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Unit Cell Modelling of Auxetic Structure

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Abstract

Auxetic material structures exhibit a negative Poisson ratio. The structure expands in the axial and transverse directions under tensile loading and vice versa under compression loading. Many fabricated designs for auxetic materials exist such as re-entrant hexagonal, chiral, and arrowhead geometries. This paper studies the unit cell of the re-entrant hexagonal geometry to understand how changing the internal angle and fillet radius of the structure affects the Poisson's ratio. The material chosen for this study is acrylonitrile butadiene styrene (ABS) due to its availability and frequent use in additive manufacturing. The study was based on finite element analysis. It is observed that the direction of load applied to the unit cell affects the unit cell strain, Poisson's ratio, and maximum load capacity before failure responses. It is noticed that the re-entrant cell starts by showing a standard non-auxetic behavior until it reaches a specific axial strain value. A quadratic correlation is identified between axial and transverse strain. Designing an auxetic structure starts with understanding the behavior of a unit cell structure. The auxetic structure design is a complex process that requires a compromise between auxetic property to be achieved and load capacity via avoiding stress concentration zones.

Keywords

Auxetic Material, Negative Poisson's Ratio, Re-Entrant Hexagon, Finite Element Analysis, Unit Cell Design

1. Introduction

Auxetic structures have a negative Poisson's ratio property, where the structure expands in both directions, along the direction of the force applied and perpendicular to the direction of force. Negative Poisson ratio is beneficial for multiple applications, such as implants, stents, medical devices, and padding [1] [2] [3].

Negative Poisson's ratio structure promotes other properties such as vibration damping, higher indentation resistance and shear modulus, and an improved fracture toughness [1] [2] [4].

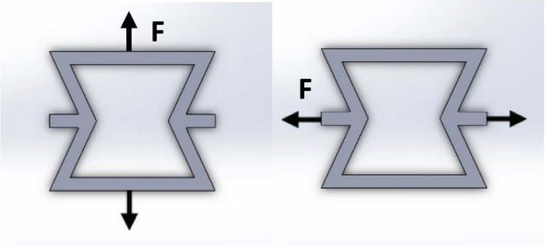
Typical auxetic structures are composed of multiple connected unit cells that work cohesively to provide the auxetic effect [1]. There are some naturally occurring auxetic materials, for example skin and specific minerals. Research has focused on how to synthetically create an auxetic material from one lacking natural auxetic [3] [4]. The type of material affects the overall performance of an auxetic designed structure. Wang *et al.* [5] investigated the effect of a conventional single material versus dual material structure on the overall performance of auxetic structure. The key parameter to produce an auxetic property behavior is the design of the structure.

Among the various designs of auxetic structures, including the re-entrant, chiral, and arrowhead geometries, the re-entrant design is at the forefront of research for redesign and had been used as the benchmark for comparison [1] [2] [4]. Although re-entrant design produces desirable properties associated with a negative Poisson's ratio, corners enclose high stress concentrations due to sharp corners [3]. Xiong *et al.* [6] have explored the effect of filleted corners on the stress concentration and Poisson's ratio value using an adapted re-entrant design. Xiong *et al.* concluded that fillets reduced the stress concentration and the observed Poisson's ratio [6].

Prior research has studied the internal angles of the re-entrant design to determine the angle that produces the most negative Poisson's ratio. Li *et al.* conducted finite element anaylsis (FEA) on two re-entrant designs, one unaltered and one with inclined overhanging segments [7]. It was determined that internal angles of 75˚ produced the lowest negative Poisson's ratio when the design was subjected to compressive force [7]. It was also found that a more negative Poisson's ratio was recorded when the unaltered re-entrant design of 75˚ angles was compressed, as opposed to the re-entrant design with inclined overhanging segments [7].

Alomarah *et al.* experimentally compressed different auxetic structures and reported Poisson's ratio values. A re-entrant structure was compressed in both the x-direction and y-direction on multiunit cell structure. Direction of the load applied relative to the structural design generated a higher value of negative Poisson's ratio in the y-direction, than in the x-direction [8].

The unit cell is the foundation of a re-entrant structure and its auxetic property is the focus of this study. This paper presents the difference in Poisson's ratio values exhibited when tensile force is applied to a re-entrant unit cell in two different orientations, as shown in **Figure 1**. Tensile force is applied to the flat side (FS) and connective segment (CS), respectively. As a result of increased stress concentration due to sharp edges, different fillet radii are considered and compared based on the ability to produce a negative Poisson's ratio while reducing stress concentration.



(a) (b)

Figure 1. Re-entrant unit cells with 0 mm fillet radii displaying (a) FS orientation and (b) CS orientation.

2. Methods

2.1. Internal Angle Design

Individual re-entrant unit cells were drafted using SOLIDWORKS 2018 software. Unit cells with different internal angles, θ, of 55˚, 65˚ and 75˚ were designed. The internal angle of 75˚ was observed to produce a negative Poisson's ratio by Li *et al.* [7]. Since the smaller the internal angle, the more the structure would axially and transversely displace when subjected to tensile force, smaller internal angles of 55˚ and 65˚ were considered with no fillet radius. Tensile force was applied in the CS orientation for the sake of comparison to other research that predominantly applied compressive force in the corresponding direction [1] [6] [7]. The data, shows that internal angle 65˚ produced a comparable negative Poisson's ratio without failing compared to 75˚ at slightly higher load (5N). The 55˚ angle showed smaller Poisson ratio value but handled higher force before failure.

The unit cell with the internal angle of 65˚ was selected as a base design for the remainder of the study. The forces displayed in brackets under the corresponding Poisson's ratio values in **Table 1** were the forces beyond which failure occurred as per von Mises stress analysis.

2.2. Orientation of Force Applied Effect

The basic re-entrant unit cell geometry of the model was designed such that the internal side "a" is double in length to side "b", as shown in **Figure 2**. The extrusion of the unit cell was 1.2 mm, and the cell wall thickness was 0.5 mm. The re-entrant unit cells with internal angles, θ, of 65˚ were used and simulated with fillet radii of 0 mm, 0.5 mm, and 1 mm. As shown in **Figure 3**. Fillets were added to the corners where the connective segments protrude from the re-entrant structure and to the internal corners of the structure.

FEA was performed using SOLIDWORKS on the unit cells. The XZ plane was used as the "Section Plane". The "Section Depth" was 1.2 mm. The same size of mesh was used for all unit cells for direct comparison. The simulated material used was acrylonitrile butadiene styrene (ABS), the elastic modulus used was 2.415 GPa, the tensile strength was 44.8 MPa, the yield strength was 42.05 MPa, Poisson's ratio was 0.4, and the mass density was 1.045 gm/cm^3 [9]. The "Model

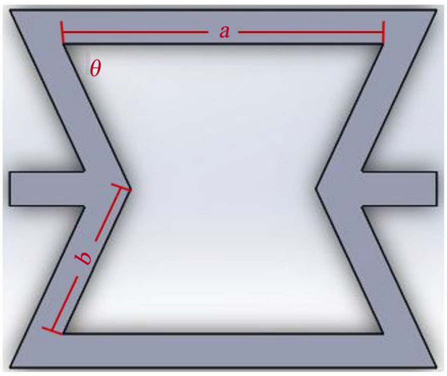


Figure 2. Dimensional representation of 0 mm fillet radius re-entrant unit cell.

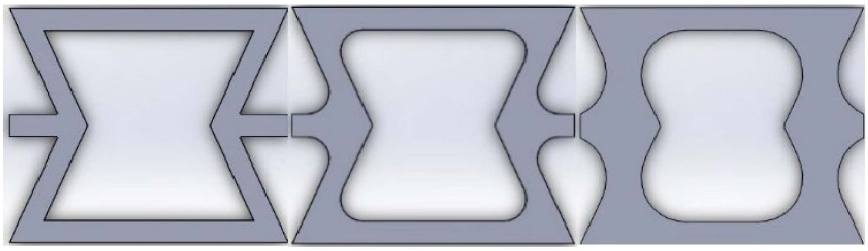


Figure 3. Re-entrant unit cells with (a) 0 mm fillet radii; (b) 0.5 mm fillet radii; and (c) 1 mm fillet radii.

Table 1. Negative Poisson's ratios observed for select angles.

Fillet Radius (mm)	Internal Angle (θ)		
	55˚	65˚	75˚
		Poisson's Ratio (Force)	
0	−5.48E−02 (15 N)	−8.46E−02 (5 N)	−9.59E−02 (4 N)

Type" used was "Plasticity-von Mises" to capture the failure point relative to von Mises values and yield strength limit [10].

Tensile force was applied to each unit cell consisting of the different fillet radii on both the FS orientation and the CS orientation. A range of magnitudes of force were applied to each configuration until failure limit was reached.

2.3. Calculation

The Poisson's ratio was calculated using the equation

$$\nu = -\frac{\varepsilon_x}{\varepsilon_z}$$

where ε_x is the strain in the direction perpendicular to the force applied and ε_z is the strain in the direction the applied force. The sum of the resultant nodal strains in the corresponding x-and z-directions were obtained from SOLIDWORKS and used as the data for the Poisson's ratio calculations.

3. Results and Discussion

3.1. Impact of Fillet Radii & Cell Orientation on Strain

Transverse strain had a consistent second-degree polynomial trend against axial strain for all three fillets as shown in Figure 4. Strain are unitless and the plot of strain at the axial direction versus strain at the transverse direction shows an inverse relationship, up to a certain point, then it reverses. The local minimum point, indicates the initiation of auxetic property. The local minimum point of the polynomial trend for each cell design is calculated for both loading directions, CS and FS. It is observed that the minimum point is achieved at lower strain values for sharper angle with no fillet radius (0 mm), compared larger filler radius (1.5 mm).

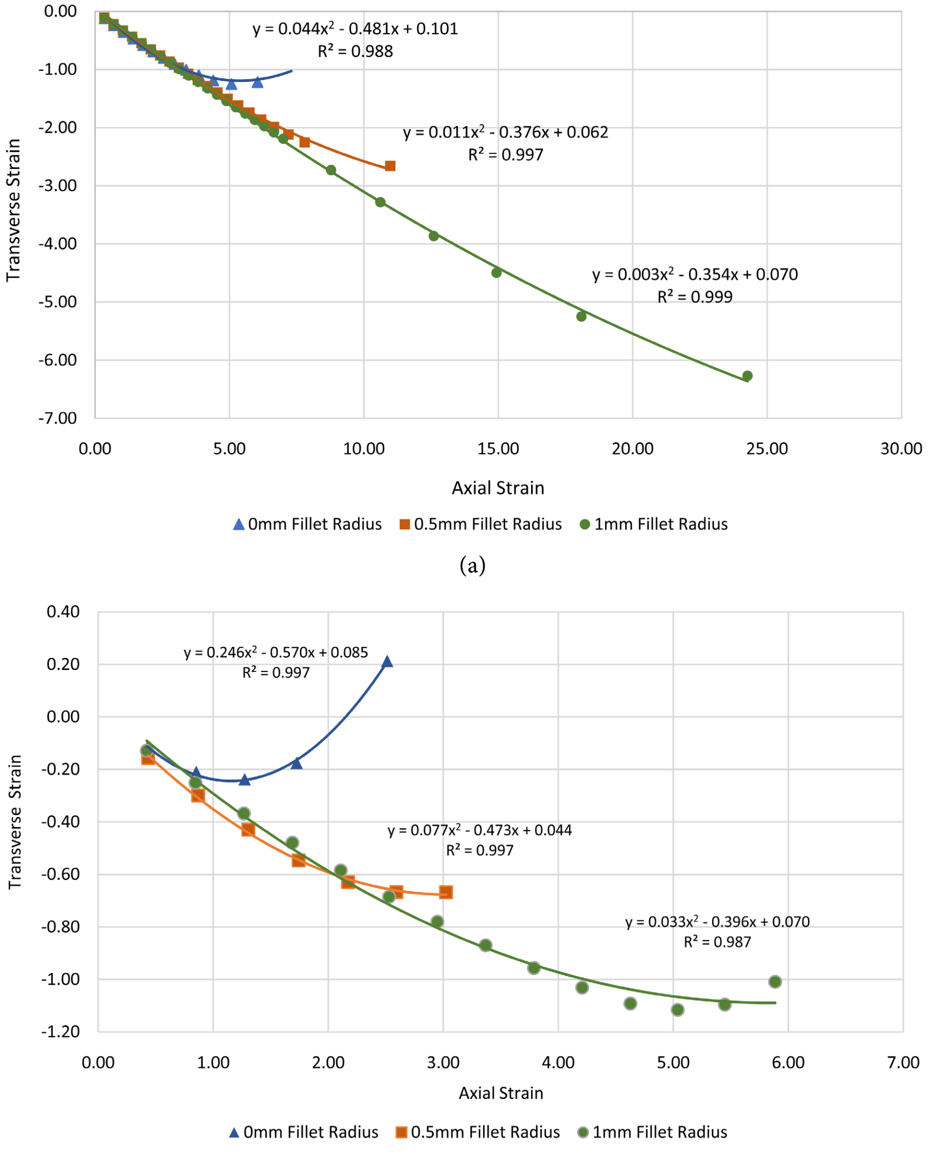


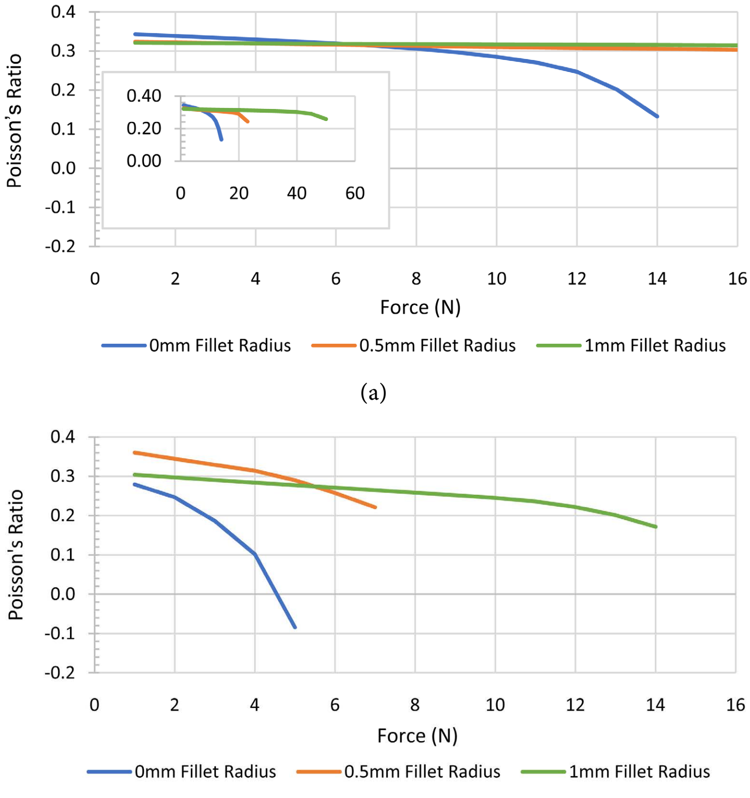
Figure 4. Transverse strain vs. axial strain. (a) FS; (b) CS.

The direction of load applied on the structure has a direct effect on the amount of axial strain needed to reverse the transverse strain. As presented in **Table 2**, strain applied on the CS direction reaches the minimum point at 5 times less than the FS strain direction for the 0- and 1-mm fillet radius cell design. The more generous fillet (1.5 mm) required 8 times axial strain to reverse the transverse strain for FS loading direction, compared to the CS direction. The effect of the fillet radius on the axial strain required to reach the minimum point that would lead to auxetic property increases quadratically for both CS and FS loading directions.

Therefore, to achieve an auxetic property, the smallest fillet radius would be the preferred design.

3.2. Impact of Fillet Radii & Cell Orientation on Stress

The force applied to each unit cell was incrementally increased until the model failed. Failure is indicated by exceeding yield stress of the material utilizing von Mises stress calculation. The endpoints of the data collected and depicted in **Figure 5** are the maximum force value that would reach the von Mises stress point. As the fillet radius increases, for both the CS and FS orientation, the structure can withstand higher load before failure. The force limit increases 1.5 times when fillet radius increases from 0 to 0.5 mm, and the force limit doubles



(a)

(b)

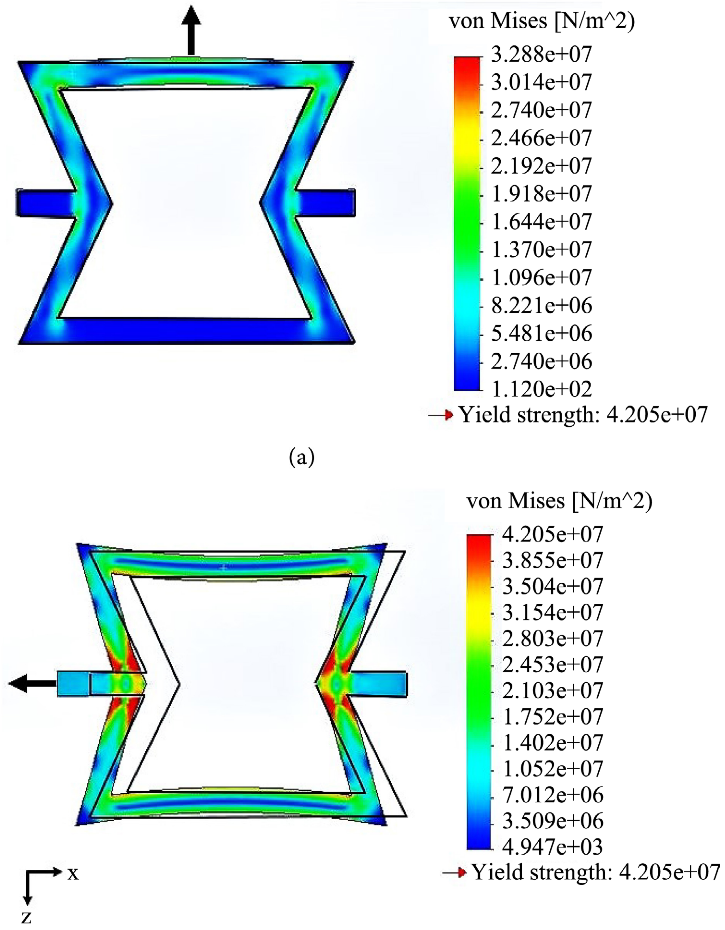
Figure 5. Poisson's ratio vs. force for re-entrant unit cells of three fillet radii, force applied in (a) FS & (b) CS orientation.

between 0.5- and 1-mm fillets. Connective segment (CS) loading direction handles less forces and steep decrease of Poisson's ratio response is observed.

When 5N of force is applied to a non-filleted unit cell in both the FS and CS orientations, the corners of the cell experience greater displacement for CS orientation in the direction of the applied load, compared to the FS orientation, as shown in Figure 6. At this low load, the Poisson's ratio exhibited a negative value for the CS orientation, which is promising for exhibiting auxetic properties. The disadvantage of the non filletted design, along with the CS loading direction is that the structure withstands the lowest stress before failure.

Table 2. Minimum point of axial-transverse strain.

Fillet Radius	FS – Minimum strain point (Axial, Transverse)	CS – Minimum strain point (Axial, Transverse)
0	(5.4, −1.2)	(1.2, −0.2)
1.0	(16.8, −3.1)	(3.1, −0.7)
1.5	(47.9, −8.4)	(5.9, −1.1)

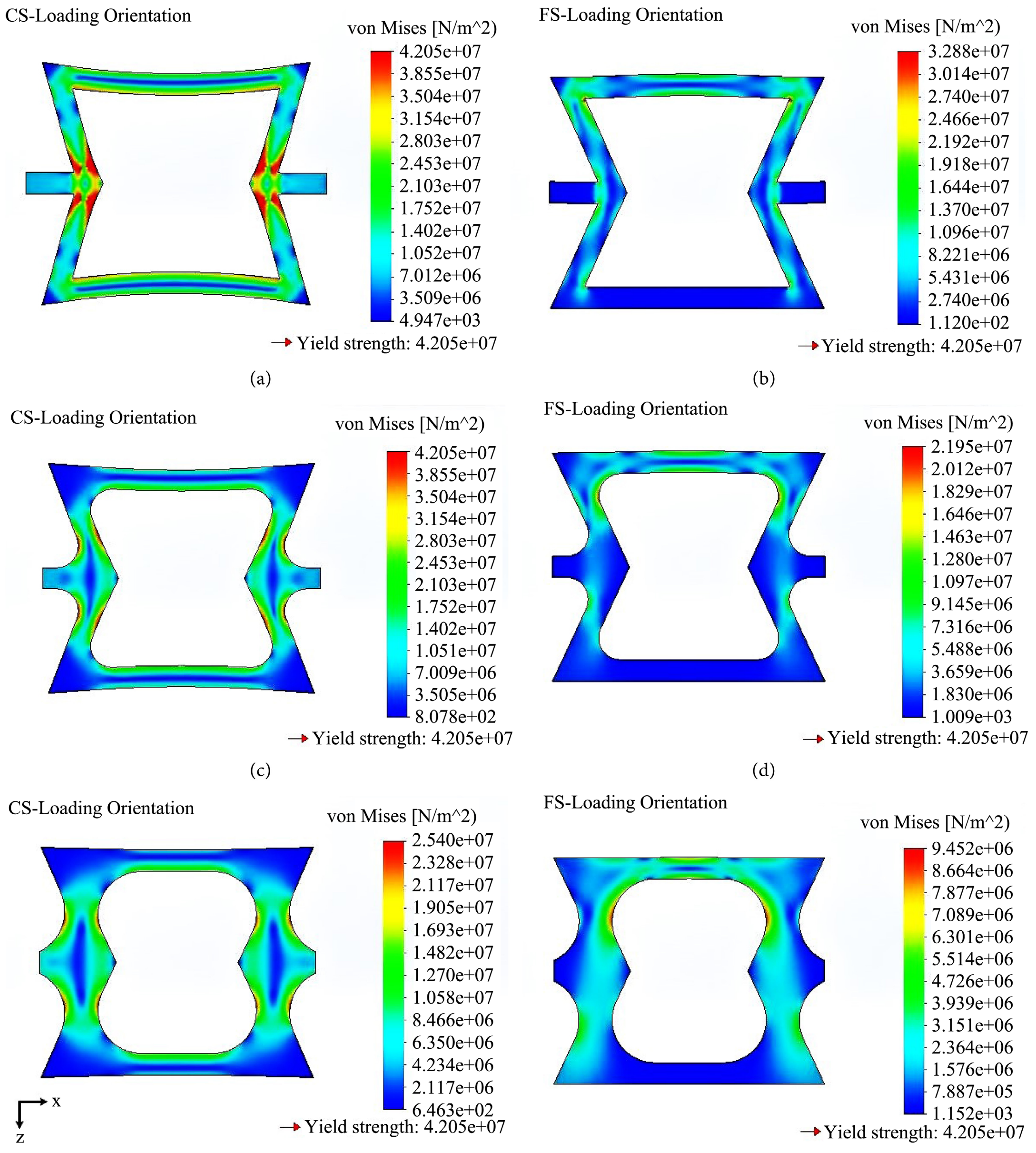


(a)

(b)

Figure 6. Von Mises stress distribution of re-entrant unit cells with unit cell prior to deformation outlined in black (a) FS orientation and (b) CS orientation.

For the sake of visualizing stress distribution across the unit cell for the 3 fillet radii under study and direction of loading, a 5 N load simulation model is captured and shown in Figure 7. Although filleted corners reduce stress concentration, the stress distribution are observed in similar locations with decreasing



(a) (b)

(c) (d)

(e) (f)

Figure 7. Von Mises stress distribution of deformed re-entrant unit cells after simulation force of 5N Fillet radii: (a) and (b) 0 mm, (c) and (d) 0.5 mm, (e) and (f) 1 mm.

magnitude and decreasing affected area. A non-filleted unit cell experiences highest stresses around the sharp corners of the connective segments when force is applied in the CS direction. A compromise between stress distribution, maximum allowable load before failure, and strain response needs to be considered in designing auxetic structures.

4. Conclusions

The re-entrant unit cell design is one of the common designs used to promote auxetic properties. However, the common re-entrant design has the disadvantage of high stress concentration zones at the sharp inner corners. This study addressed effect of fillet radius on the design performance from the stress distribution perspective and Poisson's ratio response. The unit cell has different geometry structures on the x and z direction that affected the response when load is applied. The re-entrant unit cell design started with a 60˚ internal angle and varied the fillet radius to avoid stress concentration factor. Three fillet radii were studied, 0, 0.5 and 1 mm. The applied model was on ABS material that has an average ductility (~30%). The second variable was the direction of load applied on the unit cell, along the flat side (FS) and connective segment (CS).

The computer model showed that the direction of load applied on the unit cell affects the strain response. CS load direction led to identifiable displacement. Negative Poisson's ratio (auxetic property) was recognized at the CS loading sample with zero fillet radius, however, the maximum loading sample handled before failure was the lowest.

Plotting axial strain against transverse strain showed that all fillet designs for both directions of loading (CS and FS) have a second-degree polynomial relationship with a minimum point. Such an observation indicates that auxetic property (negative Poisson's ratio) for the re-entrant would be evident if axial strain reaches the minimum point of the quadratic function. The CS direction loading reaches auxetic feature at lower axial strain than FS load application. Auxetic properties are more dominant with smaller fillet angle at lower strain rate, compared to larger fillet angle.

Studying the failure limit of the unit cells, showed that the smaller the fillet radius, the loading capacity drops quadratically. Therefore, designing auxetic structure, will require close attention to unit cell geometry, internal angle, fillet radius, direction of loading. It is anticipated that a unit cell of ductile material would give a better performance from the load capacity perspective.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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