Finite Element Analysis of Re-Entrant and Modified Curved Re-Entrant Auxetic Structure for Energy-Absorption

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Abstract

Auxetic cellular materials have unique and superior physical properties with negative Poisson's ratio which is caused by the structural deformation of the cells, which increases their lateral dimension when stretched. The re-entrant and the proposed curved re-entrant structure with varying thicknesses (1 mm and 0.5mm) is analyzed in ABAQUS by considering the properties of Acrylonitrile butadiene styrene (ABS). A curved re-entrant structure with a thickness of 1 mm was found to be capable of bearing more load than that of a 0.5 mm thickened structure. Also, the nominal stress was found to increase by 6 times when the thickness was doubled.

Keywords Auxetic cellular material, Poisson's ratio, Re-entrant structure, curved re-entrant.

1. INTRODUCTION

In a confined space and weight, where high damping absorption is required that too with high strength, rigidity, lightweight, and good impact resistance. The auxetic materials stand at the top with the above-mentioned properties [1-2]. It has the properties to shrink when applied with compressive force as it is defined as a negative poison's ratio material. The deformation modes, structure, loading circumstances, material qualities, and hybrid configurations all have an impact on the energy-absorption capacity of materials [3].

Many writers have proposed various structures for auxetic materials, such as hexagonal, re-entrant, kagome, diamond, star-shaped honeycomb, and many more. A hexagonal structure [13] consists of a 2D structure with a hexagon as a unit cell as shown in Fig. 1(a). These hexagonal unit cells get repeated horizontally and vertically as per the required property and energy absorption capacity. When a hexagonal unit cell is put on an orthogonal plane, such that the opposing sides are parallel and horizontal, and both neighboring sides are pushed inside, the hexagonal unit cell is turned into a re-entrant structure. Fig. 1(b) depicts the re-entrant structure's unit cell [9]. To investigate the desired qualities, the angle of inclination of inclined sides can be changed. Kagome structure [7] consists of two triangle-shaped structures placed inverted such that all the three sides of both the triangles intersect each other twice, forming a shape as shown in Fig. 1(c). As illustrated in Fig. 1(d), a diamond-shaped [7] unit cell is made up of two triangular-shaped structures that are inverted such that the peak points of both structures coincide with the base of each triangle. When an eight-sided polygon is made in such a way that all alternate vertices are pushed towards the center and other remaining alternate vertices are constrained at their original position as shown in Fig. 1(e) to form a star-shaped structure [8].

In terms of differences in deformation and mechanical reactions of different cells many experiments and simulation has been studied and also new designs are proposed. Gao et al. [2020] purposed a double arrowed honeycomb (DAH) and studied its deformation under different impact velocity conditions and found that crushing strength increase with impact velocity and relative density [4]. The re-entrant structure possesses better energy absorption properties as compared to conventional hexagonal structure and also possesses anisotropic dynamic mechanical properties [5]. The honeycomb structure is considered the basic structure for such properties. As the honeycomb structure was made hierarchical with the first and second-order, the specific energy absorption increases many times as compared to the basic structure [6] thus increasing the potential in the energy absorption field. Quadri-arc honeycomb designed by Zhang et al. shows a better energy absorption efficiency than that of circular in quasi-static and low-velocity impact and relative density [7]. In-plane dynamic crushing and energy absorption characterization were also studied by Lu et al. with the different proposed structures. The result showed that the star-circle honeycomb structure's energy absorption efficiency increased as impact velocity increased as compared to star-shaped honeycomb indicating higher impact resistance [8]. When the load is applied at in-plane and out-of-plane for re-entrant samples, the in-plane is applied to provide a better impact strength and absorption of energy than another plane [9]. Till now, several reviews and works have been published. Because of the folding and rotation of cell walls, the auxetic structure's load-bearing abilities are limited [10]. Therefore, the mechanical properties enhancement became the main concern of the researchers through different structure design, material, and parametric variations. To check the mechanical response Wang et al. [11] developed the 3D cross-chiral structures. The author examines the result theoretically and also performed experiments and simulation work. The authors found that the young's modulus of the structure is also dependent on the tilt angle and the proposed design by the author showed a significant increase of approximately 8-fold this structure shows a wide range of mechanical properties stability. To check the effect of cell numbers Carneiro et al. concluded that as the cell numbers increases, the Poisson's ratio value also increases exponentially. It is also stated that to get the internal bulk behavior, the structure must contain a minimum of 13 cells per row [12].

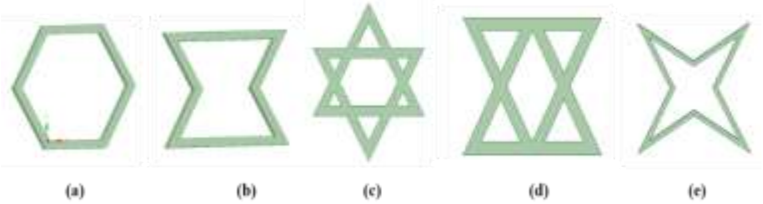


Figure 1. Various auxetic structure (a) Hexagonal (b) Re-entrant (c) Kagome (d) diamond (e) star shaped

The present study proposes a modification in the pre-existing design for the auxetic behavior. Here, we compare existing re-entrant and modified curved re-entrant structure with varying parameters in ABAQUS to study and shows the comparison of the in-plane dynamic response.

2. NUMERICAL ANALYSIS

2.1 Model Design

In this study, the basic model was simulated and the result was studied. A modified re-entrant curved design is also proposed for the auxetic properties. The re-entrant and proposed models are shown in Fig. 2 (a) and 2 (b)

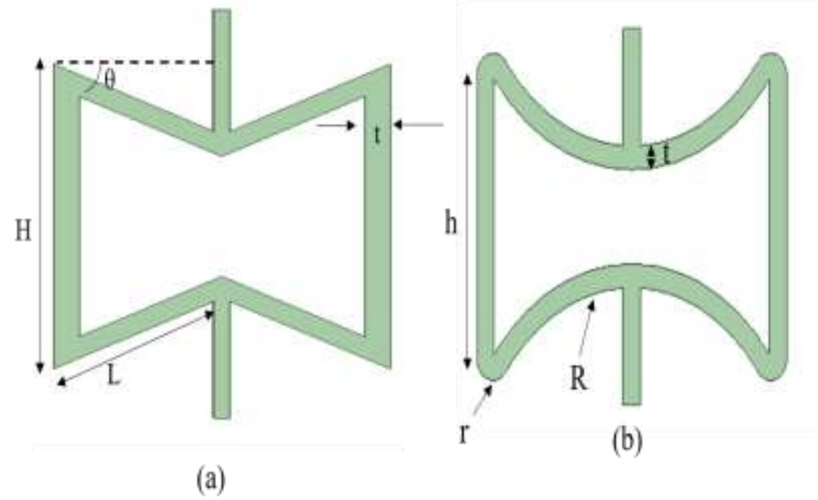


Figure 2. Unit cell of structure design (a) Re-entrant (b) Curved re-entrant

The dimension of two different structures is as follow: H and h is the height of the vertical strut of the re-entrant and curved re-entrant respectively, L is the length of the inclined strut of the re-entrant structure, θ is the angle of incidence of the inclined strut, R is the radius of curvature of the curved strut of curved re-entrant, r is the radius of curvature of corner joining vertical strut and curved re-entrant and t is the thickness of both the structures. The values of all the parameters are given in table 2. The depth of all the structures is kept at 45 mm. The three models whose analysis is studied are re-entrant unit cell structure, curved re-entrant unit cell with thicknesses 1 mm and 0.5 mm. The code given to the models is tabulated in table 1.

Table 1. Model code for different Structure

Sl. No.	**Structure**	**Model code**
1.	Re-entrant Unit cell	RS

2.	Curved re-entrant Unit cell with a thickness of 1 mm	CRS1
3.	Curved re-entrant Unit cell with a thickness of 0.5 mm	CRS2

Table 2. Dimension of the structures

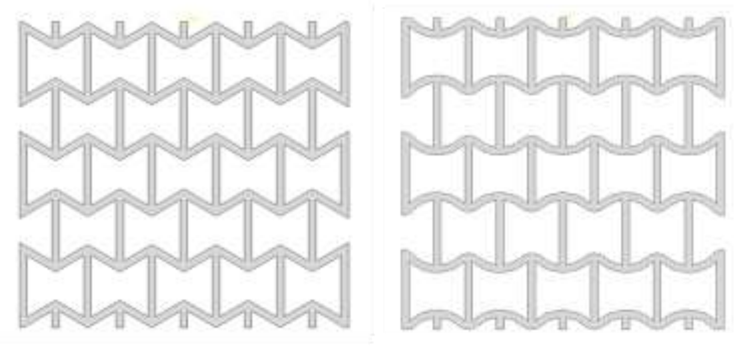
Re-entrant Structure (RS)	
Parameter	Value
H	10 mm
	5 mm
θ	- 30˚
t	1 mm

Curved Re-entrant Structure (CRS)	
Parameter	Value
h	9 mm
R	5 mm
r	0.5 mm
t	CRS1 =1 mm CRS2 = 0.5mm

The proposed structure i.e., curved re-entrant was modeled and analyzed with two different thicknesses, t, that is thickness t=1mm and t=0.5 mm. The proposed models were analyzed using ABAQUS and the results are compared with the re-entrant model.

2.2. Simulation

The finite element method was done to analyze the result using ABAQUS. An explicit dynamic model was done for all the structures. The ABS thermoplastic material properties is assigned to the model which has young's modulus E_s of 2.2 GPa with Poisson's ratio of 0.35 and density of $1.05 g/cm^3$ [2]. The unit cell of both the structure is modeled with five unit cells horizontal such that the right vertical strut of one cell coincides with the left vertical strut of another cell and three in a vertical direction as shown in Fig. 3. In total, 23 unit cells were considered for simulation and analysis.



Reentrant Structure

Curved Reentrant Structure

Figure 3. Model of re-entrant and curved re-entrant structure

These models are kept between two rigid plates in a sandwich style. The bottom plate was fixed restricting any movement in all directions and the top plate was given displacement only in the negative y-direction while movement in the other two directions was constrained to perform a uniaxial compression test in the y-direction. The maximum downward movement of the top plate given was 20 mm. Interaction of the upper and lower side of the structure with top and bottom plates respectively penalized with a frictional coefficient of 0.2. The depth of the structure was kept at 45 mm to avoid the buckling of the structure. The aforementioned boundary condition applied is shown in Fig. 4. S4R elements were used to mesh the model, which was swept with a quad-dominated elemental shape utilizing a free technique and linear geometric order. The element size of mesh was half the thickness of the model.

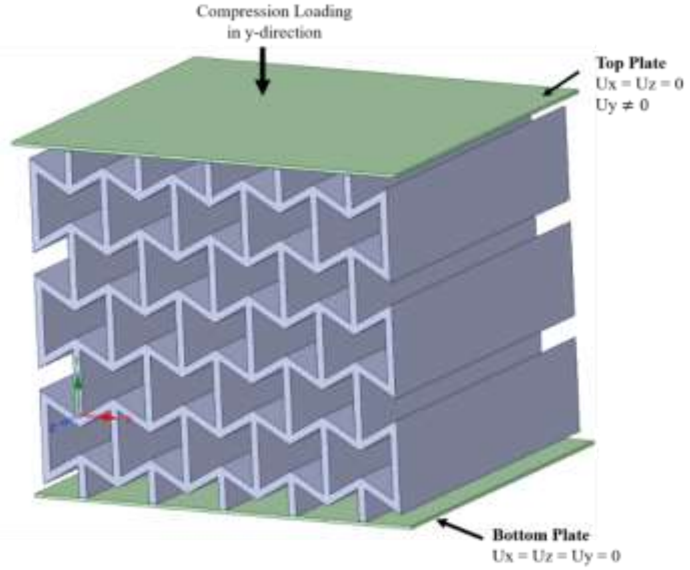


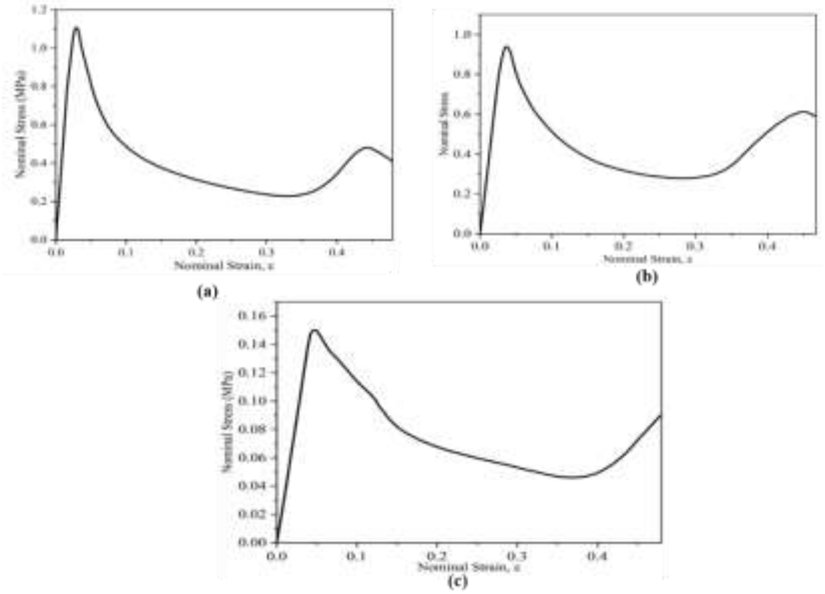
Figure 4. Boundary conditions are used in the model.

3. RESULTS AND DISCUSSIONS

The structures are crushed in the y-direction to study the mechanical properties such as stress, strain, force, and displacements of the structures. The stress-strain curve of the re-entrant structure, the curved re-entrant structure with a thickness of 1 mm, and the curved re-entrant structure with a thickness of 0.5 mm are shown in Fig. 5. The maximum stress induced in the re-entrant structure is 1.10741 MPa at a strain of 0.029056 mm/mm. The maximum stress occurred for curved re-entrant structure CRS1 (thickness 1mm) is 0.93991 MPa at a strain value of 0.03782 mm/mm whereas CRS2 (thickness 0.5mm) has the maximum stress of just 0.15029 MPa at a strain of 0.04741 mm/mm.

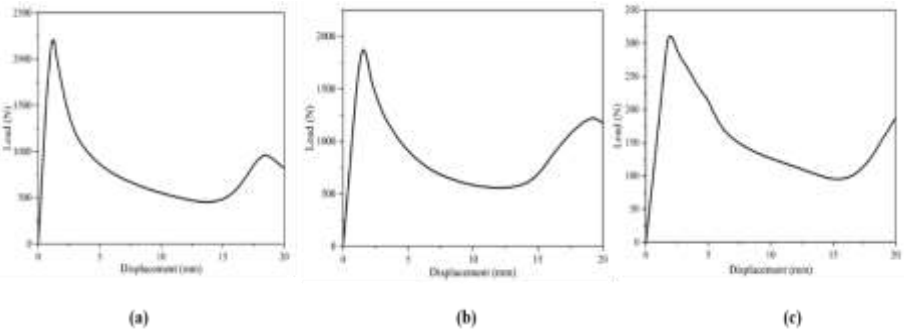
From the Stress-strain curve shown in Fig. 5, the stress produced in the Re-entrant structure (RS) is higher than compared to the proposed design. At a particular strain value, the maximum stress reached is more than 1 MPa whereas the curved re-entrant has a stress of less than 1 MPa. The CRS1 has a stress value much higher than that of CRS2. The deformation of structures under compression load at different strain values is shown in Fig. 7. The deformation pattern in all three structures is same as the strain in the structure increases.

The load variation concerning the deformation displacement of all structures is shown in Fig. 6. The re-entrant-shaped structure has the maximum load applied is 2208.7 N displacing 1.2125 mm of structure in the negative y-direction. When the top plate is displaced downward in negative y-direction compressing the structure the curved re-entrant CRS1 is imposed by a maximum load of 1873.7 N at the displacement of the plate at 1.6178 mm vertically downward whereas the CRS2 suffered a maximum load of 310.6 N at plate displacement of 1.9769 mm vertically downward. The pattern of the curve shows that when the structure is compressed, at the beginning the structure is imposed with linearly increasing loads and this load continues to decrease up to a certain limit after which it again starts increasing exponentially as the structure is further compressed. The stress-strain plot of the structure also depicts that the modified curved re-entrant structure has lower toughness as compared to the base re-entrant structure for ABS material.



(a) (b) (c)

Figure 5. Stress-strain plots for (a) RS (b) CRS1 and (c) CRS2



(a) (b) (c)

Figure 6. Load-displacement plot of (a) RS (b) CSR 1 (c) CSR 2

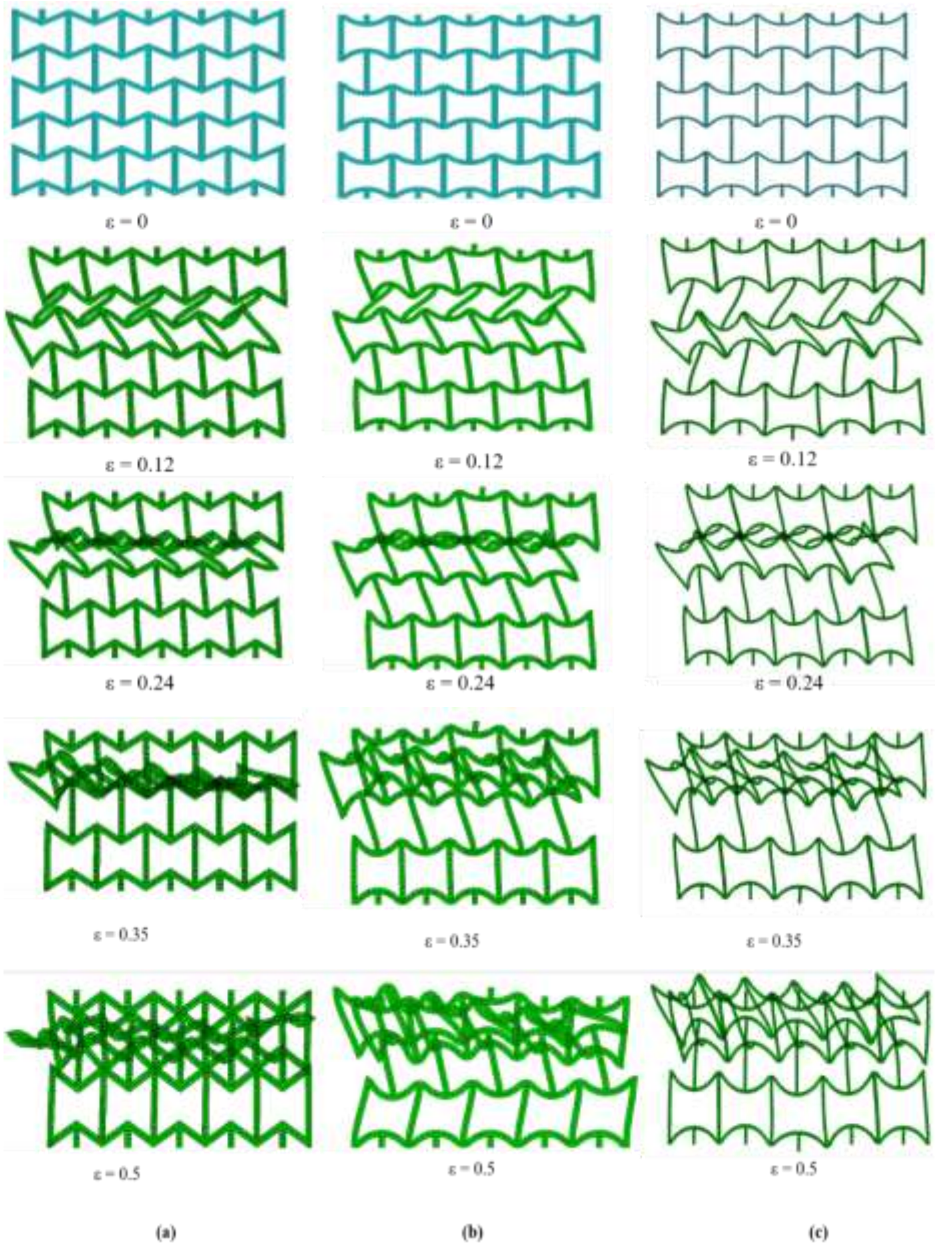


Figure 7. Deformation of shape under compression at different strain values (from ε=0 to ε=0.5) of **(a)** RS (**b)** CRS1 **(c)** CRS2

4. CONCLUSION

In this paper, investigation is done on the ABS-based curved re-entrant structure with a thickness of 1mm which is capable of bearing about 6 times more load than that of 0.5mm thick. When the thickness was doubled, the nominal stress is raised by 6 times, demonstrating that the 1mm thick structure had a larger energy absorption capacity. The modified curved structure has lower energy absorption as compared to the base re-entrant structure. Further studies will focus on improving the energy absorption property of this modified structure by varying the geometric parameters.

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