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Enhanced Protection: Exploring the Penetration Resistance of Star Shape Auxetic Material

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Abstract: This study investigates the performance of star-shaped auxetic structures as protective materials in aluminum containers, designed to safeguard sensitive or hazardous materials during road transport. Finite element analysis (FEA) was conducted to assess the impact resistance of the star-shaped auxetic structure under high-speed collisions, simulating potential events such as explosions or sudden impacts. The simulations were performed using Autodesk's event simulation algorithm. In the first analysis, the auxetic structure was subjected to loading conditions applied to the metallic casing, while in the second, the metallic casing was considered rigid, with the focus placed on the structural behavior of the auxetic material under extreme stress conditions. Both scenarios examined the response of the auxetic structure in the plastic deformation region. The results indicate that the maximum stress developed in both loading cases approached 80 MPa. Notably, in the second scenario involving the rigid casing, the maximum displacement of the auxetic structure increased threefold compared to the first study. Despite the extreme loading conditions, the auxetic structure maintained significant cohesion, ultimately failing in a controlled manner. The ability of the star-shaped auxetic structure to absorb substantial impact loads is attributed to the twisting deformation of the structure, which redirects the applied stress towards the center of the impact area. These findings highlight the potential of star-shaped auxetic materials in providing enhanced protection for sensitive materials during transport, demonstrating their ability to withstand severe dynamic loading and to effectively dissipate energy upon impact.

Keywords: Auxetic structure; Protection; Finite element analysis; Star-shaped honeycomb; Penetration resistance

1 Introduction

Increasing industrial production and the need for transporting materials have led people to protect the loads they carry. As societies evolve and industry develops, the need for efficient and safe transportation of goods and raw materials has become urgent. The increase in production requires new distribution methods that ensure the integrity and safety of the loads, leading to the development of specialized packaging and transportation methods. Nowadays, containers and crates have become the primary tools for transporting goods. Containers are designed to withstand harsh transport conditions and provide protection during storage and transit. Crates are mainly used for transporting smaller quantities and delicate items [1]. The transportation of hazardous cargo is a process that requires exceptional care. According to the Oxford Dictionary, hazardous cargo is defined as "materials or objects that may cause harm to people, animals, or the environment due to their chemical or physical nature." This includes chemical products, explosives, radioactive materials, and biohazardous materials. The purpose of this study is to explore the utilization of auxetic materials that, due to their properties, may provide enhanced protection for hazardous cargo during road transport.

The main feature of the auxetic materials is the negative Poisson's ratio ($v<0$). They form a particular category of materials characterized by special and unusual mechanical properties. Their unusual behavior lies in the fact that once stretched in one direction, the materials get thicker in the perpendicular direction, unlike common materials which present thinness. In addition, when part of the material is being squeezed, the rest of it tends to shrink rather than expand and it gets denser in the process.

Their name derives from the Greek word "$\alpha\upsilon\xi\eta\tau\iota\kappa\grave{o}\varsigma$" meaning "that which is tending to increase" [2]. The growing interest in auxetic materials stems from their enhanced mechanical properties, such as shear strength, resistance to strain and strength against fracture [3, 4]. The auxetic materials belong to the group of metamaterials and owe their unique properties, not to their composition, but to the form of their (micro)structure. These properties are usually not found in nature. Their name derives from the Greek word "$\mu\varepsilon\tau\grave{\alpha}$" which means "beyond" and from the Latin word "materia" which means material. The fields of use of auxetic materials vary and are constantly increasing.

2 Methodology

A particularly important application field is the use of auxetic materials in protective equipment. Constructing auxetic structures using conventional production methods is often unfeasible due to their highly complex geometry. Yang et al. [5] studied the potential uses of reentrant hexagon and arrowhead-type printed auxetic structures made from common polymers for application in body protection. Imbalzano et al. [6–8] investigated the blast resistance of hybrid sandwich panels. Han et al. [9] developed two auxetic material structures for high energy absorption. Alomarah et al. [10] studied the in-plane mechanical properties of auxetic structures under dynamic compression using both experimental and numerical methods. Madke and Chowdhury [11] investigated the effectiveness of a sandwich structure with an auxetic 3D reentrant lattice core and semi-auxetic braided composite face sheets under high-velocity impact. The auxetic behavior of materials in engineering applications is still an active area of research [12]. The purpose of this study is to provide a comparative evaluation of star-shaped auxetic structures under high-velocity impact using FEA [13].

Auxetic honeycombs are lightweight structures that provide good insulation and mechanical strength (Figure 1) [14]. They are widely used in applications, such as packaging and construction, offering increased stability and reduced weight [15]. The first example of an auxetic honeycomb is the reentrant hexagon developed in the 1980s. The star-shaped form is a geometric arrangement observed in various fields, including engineering, architecture, and nature (subgraph (b) of Figure 1). This shape combines characteristics that offer both aesthetic and functional value. The main characteristics of the star-shaped form are: a) structural stability: The star-shaped form has the ability to distribute forces across multiple points, enhancing the overall stability of the structure. This is particularly useful in structures exposed to significant loadings. b) shock resistance: The geometric configuration of the star-shaped form allows for better shock absorption, making it suitable for applications, such as aerospace and high-strength structures. c) aesthetics: The star-shaped form offers visual variety and interest, often used in architectural creations and product design. Its symmetry and angles add a unique visual dimension.

(a) (b) (c) (d)

Figure 1. Examples of auxetic structures: (a) Reentrant honeycomb; (b) Star-shaped honeycomb; (c) Double arrow honeycomb; (d) Chiral honeycomb

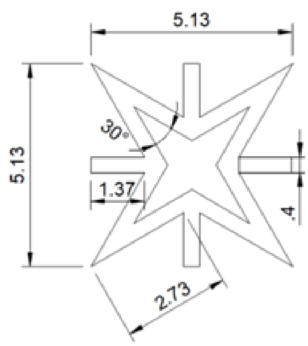


Figure 2. The layout of the auxetic star-shaped core

2.1 Auxetic Sandwich Structure Design

Gibson [16] proposed the properties of the cell based on the beam theory and also discovered that a unitary cell of a cellular structure can be used as a prediction tool for the behavior of the sandwich panel. Figure 2 presents the unitary cell of the auxetic structure, along with the parameters that define the geometry of the cell. The main design parameters of the cell size are the height of the cell, the length of the cell wall, the thickness of the cell wall and the angle between the cell wall and the horizontal axis.

Figure 3 shows the layout of the sandwich-type structure used in the FEA to examine its behavior in puncture or penetration protection. The structure is a representative sample of a box wall, consisting of an auxetic structure designed to protect sensitive goods during transportation.

2.2 FEA

FEA was conducted to investigate the puncture resistance behavior of the auxetic structure. Specifically, the simulation study involves a metallic casing with dimensions of 10×10×6 mm impacting the auxetic sandwich structure at a speed of 800 m/sec after traveling a distance of 300 mm. The total duration of the dynamic analysis was 1 ms. The materials used in the auxetic structure and the metallic casing are listed in Table 1.

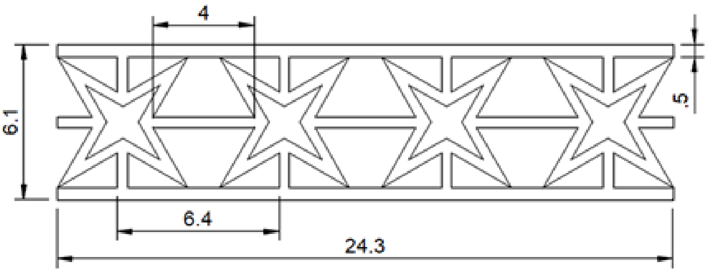


Figure 3. The layout of a model auxetic sandwich structure

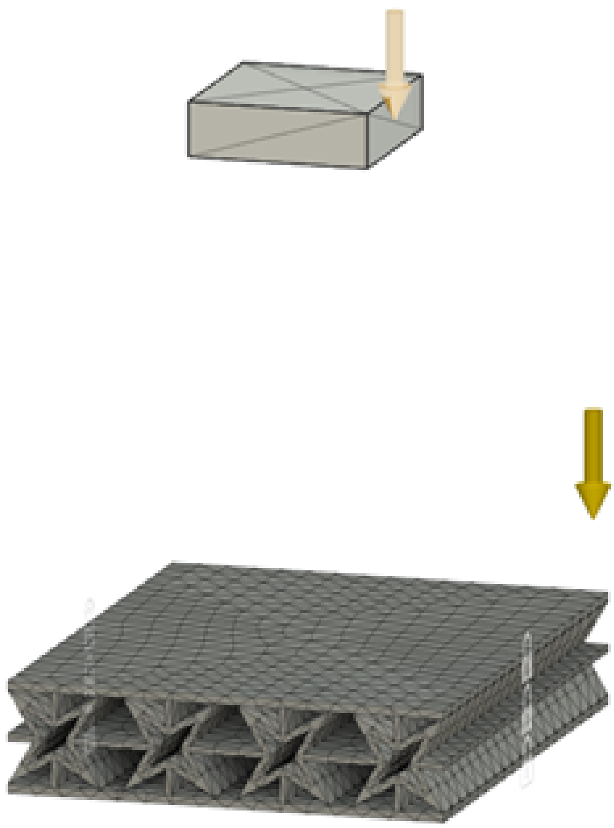


Figure 4. FEA boundary conditions

Table 1. Material properties

Material	Young's Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Tensile Strength (MPa)	Shear Modulus (GPa)	Density (gr/cm^3)
Aluminum (auxetic structure)	68.95	0.33	34.47	89.63	25.92	2.71
High-density steel (metallic part)	200	0.29	344	448	77519	7.85

For the execution of the FEA, a model consisting of 21,956 tetrahedral elements was created. A full constraint was applied to both sides of the auxetic structure. The metallic casing was used to impact the auxetic structure at a speed of 800 m/sec (Figure 4).

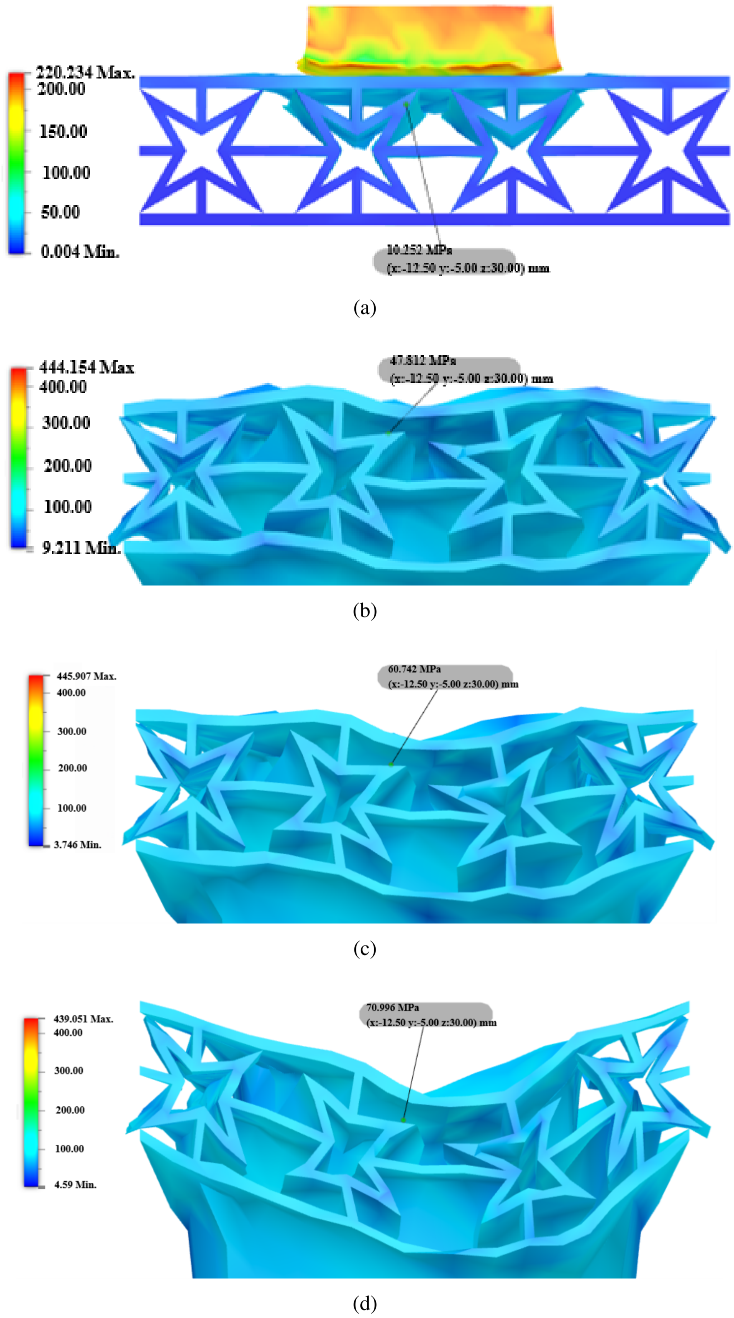


Figure 5. Auxetic structure behavior during the study duration

3 Results

The study aims to investigate the behavior of a protective wall of a container or other means of transporting sensitive or hazardous loads during road transport. Specifically, the protective wall was evaluated for the protection it provides in the event of an explosion or impact where a metallic object would collide with it at a high speed. The structure chosen for evaluation has a total thickness of 6 mm. Internally, the structure is not solid but consists of an auxetic star-shaped structure, which has been proven by several studies [17–20] to exhibit very good impact resistance. On the inner and outer sides of the auxetic structure, a solid layer with a thickness of 0.5 mm was inserted on each side. The following results were summarized in two separate finite element studies. In the first study, a high-strength metallic body collided with the protective wall from a distance at a high speed. The metallic body may represent a fragment created by an explosion or the result of a collision during cargo transport. The analysis results showed the deformation of both the metallic fragment and the protective auxetic wall. In the second study, the metallic fragment was used as a rigid body with infinite stiffness, meaning it does not deform upon impact.

Figure 5 shows the gradual deformation of the auxetic structure at different time intervals during the analysis. The study was conducted over 25 steps with a total duration of 1 ms. In this study, both bodies underwent deformation. Consequently, the stresses developed were very high in the metallic casing as it impacted the auxetic structure at a high speed. Figure 6, Figure 7 and Figure 8 show the Von Mises stresses, total displacement, and strain, respectively. These graphs pertain to the auxetic structure and were derived from measurements at a specific location within the structure. As shown in Figure 5, the maximum Von Mises stress at a chosen point of the structure is up to 80 MPa, the total displacement is not greater than 5 mm, and the maximum strain is less than 0.25.

In the second finite element study, the behavior of the auxetic structure was presented with the same boundary conditions, with the difference of a rigid metallic component (Figure 9). On one hand, using a rigid body simplified the model's complexity, allowing the study to focus on the forces and loads exerted by the rigid body on the auxetic structure. On the other hand, the rigid body represented other, higher-hardness materials, enabling the evaluation of the auxetic structure under extreme impact scenarios.

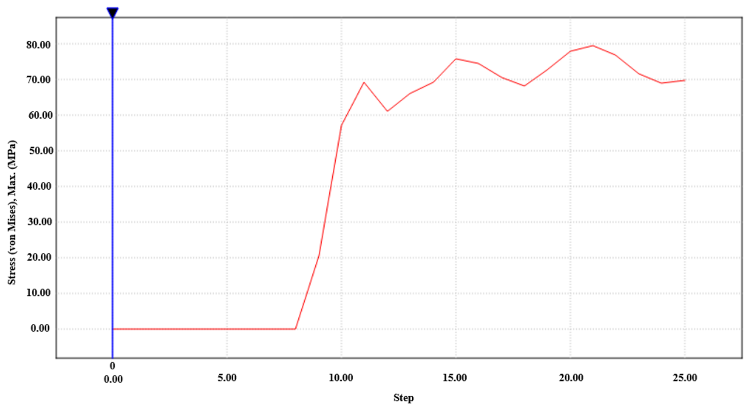


Figure 6. Von Mises stress of the auxetic structure

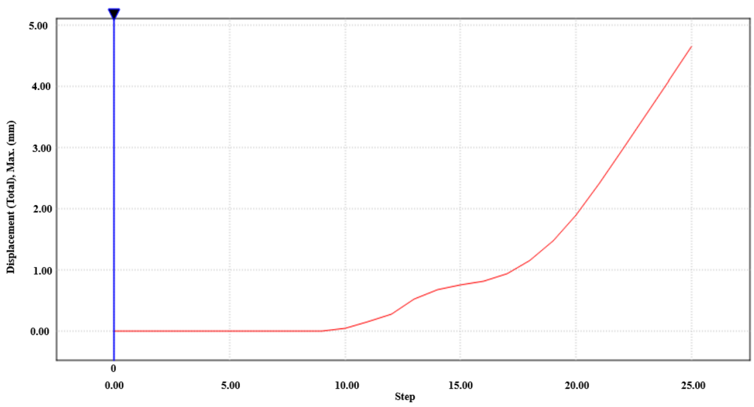


Figure 7. Total displacement of the auxetic structure

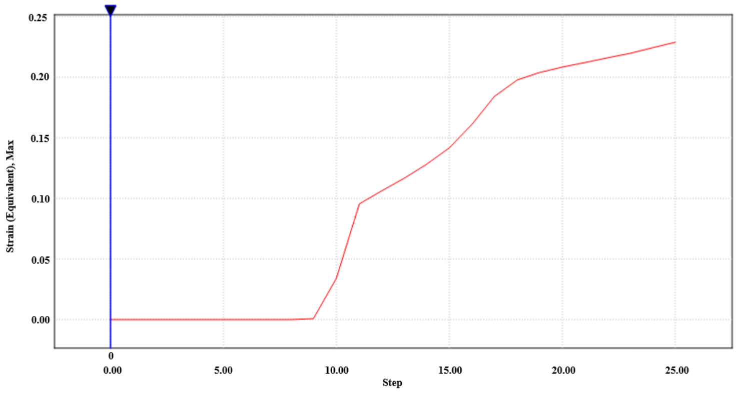
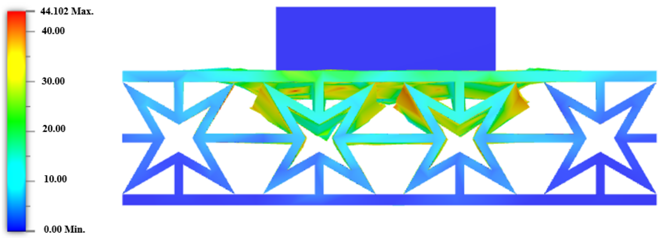
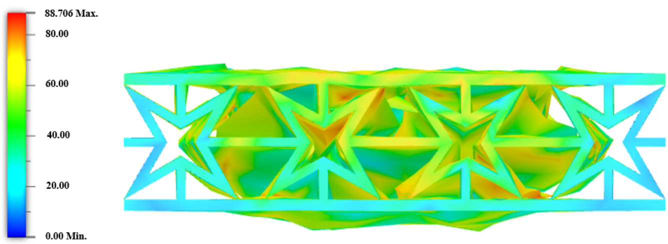


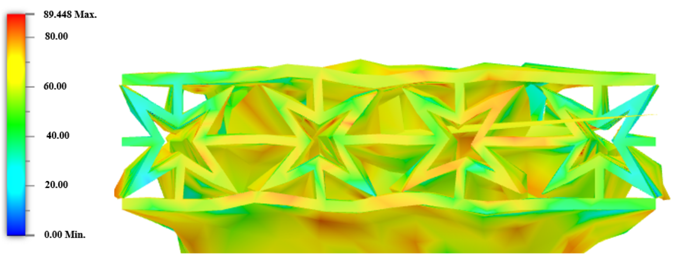
Figure 8. Maximum strain of the auxetic structure



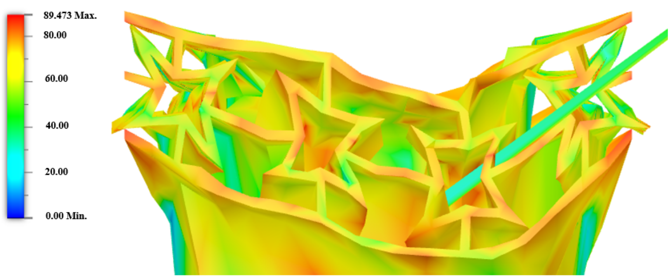
(a)



(b)



(c)



(d)

Figure 9. Auxetic structure behavior during the study with the rigid metallic part

Figure 10, Figure 11 and Figure 12 depict the behavior of the auxetic structure under extreme loading scenarios, with the metallic component defined as rigid and impacting the auxetic structure at a speed of 800 m/s. The maximum Von Mises stress on the surface of the structure did not exceed 80 MPa. The maximum displacement of the auxetic structure reached up to 12 mm, while the maximum strain value exceeded 0.60.

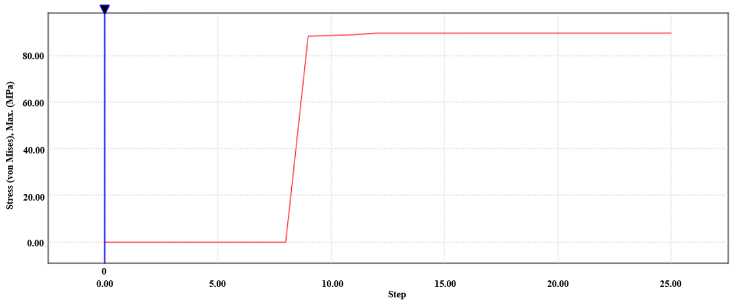


Figure 10. Von Mises stress on the auxetic structure with the rigid metallic part

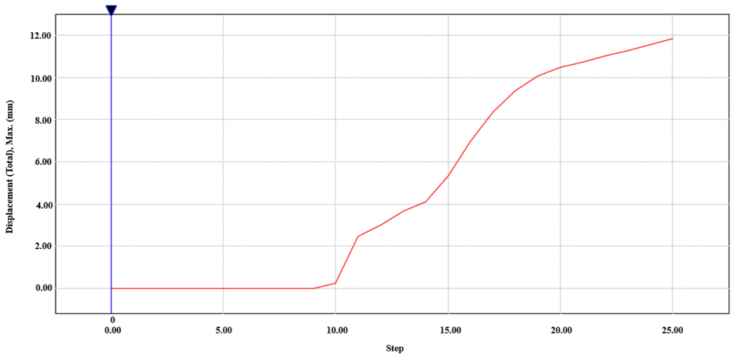


Figure 11. Maximum displacement on the auxetic structure with the rigid metallic part

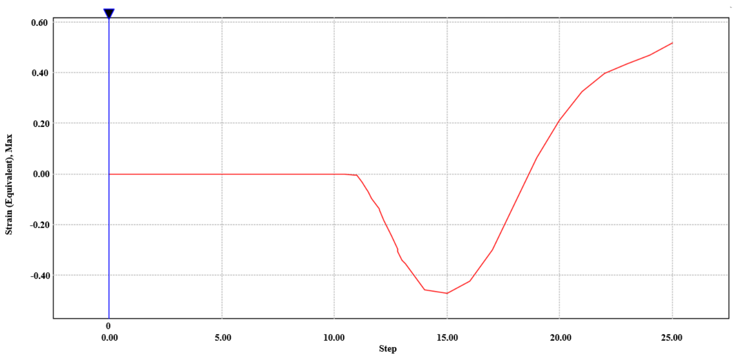


Figure 12. Maximum strain on the auxetic structure with the rigid metallic part

4 Discussion

The results of this study present the behavior of the star-shaped auxetic structure in impact scenarios, with FEA performed under two loading scenarios. The structure's behavior was examined in the plastic region under extreme loading conditions. In the initial study, the maximum stresses developed exceeded the yield limit, with the structure exhibiting good elastic behavior in the early stages of testing. However, it eventually collapsed and deformed. In the second loading scenario, where the metallic part was defined as rigid, the auxetic structure's behavior did not show a significant change in the stresses developed compared to the first test, even though the loading scenario was extreme. However, the extreme loading led to significant deformation of the structure. A particularly positive finding is that, despite the extreme loading of the auxetic structure, the torsion of its core toward the loading area results in a reduction of the stresses developed. This positive response is evidently caused by the star-shaped design of the structure.

5 Conclusions

In summary, this study focuses on the use of auxetic structures in the walls of transport aluminum boxes for sensitive or hazardous materials during road transport. The potential risks during transport can lead to extreme loading situations for the transported goods, which may result in dangerous situations for human life. It is essential to consider extreme loading scenarios to mitigate these risks. The examined auxetic structure was tested and evaluated under highly extreme loading conditions, allowing it to be studied in its plastic region to demonstrate its behavior in extreme situations. The excellent performance of the star-shaped auxetic structure, as documented in the literature, was also confirmed in this study, highlighting the necessity of positively evaluating this type of structure for transport container walls. The findings of this study can be used in future studies to assess the structure at different sizes, materials and configurations to find the optimal solution for more effective protection of transported goods.

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Data Availability

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

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