Cellular Arrowhead Shaped Auxetic Structure with Significantly Reduced Stress Concentration Effects

Shubham Nitinkumar Wani[1], M. V. Walame[2]

[1]M. Tech-Mechanical Engineering (Design) Student, Vishwakarma Institute of Technology, Pune, India.
[2]Professor, Department of Mechanical Engineering, Vishwakarma Institute of Technology, Pune, India.

Abstract – *Auxetic material is a unit cell structure arranged in a cellular pattern such that it gives negative Poisson's ratio. The cellular structure expands when stretched and contracts when compressed. It is different from regular structure. Cellular auxetic structure exhibits some unique characteristics like high strength, light weight, impact damping capabilities, high energy absorption and reduced stress concentration effect etc. due to the number of unit cells arranged in a network. These unique characteristics provides potential applications in aerospace, military protection equipment, medical, textile and automobile field. Although different cellular auxetic structures are analyzed and studied because of their stress concentration effect, strength to weight ratio and negative Poisson's ratio etc., there is need of development of new cellular structure to improve these properties. The aim of our work is to focus on stress concentration effect of cellular arrowhead shaped auxetic structure. In this work, the cellular arrowhead shaped auxetic structure is modelled and the stress concentration effects and the stress distribution patterns are studied by using Finite Element Analysis (FEA) in ANSYS software. It is compared with the cellular honeycomb (re-entrant honeycomb) auxetic structure [1]. It led to the conclusion that cellular arrowhead shaped auxetic structure has reduced stress concentration effect as compared to the re-entrant honeycomb auxetic structure. Overall stress distribution patterns of cellular arrowhead shaped auxetic structure are good in comparison with the re-entrant honeycomb auxetic structure.*

Key Words: Cellular auxetic structure, Stress Concentration, Arrowhead structure, Re-entrant structure, Auxetic structures, Auxetic simulation, Finite element method, Smart materials.

1. INTRODUCTION

Poisson's ratio is the negative ratio of the lateral strain to the longitudinal strain of material. Almost all materials having positive Poisson's ratio, shrink when they stretched and expand when they compressed. In contrast, materials / structures having negative Poisson's ratio (NPR) are called auxetic materials / structures. These auxetic structures are arranged in such a manner that they show certain exceptional behaviour of lateral expansion when they are stretched and lateral contraction when they are compressed. Such arrangement of auxetic unit cell structure in particular pattern is called cellular structure. Cellular structures are designed for producing auxetic materials with enhanced mechanical properties like reduced stress concentration effect [1], increased indentation resistance [2], increased shear modulus [3], higher energy absorption capabilities [4], better fracture toughness and better strength to weight ratio of the materials [5].

Geometrical structure plays significant role in the analysis of auxetic materials [6] [11]. In last thirty years, the researchers have developed numerous different auxetic structures like a re-entrant (honeycomb, S-shaped, triangle, etc.) structures, chiral structures and rotating rigid structures that express their individual impact on negative Poisson's ratio as well as on different mechanical properties [7][8]. Auxetic materials have wide applications in textile field, aerospace, packing materials, shock absorbing materials, automobile field, sports applications, ballistic resistance, personal protective equipment and medical field etc. [9][10].

Shubham Nitinkumar Wani et al. [11] were developed, designed and modelled the unit cell of arrowhead auxetic structure. They studied the effect of geometrical parameters of arrowhead shaped auxetic structure on negative Poisson's ratio. In this work, the equation of Poisson's ratio for unit cell of arrowhead shaped auxetic structure was derived. The graphs were plotted for Poisson's ratio versus angle α, Poisson's ratio versus wall thickness and Poisson's ratio versus length of small wall of unit cell. It was found that Poisson's ratio of arrowhead unit cell structure is a function of angle α, wall thickness and length of small wall of unit cell.

Kusum Meena et al. [1] were developed and designed S-shaped auxetic structure to reduce the stress concentration effect on its sharp edges. In this paper, derivation of Youngs modulus and Poisson's ratio of the S-shaped auxetic structure were derived analytically. A comparative study of stress concentration effect has been carried out for newly developed S-shaped auxetic structure and re-entrant honeycomb by using finite element analysis (FEA). These results were compared with experimental analysis. It was proved that S-shaped auxetic structure has less stress concentration effect than re-entrant honeycomb and also proved that auxetic limit of the structure is up to 15% of the strain and maximum Poisson's ratio is up to -2.5.

Kan Wang et al. [12] proposed the dual material concept, it means rigid materials at the walls and flexible materials at the joints of structure to enhance reduced stress concentration effect of the 3D re-entrant auxetic structure and Poisson's ratio without compromising the other properties like Young's modulus. They also studied that most of the current auxetic structures suffer from design limitations arising due to the numerous sharp corners and joints in the structure. As a result, more the joints, more the possible points of high stress concentration and higher the chances of failure of the structure due to the critical stresses generated at the joints.

According to D. H. Abdeen et al. [13] additive manufacturing is used for producing both 2D and 3D complex auxetic structures. But it may produce surface defects and lead to stress concentration issues. Igor Yadroitsev et al. [14] studied that residual stresses and crack formation are also common with structures built by selective laser melting of metals.

Li Yang et al. [15] investigated that melting and solidification of metals could also lead to metallurgical defects. Jiapeng Xiong et al. [16] developed an improved 3D re-entrant structure with fillets and optimized in terms of the wall inclination and re-entrant angle. It was observed that increasing the fillet radius would reduce the stress concentration effects up to some extent.

It was observed that both the structural design and the manufacturing process could lead to stress concentration issues in auxetic structure. These issues are more specific if the structure has more joints with sharp corners.

Previous researchers have focused their studies on the stress concentration effects and stress distribution patterns of the re-entrant honeycomb and S-shaped cellular auxetic structure etc., but less work was done on arrowhead shaped cellular auxetic structure.

In this paper, the already designed arrowhead shaped auxetic unit cell structure is arranged in a cellular pattern [11]. This cellular arrowhead shaped auxetic structure is modelled by using ANSYS design modeler and finite element simulation is carried out by using ANSYS software. A couple of trials were made attempting to resolve the stress concentration aspects through local modification of geometrical parameters and modification of sharp corners by filleting. Finite element simulation clearly shows the reduced stress concentration levels of cellular arrowhead structure in comparison with the re-entrant honeycomb structure of similar size and other geometrical parameters.

2. FINITE ELEMENT ANALYSIS (FEA)

Fig-1 shows arrowhead shaped unit cell structure. In this structure, α is the angle between wall FP and horizontal axis, β is the angle between wall FE and horizontal axis, K is the length of small wall of unit cell, R is the length of large wall of unit cell and t is the thickness of wall.

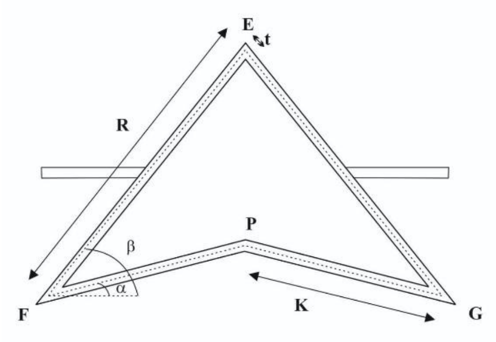

Fig -1: Arrowhead shaped unit cell

The arrowhead structure was optimized numerically by varying the geometrical parameters but maintaining the balance between the negative Poisson's ratio and the Von Mises stresses generated under loading. The typical values of a unit cell were taken as length of small wall of unit cell (K)= 20 mm, wall thickness (t) =1.5 mm, width (W) = 10 mm, angle (α) = 15 degree and length of large wall of unit cell (R) = 31.73 mm [11]. The arrowhead unit cell structure with above dimensions is arranged in a cellular pattern of 4 rows × 4 columns as depicted in fig-2.

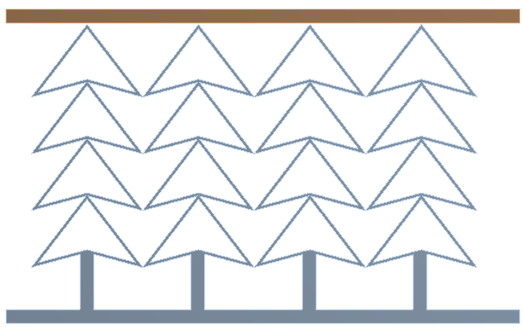

Fig -2: Cellular arrowhead shaped structure

To check the stress concentration effect and the mechanical behaviour of the cellular arrowhead shaped auxetic structure, finite element simulation was performed in ANSYS software. The 3D CAD model of the cellular arrowhead shaped auxetic structure was designed and modelled in the ANSYS design modeler software. The designed structural model was imported into static structural module of ANSYS software.

As we know that, in typical stress - strain curve before the elastic limit is reached, upon unloading, the material can return to its original state. But once the stress developed in the material goes beyond an elastic limit the response is no longer linear, because the material starts developing plastic strain i.e., there is permanent deformation developed in the material. Means after the elastic limit, yield strength of the material has increased due to strain hardening effect. Therefore, it is necessary to analyze cellular arrowhead auxetic structure by both linear and non-linear material conditions. This gives two different values for the Young's modulus for the linear and non-linear material conditions.

By choosing stainless steel 316L as the base material, the cellular structure was simulated for linear and non-linear material conditions. For linear and non-linear materials, the linear and bi-linear curves were selected respectively. For the non-linear material analysis, the bilinear isotropic hardening option of ANSYS was used to characterize the material property. The contact method used between the cellular structure and the top plate in the finite element simulation was the Augmented Lagrange method having coefficient of friction 0.2. It confirms the connection between the contact elements. The tetrahedral mesh was employed all over the structure as depicted in fig-3. A uniform tetrahedral element of size 1 mm was employed on a cellular arrowhead shaped auxetic structure. For this, mesh convergence analysis was carried out and element size was reduced up to 1 mm.

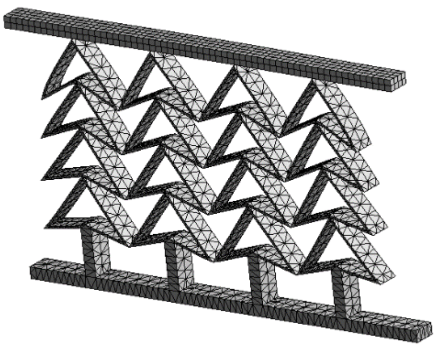

Fig -3: Meshing of cellular arrowhead structure

The boundary conditions were applied on the cellular arrowhead structure as depicted in fig-4. Compressive displacement was chosen to apply on structure. Hence face A was selected for the same. -0.1 mm of remote displacement was applied on face A for linear material analysis and -4 mm of remote displacement was applied on face A in case of non-linear material analysis, while displacement in X, Z and rotation about X, Y and Z-axis was restricted. To allow the structure to move only in loading direction displacement was set free in the Y-direction for all four faces of B and C, while displacement in X, Z and rotation about X, Y and Z-axis was restricted.

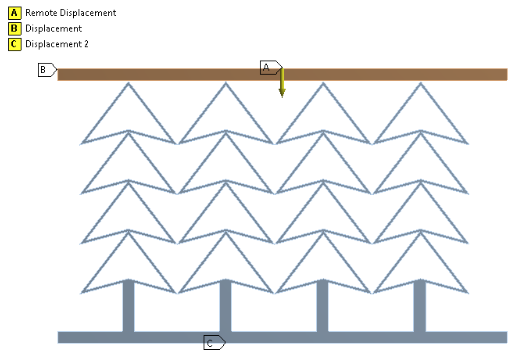

Fig -4: Boundary conditions of cellular arrowhead structure

3. RESULTS AND DISCUSSION

From the finite element simulations of the cellular arrowhead structure, the lateral displacements and the stress distribution patterns for the applied remote displacement are captured for both linear and non-linear material conditions as depicted in fig-5 to fig-8.

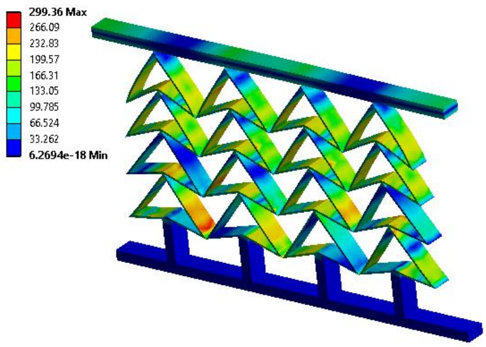

Fig -5: Von-Mises stress in non-linear material condition

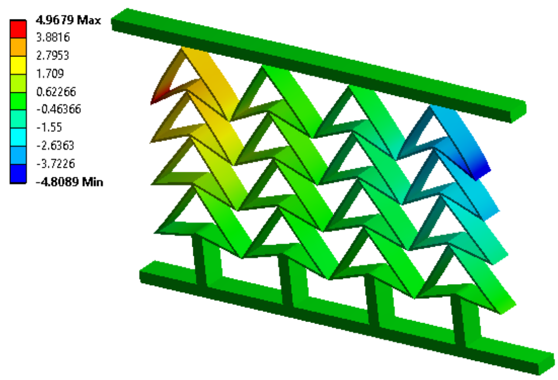

Fig -6: Lateral deformation in non-linear material condition

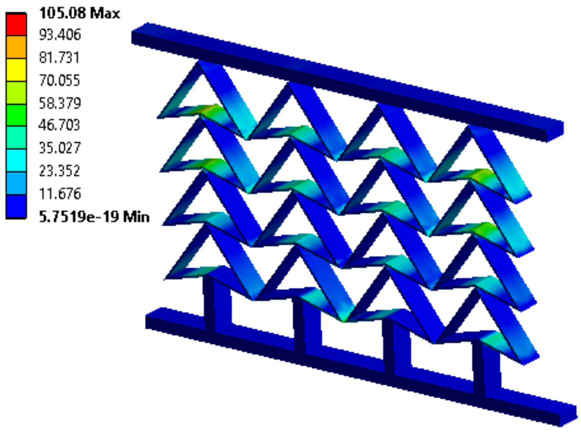

Fig -7: Von-Mises stress in linear material condition

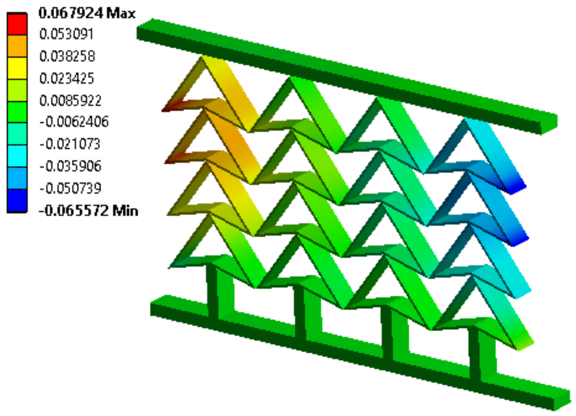

Fig -8: Lateral deformation in linear material condition

The light shaded part in fig-5 and fig-7 represents regions of stress concentration in the cellular arrowhead shaped auxetic structure.

Few stress concentration points are found in case of the cellular arrowhead shaped structure in comparison with the re-entrant honeycomb structure. Also, the maximum values of stresses are smaller in case of the cellular arrowhead shaped structure in comparison with the re-entrant honeycomb structure [1]. The range of the differences of stress value depends on nature of the material.

A comparative study of the Von-Mises stresses with linear and non-linear material conditions applied to the cellular arrowhead structure is performed by comparing fig-5 and fig-7. For same loading conditions, small variations in the locations and also the distribution patterns of peak stresses are noted for the cellular arrowhead structure and it is compared with re-entrant honeycomb structure. Quantitatively, the peak values of Von-Mises stresses observed is at around 105 MPa with the cellular arrowhead structure which is smaller in comparison with the re-entrant honeycomb structure (834 MPa) under linear material conditions. With non-linear material conditions the peak values of Von-Mises stresses observed is at around 300 MPa with the cellular arrowhead structure which is smaller as compared to the re-entrant honeycomb structure (649 MPa). In any case, the most important point is to be noted that the re-entrant honeycomb structure is stressed more severely in comparison with the proposed cellular arrowhead structure [1].

In case of the re-entrant honeycomb structure, the peak stresses are focused at the sharp corners, producing possible plastic deformation and following row wise collapsing. On the other hand, in case of the cellular arrowhead shaped structure, the peak stress locations are displaced towards the wall regions and there is less chances of failure. Also, cellular arrowhead structure producing a combined deformation of the whole structure as one unit, while in case of the re-entrant honeycomb structure each unit cell getting severely loaded and collapsing consequently. The distribution patterns between the two structures are different. This shows that the cellular arrowhead shaped structure is more flexible.

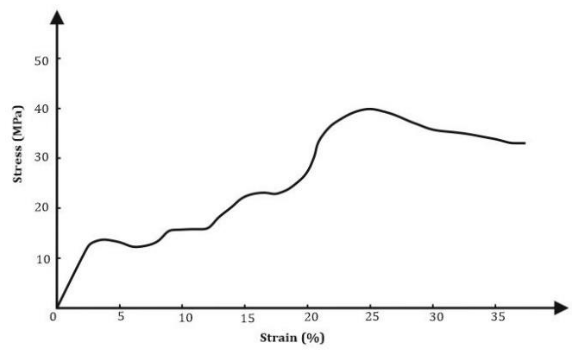

Chart -1: The nominal stress-strain curve for cellular arrowhead structure

Chart-1 shows the nominal stress-strain curve for the cellular arrowhead auxetic structure. It shows the elastic and plastic deformation responses. The initial linear stress-strain curve of cellular arrowhead structure represents the uniform deformation of the unit cells. In this case, the stress value almost linearly increased with the strain in the elastic region. In the plastic region, the curve shows the wave nature, but there is consistent increase in the stress values with increase in the strain values. Near about at 25% of strain, the structure was almost compressed to its limits. Further, there was no increase in the stress, as the walls of cells were almost being crushed against each other, leading to a densely packed distorted form.

In the nominal stress-strain graph, the re-entrant honeycomb structure was responded in a completely different manner. In the elastic region, the stress values increased linearly with the strain. Beyond the yield point, there is a decrease in the stress with the increase in the strain. Beyond 15% of strain, the curve gets stabilized to a great extent [1]. For the same applied load, the peak compressive stress produced in the honeycomb re-entrant structure was about 55 MPa, which is much more as compared to the stress produced in the cellular arrowhead structure (40 MPa). This is possible due to the relatively lesser design complications in the form of the arrowhead structure. There are four corner points in the arrowhead unit cell structure, whereas in case of the honeycomb unit cell structure, there are six corner points. More number of corner points and sharp edges in the structure, making it more likely to stress build up and probable instability under loading conditions.

Due to the high stress concentration effects, cracks were produced in the re-entrant honeycomb structure which led to the fracturing of the struts. In contrast, the cellular arrowhead shaped structure was completely free from cracking all through the loading.

It is observed that as the strain value increases, the re-entrant honeycomb structure quickly lost the auxetic behaviour. This is due to the geometrical weakness and the easy collapsing of the different struts around the multiple corners of the structure. The cellular arrowhead shaped structure and re-entrant honeycomb structure both follows row wise collapsing. But, in case of the re-entrant honeycomb it is not uniform i.e., structural walls start collapsing from center portion of the whole structure while in case of cellular arrowhead it is uniform. In both the structures, the loss of auxetic behaviour is due to the packing of the collapsing struts and densification of the structures over time. The total applied strain was up to 35%, where the Poisson's ratio become almost equal to zero and there is complete loss of the auxetic behaviour of both the structures.

4. CONCLUSIONS

From the comparative study of cellular arrowhead auxetic structure and reentrant honeycomb auxetic structure with the stress concentration effect, we got the following specific conclusions:

i) The deformation responses of the cellular arrowhead auxetic structure were far superior to those of the re-entrant honeycomb structure as there was no cracking and failure of the elements of the structure.
ii) With non-linear material conditions the peak values of Von-Mises stresses observed is at around 300 MPa with the cellular arrowhead structure which is smaller as compared to the re-entrant honeycomb structure (649 MPa).
iii) The peak values of Von-Mises stresses observed is at around 105 MPa with the cellular arrowhead structure which is smaller as compared to the re-entrant honeycomb structure (834 MPa) under linear material conditions.
iv) The cellular arrowhead structure shares the load uniformly across the entire structure while the re-entrant honeycomb structure shares the load nonuniformly.
v) For the same applied load, the peak compressive stress produced in the honeycomb re-entrant structure is about 55 MPa, which is much more as compared to the stress produced in the cellular arrowhead structure (40 MPa).
vi) The auxetic behaviour of the cellular arrowhead structure gradually diminishes with increasing strain levels, due to uniform load sharing.
vii) In case of the cellular arrowhead shaped structure, the peak stress locations are displaced towards the wall regions. Due to this there is reduction in the stress concentration and less chances of failure.
viii) As cellular arrowhead shaped structure was completely free from cracking throughout the loading, there is comparatively reduced stress concentration effect as that of the others.
ix) Increasing the fillet radius would reduce the stress concentration effects up to some extent.

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BIOGRAPHIES

Shubham Nitinkumar Wani
M.Tech-Mechanical Engineering (Design), Vishwakarma Institute of Technology, Pune, Maharashtra, India.
Email: shubhamwani96@gmail.com

M. V. Walame
Department of Mechanical Engineering, Vishwakarma Institute of Technology, Pune, Maharashtra, India.
Email: mahesh.walame@vit.edu