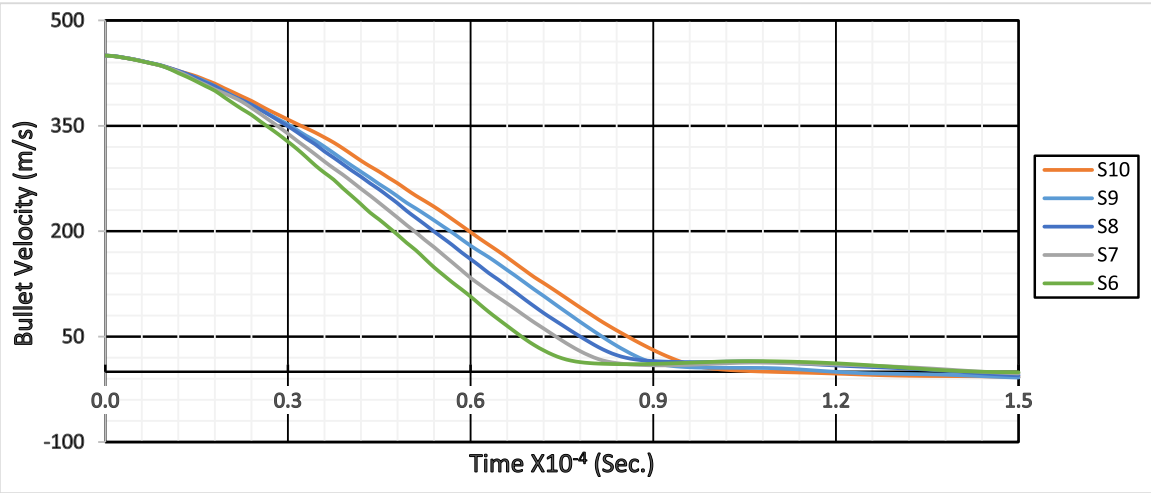


FIGURE 23 | Bullet residual velocities in partially penetrated structures.

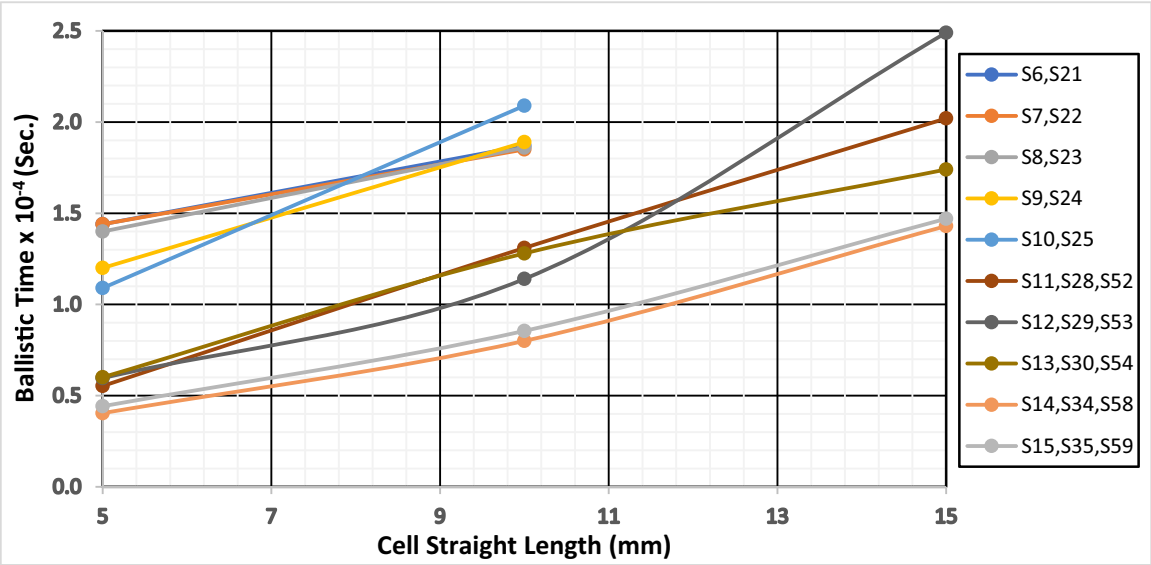


FIGURE 24 | Effect of rib length on the ballistic time at similar cell wall thicknesses and angles.

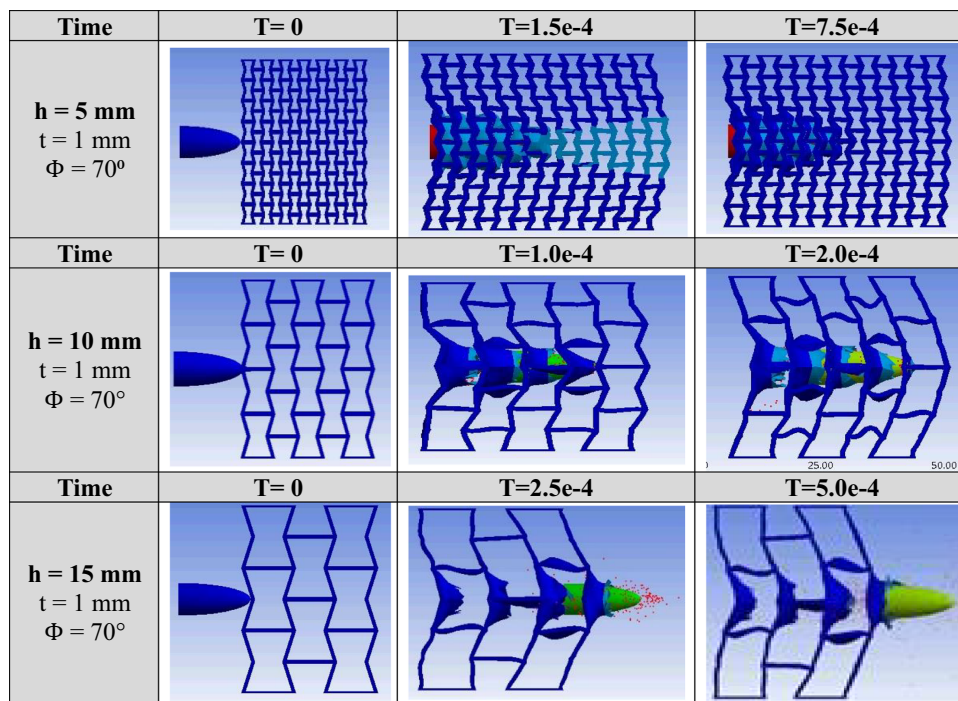


FIGURE 25 | Deformation mechanism of re-entrant structure with different horizontal cell wall lengths at $t = 1$ mm and $\Phi = 70^\circ$.

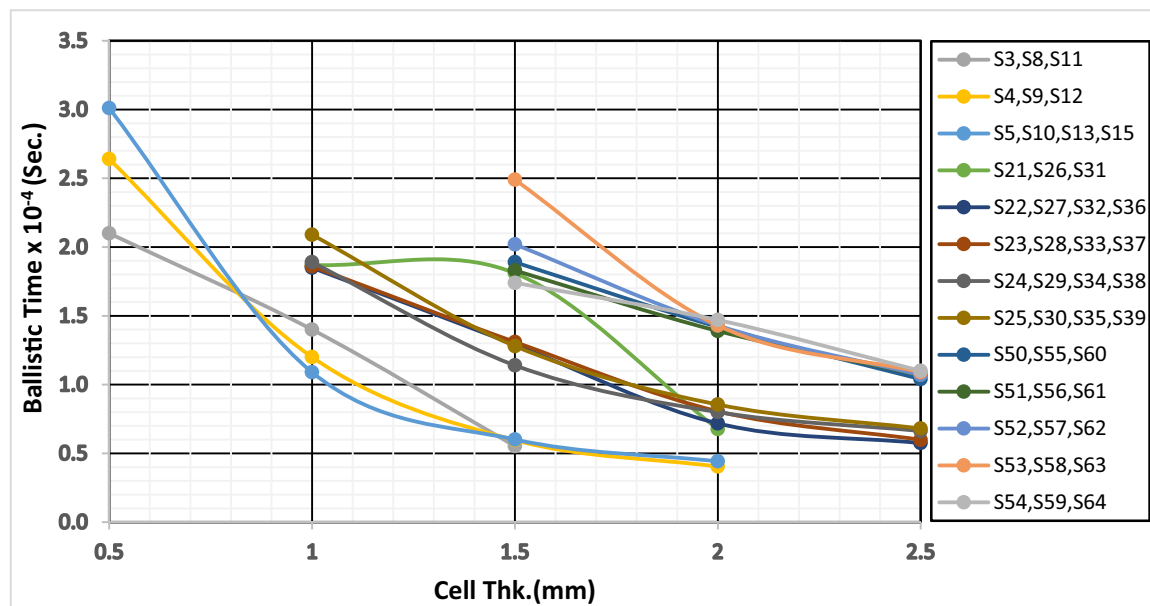


FIGURE 26 | Effect of rib thickness on the ballistic time at similar cell wall lengths and angles.

the ballistic time shows a marginal increase from 1.04×10^{-4} s at $\Phi = 65^\circ$ to 1.1×10^{-4} s at $\Phi = 85^\circ$, corresponding to an increase of approximately 5.8%. This confirms the relatively weak sensitivity of ballistic time to variations in cell rib angle.

Additionally, it is observed that the response becomes less consistent for structures with high h/t ratios (≥ 6), as seen in samples S1, S26, and S50. In such cases, the effect of cell wall angle appears irregular and less predictable. Therefore, re-entrant structures with high h/t ratios are more suitable for quasi-static.

Figure 29 further illustrates the effect of cell wall angle on ballistic resistance. Structures with smaller cell wall angles ($\Phi = 65^\circ$) demonstrate improved ballistic performance compared to larger angles ($\Phi = 85^\circ$).

Although the bullet penetrates through fewer cells (i.e., a shorter path) at smaller angles, the overall structural deformation is higher. This behavior is attributed to the enhanced auxetic effect at lower angles, where the inclined ribs can more easily deform by hinging mode, that the cell wall is rigid along its length and deflection occurs at the junction with other cell

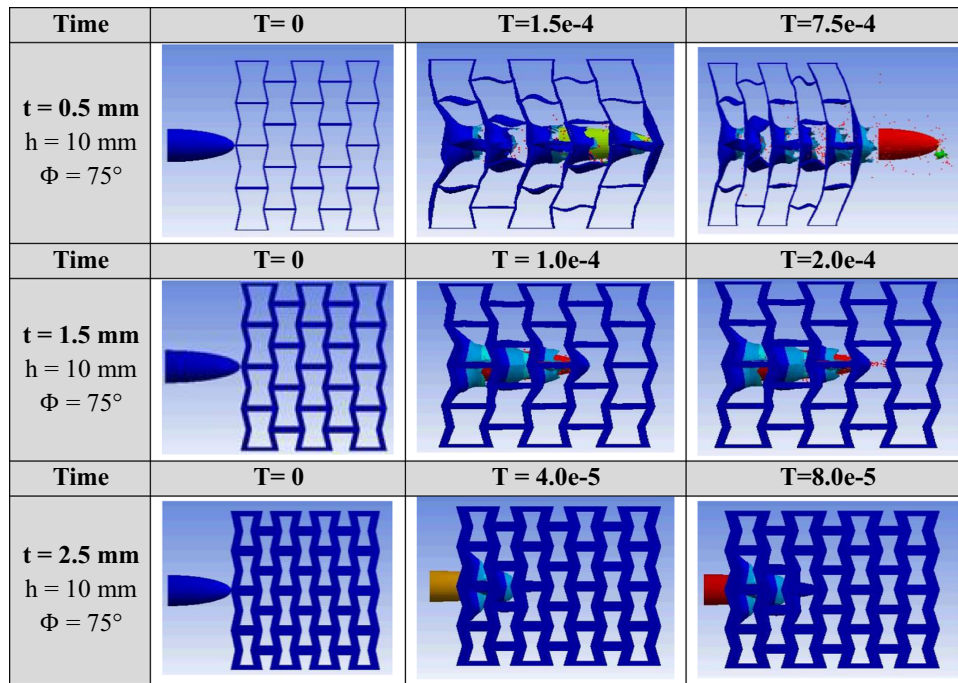


FIGURE 27 | Deformation mechanism of re-entrant structure with different cell wall thicknesses at $h = 10$ mm and $\Phi = 75^\circ$.

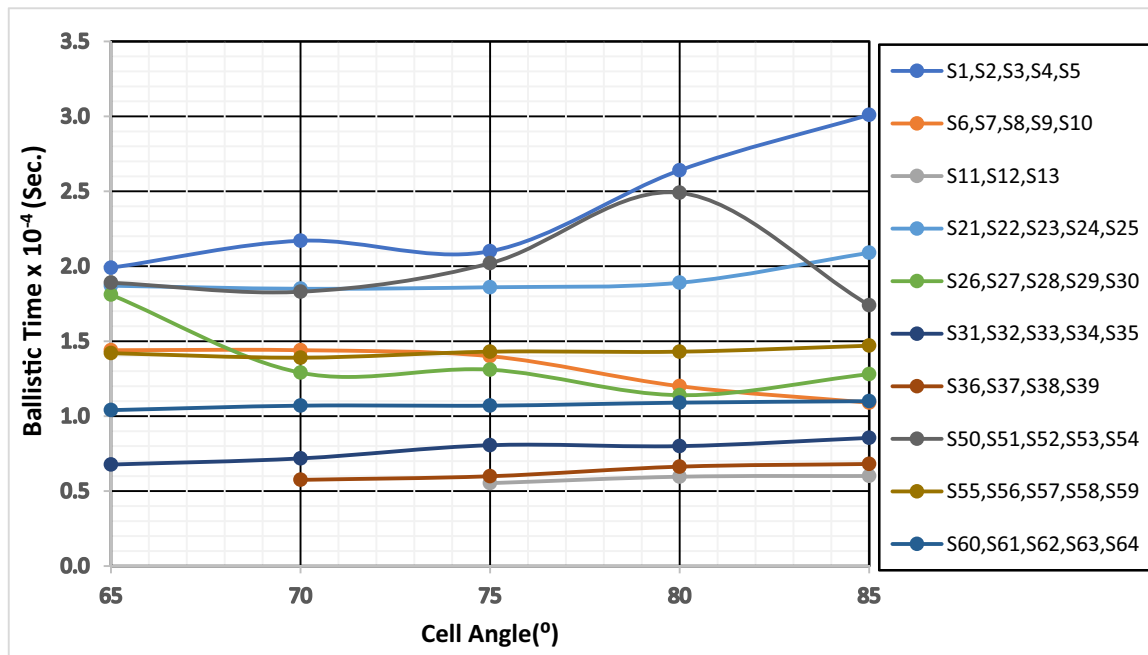


FIGURE 28 | Effect of rib angles on the ballistic time at similar cell wall lengths and thicknesses.

walls by a change of angle promoting more lateral expansion and energy absorption.

Moreover, smaller cell wall angles reduce the vertical dimension of the unit cell, thereby increasing the number of cells along the overall sample height, H . This contributes to greater energy dissipation and improved ballistic resistance.

In contrast, larger cell wall angles result in relatively straighter ribs with reduced hinged deformation capability, making them more prone to stretching-dominated deformation and tensile

failure. Consequently, structures with larger rib angles (e.g., $\Phi = 85^\circ$) exhibit lower ballistic resistance and reduced ballistic limit compared to those with smaller cell wall angles.

4 | Enhancement Ballistic Performance of the Re-Entrant Auxetic Structure

In an attempt to improve the impact ballistic resistance of the re-entrant auxetic honeycomb structure which showed complete penetration of the bullet under the assigned impact conditions, the

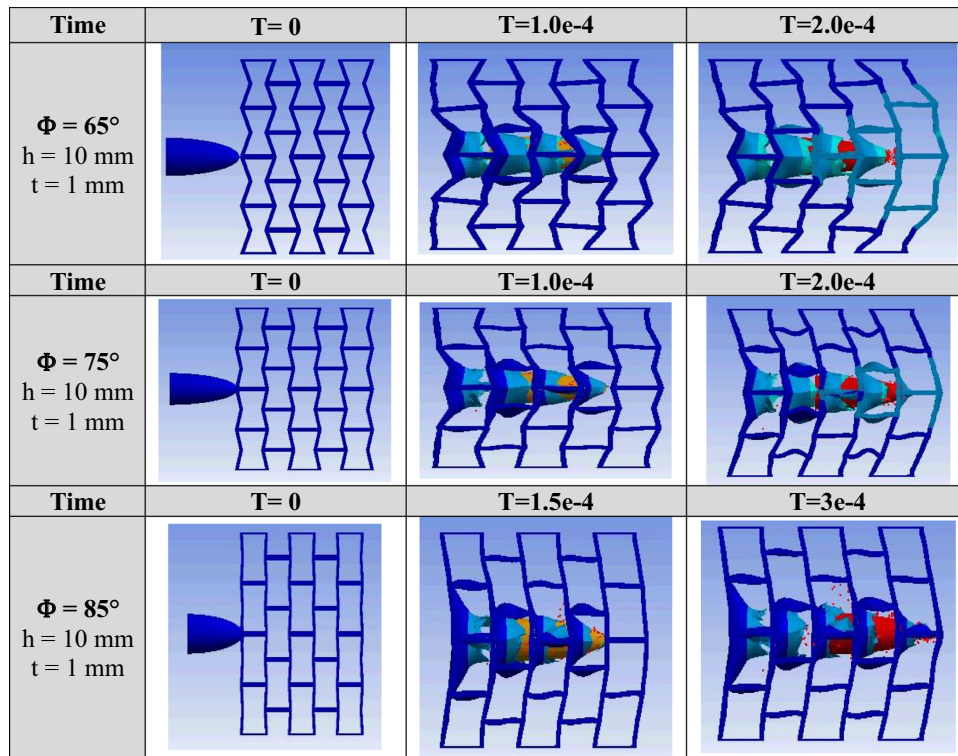


FIGURE 29 | Deformation mechanism of re-entrant structure with different cell wall angles at $h = 10$ mm and $t = 1$ mm.

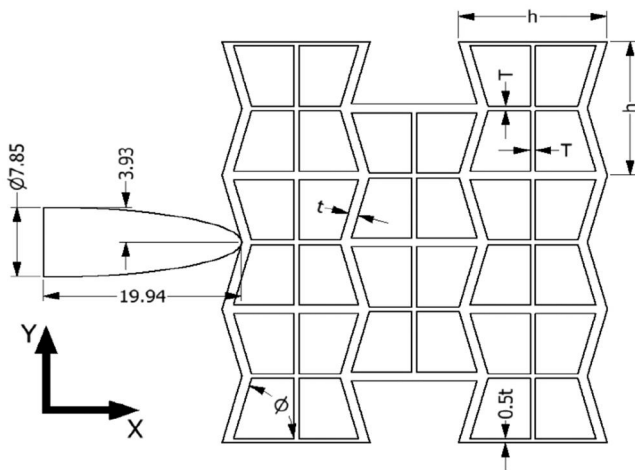


FIGURE 30 | Schematic diagram of the modified stiffened unit cells.

structure of the unit cell is modified by incorporating additional stiffening elements. Specifically, horizontal and vertical ribs were added to the baseline configuration to enhance the overall stiffness and load distribution capability of the structure under high-velocity impact as shown in Figure 30 which are initially proposed in Chen et al. [17]. The dimensions of the modified structures are listed in Table 4. For consistency and accurate comparison, the enhanced model was established with identical material properties, mesh discretization, and loading conditions as those used for the classical unstiffened re-entrant structure.

Figure 31 presents a comparative analysis of projectile velocity with impact time between the stiffened and classic re-entrant

auxetic honeycomb structures. Samples (S42 and S18) undergo relatively limited deformation, resulting in insufficient energy absorption and higher residual bullet velocities. Sample (S42) exhibits the weakest impact resistance, with the projectile retaining a residual velocity of approximately 332 m/s, while specimen (S18) reduces the velocity to nearly 221 m/s. S47 provides improved protection by lowering the projectile velocity to approximately 25.6 m/s at full perforation times. In contrast, stiffened re-entrant auxetic honeycomb structures (S65, S66, and S67) effectively arrest the projectile, with the bullet velocity approaching zero before the end of the simulation. Among these, sample (S66) achieves the most rapid deceleration, reaching zero velocity at approximately 2.24×10^{-4} s, indicating the highest rate of kinetic energy dissipation. The superior ballistic performance of these configurations is attributed to the incorporation of vertical and horizontal stiffening, which collectively increase energy absorption and reduce projectile momentum more effectively based on distributing the impact load over a larger volume and prolong the interaction time.

The results indicate that the incorporation of vertical and horizontal stiffening ribs significantly enhances the energy absorption (EA) capacity of all investigated configurations. This improvement can be attributed to several underlying mechanical mechanisms. First, the addition of stiffeners increases the overall structural stiffness, which elevates the resistance to localized deformation and delays the onset of failure. Second, the stiffeners promote more uniform stress distribution across the structure, reducing stress concentration at critical such as cell junctions. Third, the presence of additional ribs simultaneously activates multiple deformation modes, including axial stretching, cell wall bending, hinging, and progressive folding, thereby increasing plastic work energy dissipation. Moreover,

TABLE 4 | Geometric parameters' dimensions of stiffened structure.

S. N.	Horizontal cell wall length, h (mm)	Cell wall thickness, t (mm)	Cell wall angle, φ (deg)	Stiffness type	Stiffener thickness, T (mm)
S65	10	0.5	75	Horizontal/ vertical	0.5
S66	15	0.5	75		1
S67	15	1	75		0.5

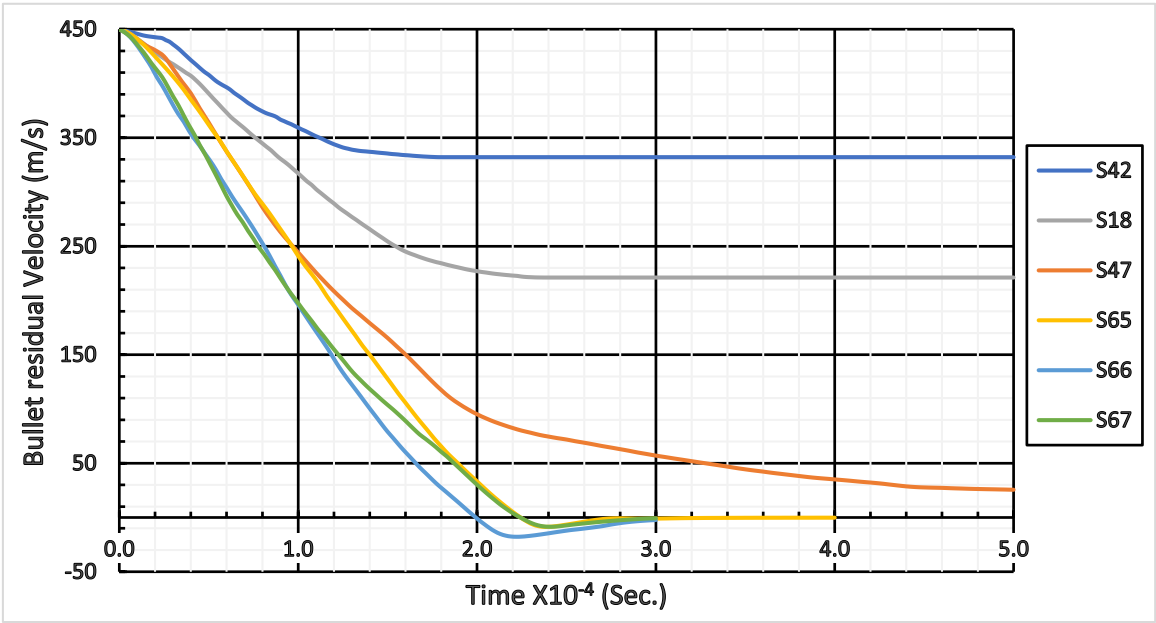


FIGURE 31 | Comparison between conventional and stiffened re-entrant auxetic honeycomb structures.

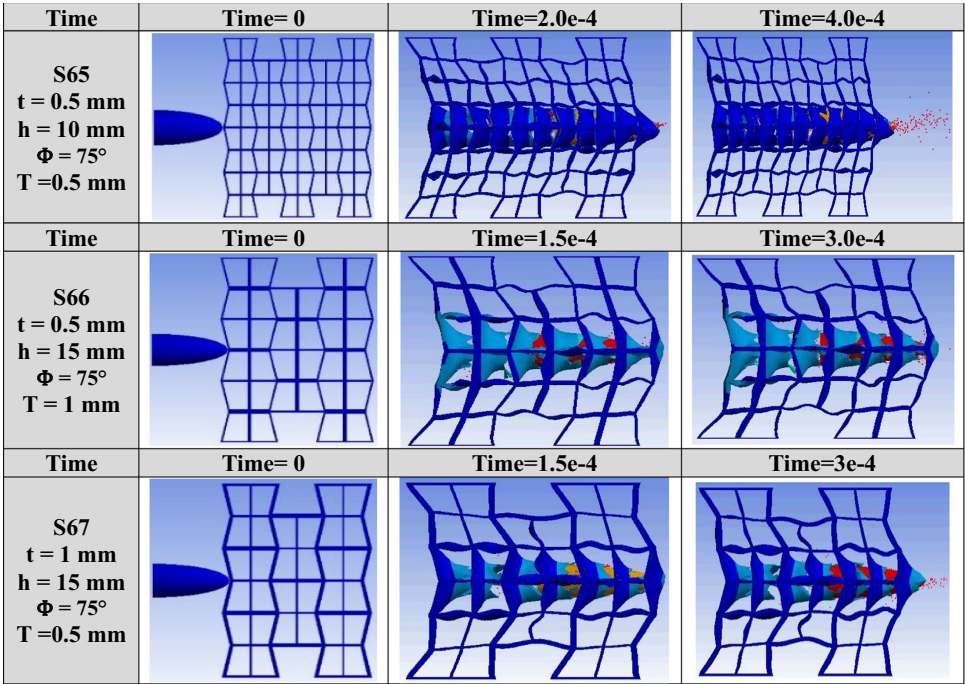


FIGURE 32 | Deformation mechanism of stiffened re-entrant honeycomb auxetic structures.

where

$$\Delta v = v_i - v_r \quad (5)$$

Δv is the reduction in projectile velocity.

The baseline specimen (S42) exhibited the lowest impact resistance, with a residual velocity of 332 m/s, corresponding to a velocity reduction of only 26.22% and an energy absorption efficiency of 45.57%. Sample (S18) demonstrated a substantial enhancement, reducing the projectile velocity by 50.89% and increasing the absorbed kinetic energy to 75.88%, representing a 66.52% improvement in energy absorption relative to (S42). Sample (S47) showed excellent ballistic performance, reducing the projectile velocity to 25.6 m/s, which corresponds to a 94.31% velocity reduction and an energy absorption efficiency of 99.68%. Finally, stiffened specimens (S65, S66, and S67) completely arrested the projectile, achieving 100% velocity reduction and 100% energy absorption efficiency. Compared with the baseline specimen, these optimized configurations improved the energy absorption capability by approximately 119.45%, confirming their superior capacity to dissipate the projectile's kinetic energy through progressive cell collapse, plastic hinge formation, and extensive plastic deformation. These findings demonstrate that the optimized auxetic geometries provide nearly complete kinetic energy dissipation and significantly enhance ballistic resistance under high-velocity impact.

Using (S18) as the reference specimen, sample (S47) achieved an 85.33% increase in projectile velocity reduction and a 31.36% increase in energy absorption efficiency, demonstrating a substantial improvement in ballistic performance. The optimized specimens (S65, S66, and S67) exhibited the highest performance, with 96.51% greater velocity reduction and 31.79% higher energy absorption efficiency than (S18), resulting in complete projectile arrest.

When (S47) is considered as the baseline, the performance differences become much smaller because (S47) already absorbs nearly all of the projectile's kinetic energy. The optimized configurations (S65–S67) provide an additional 6.03% improvement in velocity reduction, while the increase in energy absorption efficiency is only 0.32%, confirming that (S47) is already close to the optimum ballistic performance. Consequently, the main advantage of (S65–S67) over (S47) is the complete elimination of the residual projectile velocity, rather than a significant increase in absorbed kinetic energy.

5 | Conclusion

In this study, finite element simulations were employed to investigate the effect of geometric parameters on the ballistic performance of aluminum re-entrant honeycomb auxetic structures subjected to high-velocity impact ($v_i = 450$ m/s). The influence of horizontal cell wall length, in-plane cell wall thickness, and cell wall angle on ballistic limit and energy absorption (EA) was systematically evaluated.

The results demonstrate that the geometric parameters play a critical role in governing the impact response of auxetic

honeycomb structures. Specifically, increasing the horizontal cell wall length enhances the ballistic time, indicating improved resistance to bullet penetration. Conversely, reducing the cell wall thickness leads to an increase in ballistic time, suggesting a more progressive deformation mechanism that delays complete perforation. In contrast, variations in the cell rib angle exhibit a negligible effect on the ballistic performance within the investigated range, indicating that this parameter is less influential under the given loading conditions.

Consequently, moderate changes in the cell wall angle produce only minor differences in ballistic performance compared with dominant design parameters such as cell wall thickness, relative density, or material properties, whereas cell geometry (including wall angle) has a stronger influence under quasi-static or low-velocity loading than under ballistic impact.

Future work involving unconstrained projectile motion and experimental validation is needed to verify the influence of cell wall angle on the ballistic behavior of auxetic structures.

To further enhance the structural performance, stiffening strategies were introduced by incorporating horizontal and vertical ribs into the penetrated configurations. These modifications significantly improved the structural stiffness, resulting in higher energy absorption capacity and an increased ballistic limit. The enhanced designs demonstrated superior resistance to impact compared to the conventional re-entrant honeycomb structure.

Overall, the findings highlight the importance of geometric tailoring and structural reinforcement in optimizing the ballistic resistance of auxetic honeycomb systems. The study provides valuable insights for the design of lightweight, high-performance protective structures in impact and defense applications.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data can be provided upon request.

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