

Numerical investigation of a star-shaped auxetic structure under different impact velocities

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ABSTRACT

Auxetic structures are a class of mechanical metamaterials characterized by a negative Poisson's ratio and enhanced energy absorption capabilities under impact loading. In this study, the influence of impact velocity on the mechanical response of a star-shaped auxetic (SSA) structure is investigated using the finite element method implemented in ANSYS Workbench LS-DYNA. A cellular structure composed of a 6×6 arrangement of SSA unit cells was subjected to compressive impact loading at velocities of 1 m/s, 10 m/s, and 100 m/s. The deformation mechanisms, force–displacement response, kinetic and internal energy histories, and energy absorption characteristics were analyzed. The results show that the deformation patterns obtained at 1 m/s and 10 m/s are nearly identical, exhibiting the characteristic elastic, plateau, and densification stages of cellular structures. Furthermore, the quasi-static condition was satisfied for these loading velocities, as the kinetic energy remained significantly lower than the internal energy throughout the simulations. In contrast, the response at 100 m/s was dominated by dynamic effects, resulting in non-uniform deformation, increased impact forces, and significantly higher energy absorption. The findings provide insight into the influence of impact velocity on the mechanical behavior of star-shaped auxetic structures and may contribute to their application in energy-absorbing systems.

KEYWORDS

Auxetic, Energy absorption, Finite element method, Quasi-static, Star-shaped structure

1. INTRODUCTION

Auxetic structures are artificially engineered materials characterized by unique mechanical properties [1–5]. They belong to the class of mechanical metamaterials, with their most distinctive feature being a negative Poisson's ratio. For isotropic materials, the Poisson's ratio typically ranges from –1 to 0.5, while in certain special cases values outside this range may be observed [6].

The fundamental building block of auxetic materials is the auxetic unit cell [3,6]. An assembly of such unit cells forms an auxetic structure. Unlike conventional materials, auxetic structures exhibit lateral contraction under compressive loading and lateral expansion under tensile loading, resulting in a negative Poisson's ratio, as illustrated in Figure 1(a). Owing to this deformation mechanism, auxetic structures demonstrate enhanced energy absorption capabilities under impact loading.

The deformation process of an auxetic structure subjected to compression can generally be divided into three stages: the elastic stage, the plateau stage, and the densification stage, as shown in Figure 1(b). Due to their ability to undergo large recoverable deformations and efficiently absorb impact energy, auxetic structures have attracted considerable attention in a wide range of engineering applications, including robotics, sports equipment, textiles, construction, composite materials, biomedicine, automotive engineering, defense systems, aerospace structures, and sensor technologies.

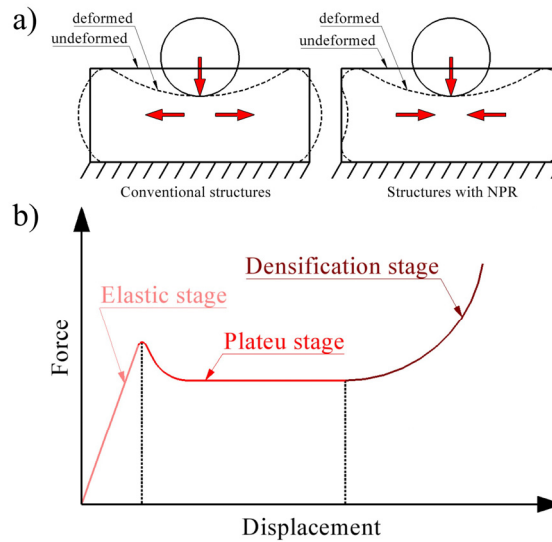


Figure 1: (a) Comparison between conventional and auxetic structures [4] and (b) schematic representation of the deformation stages during the compression process

In this study, the influence of impact velocity on the mechanical response of a star-shaped auxetic structure is investigated using the finite element method. Section 2 presents the design of the star-shaped auxetic unit cell and the corresponding cellular structure. Section 3 describes in detail the development of the finite element model and the simulation procedure employed to analyze the structural response under different impact velocities. Finally, the numerical results obtained from the finite element simulations are presented and discussed.

2. DESIGN OF A STAR-SHAPED AUXETIC STRUCTURE

The Star-Shaped Auxetic (SSA) unit cell represents a conventional re-entrant auxetic configuration in both directions. The unit cell consists of four arrow-shaped elements, together with two vertical and two horizontal struts, as shown in Figure 2.

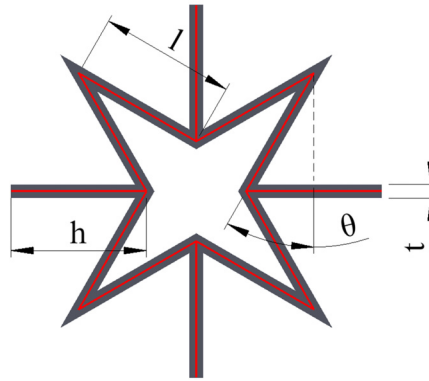


Figure 2: Geometric parameters of the SSA unit cell

The geometric parameters describing the SSA unit cell are h - the length of the horizontal and vertical struts, θ - the angle between the re-entrant and vertical struts, l - the length of the re-entrant struts, and t - the strut thickness. Based on these geometric parameters, the relative density ρ_r of the SSA structure is defined as the ratio between the volume of the unit cell V_{UC} and the volume of the space V_s occupied by that unit cell, and it is expressed by the following equation [7,8]:

$$\rho_r = \frac{V_{UC}}{V_s} = \frac{(4l + 2h)t}{2 \left(\sqrt{2}l \sin\left(\frac{\theta}{2}\right) + h \right)^2} \quad (1)$$

The geometric parameter values were taken from references[7–9]: $l = 4 \text{ mm}$, $h = 4 \text{ mm}$, $\theta = 30^\circ$, and $t = 4 \text{ mm}$. A 6×6 array of unit cells was used to form the structure, which is placed between two plates with a thickness of 1 mm. The designed structure is shown in Figure 3, and its overall dimensions are: height $H = 67.57 \text{ mm}$, width $L = 65.57 \text{ mm}$, and thickness $B = 10 \text{ mm}$.

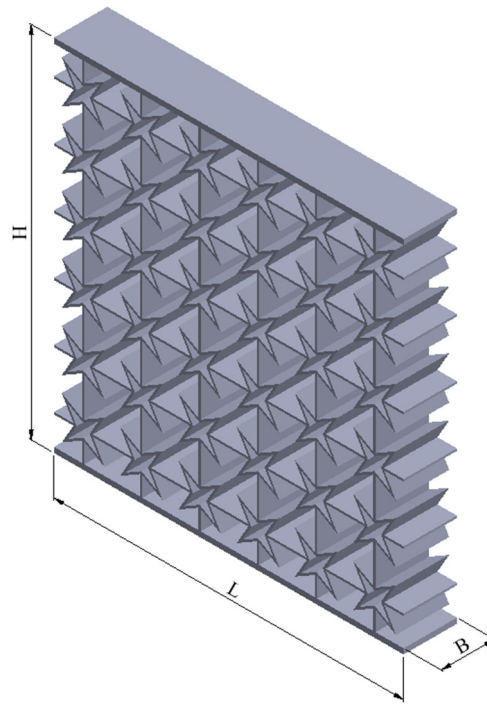


Figure 3: 6x6 structure composed of SSA unit cells

3. FINITE ELEMENT ANALYSIS OF THE SSA STRUCTURE

The mechanical properties of the SSA structure under compressive loading were investigated using the finite element method implemented in the ANSYS Workbench software package, specifically the LS-DYNA module. In this section, the structural response to the impact of a rigid plate at velocities of 1 m/s, 10 m/s, and 100 m/s is analyzed. The numerical model developed in ANSYS consists of two rigid plates and the SSA structure, as shown in Figure 4.

A constant velocity was applied to the top plate in the vertical direction, whereas the bottom plate was fixed throughout the analysis. The contact interaction between the SSA structure and the rigid plates was established using a manual contact region. Frictional contact with symmetric behavior was adopted, and both the static and dynamic coefficients of friction were assigned a value of 0.2. The planar surfaces of the SSA structure were specified as the contact bodies, while the lower surface of the top plate and the upper surface of the bottom plate were defined as the target bodies. Figure 5 presents the contact definition between the bottom plate and the SSA structure. The contact settings defined for the SSA self-contact were identical to those used for the contact interaction between the rigid plates and the SSA structure. The only difference was that both the contact and target bodies were assigned to the SSA structure, enabling the detection of potential interactions between its deformable components during compression.

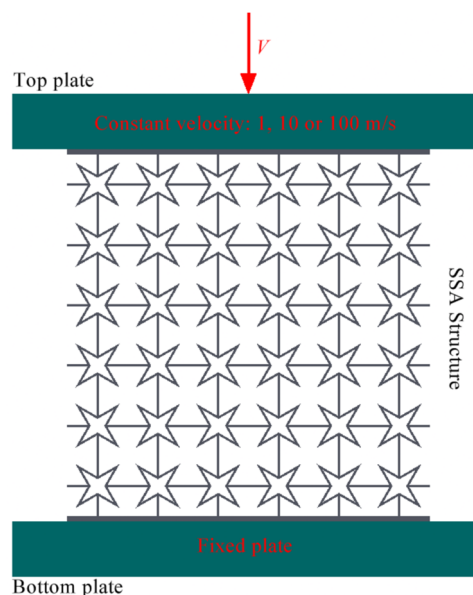


Figure 4: FEM of SSA structure under compressive loading

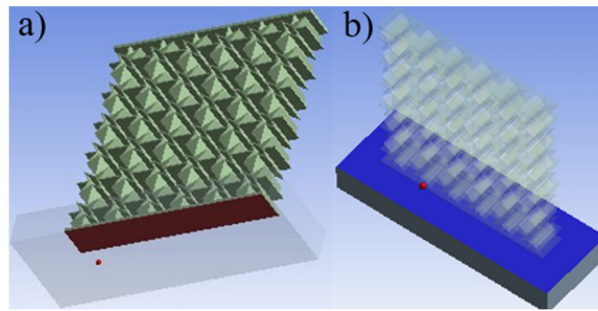


Figure 5: Contact Between the SSA Structure and the Bottom Plate: (a) Contact Body and (b) Target Body

The material used for the rigid plates in the numerical simulation was Structural Steel, with a density of $\rho=7850 \text{ kg/m}^3$ and a Young's modulus of $E=200 \text{ GPa}$. The SSA structure was modeled using a nonlinear material, Stainless Steel NL, with the following mechanical properties: density of $\rho=7750 \text{ kg/m}^3$, Young's modulus of $E=193 \text{ GPa}$, and yield strength of $\sigma_{YS}=210 \text{ MPa}$.

In the analysis settings, the same parameters were used for all loading velocities: the time step safety factor was set to 0.9, the solver type was structural analysis only, and the Hourglass control was defined using the Flanagan–Belytschko stiffness form with a standard Hourglass coefficient of 0.1. The end time for the 1 m/s case was 0.033785 s, while for the 10 m/s and 100 m/s cases the end time was reduced by factors of 10 and 100, respectively. The selected simulation time durations correspond to a structural compression of 31.046 mm, which represents approximately 46% compression relative to the total height H .

In this study, no mesh convergence analysis was performed. The element type was selected as automatic with the physics preference: explicit, using a linear element order. The element size for the rigid plates was 3 mm, while for the SSA structure it was 0.4 mm.

The output results from the numerical simulation include the vertical contact force between the top plate and the SSA structure, as well as the vertical deformations of the top plate.

3.1. Numerical Simulation Results

Figure 6 illustrates the deformation behavior of the SSA structure under three different impact velocities of the rigid plate. It can be observed that, for impact velocities of 1 m/s and 10 m/s (Figure 6 (a-b)), the SSA structure exhibits nearly identical deformation patterns. During the initial stage of impact, the structure deforms uniformly until reaching the densification phase, characterized by the collapse of the unit cells. In contrast, for an impact velocity of 100 m/s (Figure 6 (c)), a significantly different deformation mode is observed. The deformation is concentrated in the upper layers of the structure, while the lower layers remain almost undeformed throughout the simulation. This behavior indicates the presence of a pronounced strain-rate effect and non-uniform deformation propagation under high-velocity impact loading.

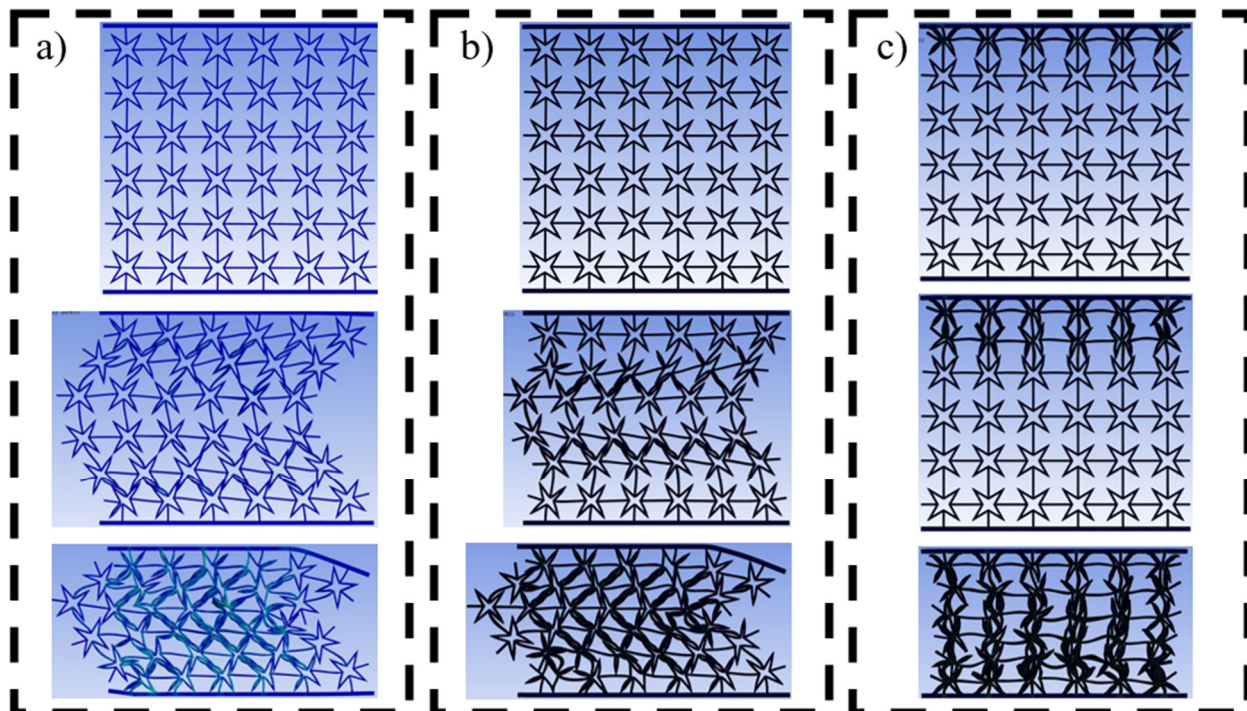


Figure 6: Deformation of the SSA structure under impact velocities of: (a) 1 m/s, (b) 10 m/s and (c) 100 m/s

To ensure quasi-static loading conditions in an explicit finite element analysis, the kinetic energy should remain significantly lower than the internal energy, typically below 5% of the internal energy throughout the simulation [10]. Figure 7 presents the histories of kinetic and internal energies for the entire duration of the simulations.

As shown in Figure 7(a), for an impact velocity of 1 m/s, the kinetic energy remains at a low level while the internal energy continuously increases during the loading process. Therefore, the quasi-static condition can be considered satisfied. A similar trend is observed for the impact velocity of 10 m/s (Figure 7(b)). Although a rapid increase in kinetic energy occurs at the beginning of the simulation, it subsequently stabilizes at a relatively low value, whereas the internal energy continues to increase. Consequently, the quasi-static condition is also satisfied in this case.

In contrast, for the impact velocity of 100 m/s (Figure 7(c)), the kinetic energy remains substantially higher than the internal energy throughout most of the simulation. As a result, the quasi-static condition is not fulfilled, indicating that the structural response is dominated by dynamic effects.

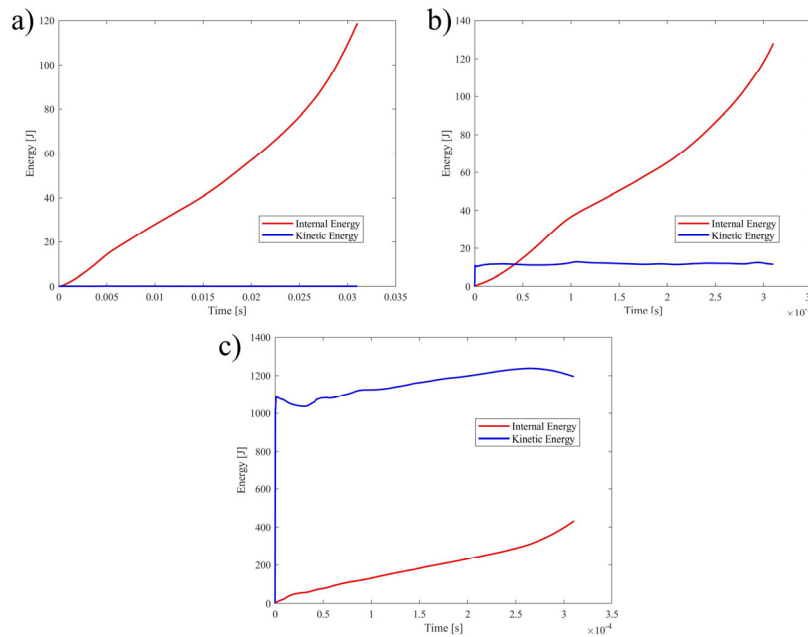


Figure 7: Internal and Kinetic energy of the SSA structure under impact velocities of: (a) 1 m/s, (b) 10 m/s and (c) 100 m/s

Figure 8 presents the force–displacement curves of the SSA structure subjected to impact velocities of 1 m/s, 10 m/s, and 100 m/s. It can be observed that, for impact velocities of 1 m/s and 10 m/s, the force–displacement response exhibits the characteristic behavior of cellular structures, consisting of three distinct stages: an initial elastic region, a plateau region associated with progressive cell collapse, and a densification region characterized by a rapid increase in force.

In contrast, the response obtained at an impact velocity of 100 m/s differs significantly. The force–displacement curve exhibits pronounced force oscillations and substantially higher peak forces, indicating the dominance of dynamic effects during impact loading. As a result, the deformation process becomes non-uniform and the characteristic quasi-static response of the structure is no longer observed.

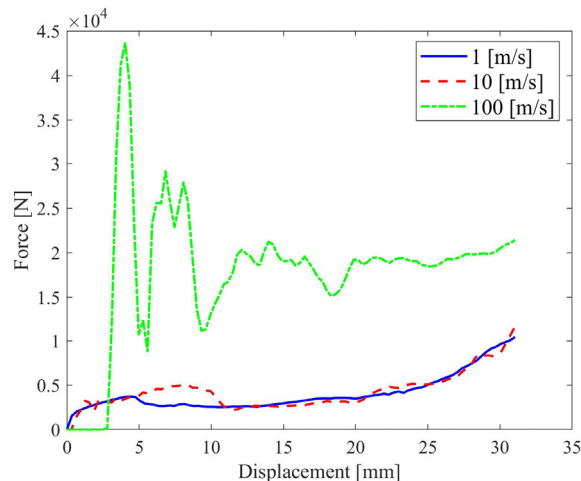


Figure 8: Force–Displacement curves of the SSA structure under impact velocities of 1 m/s, 10 m/s, and 100 m/s

Under impact loading conditions, the energy absorption (EA) capacity of the SSA structure is evaluated as the area under the force–displacement curve, which can be calculated by integrating the contact force ($F(y)$) over the corresponding compressive displacement (y) [11]. Accordingly, the energy absorption is expressed as:

$$EA = \int_0^y F(y) dy \quad (2)$$

For discrete data obtained from finite element simulations, the energy absorption (EA) is calculated using numerical integration based on the trapezoidal rule, which can be expressed as:

$$EA = \sum_{i=1}^{n-1} \frac{F_i + F_{i+1}}{2} (x_{i+1} - x_i) \quad (3)$$

Based on the data from Figure 8 and Equation (3), the values for all three impact velocity cases are presented graphically in Figure 9. The results show that the energy absorption (EA) values for lower impact velocities, 1 m/s and 10 m/s, are approximately identical, with a difference of less than 6%. Due to significantly higher impact forces, the EA value at an impact velocity of 100 m/s is considerably higher, which is a consequence of pronounced dynamic effects during impact loading.

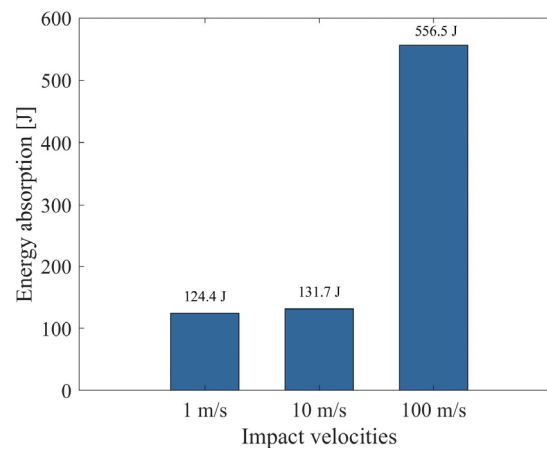


Figure 9: Energy absorption response of the SSA structure under impact velocities of 1 m/s, 10 m/s, and 100 m/s

4. CONCLUSION

This study presents a numerical investigation of the mechanical response of the SSA structure under impact loading conditions at velocities of 1 m/s, 10 m/s, and 100 m/s. Based on the results presented in this work, it can be concluded that the quasi-static condition is satisfied for impact velocities of 1 m/s and 10 m/s.

Future research should focus on the influence of different geometric parameters of the unit cell on the mechanical behavior of the SSA structure. In addition, experimental testing would be valuable to further validate the numerical results and to determine the critical impact velocity threshold required to ensure quasi-static conditions consistent with experimental observations.

Furthermore, it is of interest to investigate the evolution of the Poisson's ratio during the compression process of the SSA structure, as it may provide additional insight into its auxetic behavior under large deformations.

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