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Research Article

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Novel Double-rounded-V Hierarchical Auxetic Structure - A Finite Element Study

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Abstract

Hierarchical auxetic structures inspired by natural cellular structures possess negative Poisson Ratio (PR) due to their inherent geometric constraints. With the advancements in additive manufacturing (AM), high-performance computing and shape optimization algorithms, developing high-performance auxetic structures has emerged as an active area of research. Recently, a sinusoidal design of repeating cell with smooth and curved members, referred to as Double-U Hierarchical (DUH) structure, has been shown to perform better than the traditional Double-V Hierarchical (DVH) structure. However, the option of improving the existing DVH design is not explored so far. In the present work, we fill this research gap by incorporating curviness and roundness to its unit cell and evaluating its performance using finite element analysis. We call our improved version of DVH as DRVH (Double-Rounded-V Hierarchical) auxetic structure. The combination of straightness and roundness of DRVH members not only provides more room for absorbing impact energy than DUH design but also reduces stress concentration and enhances auxetic behaviour and static collapse stress. To confirm this, future work will be carried out in this direction by running experiments and more analyses on DRVH auxetic structure.

Keywords

Crashworthiness, Double-Rounded-V hierarchical auxetic structure, Finite element analysis, 3D auxetic, Energy absorption

Introduction

Naturally occurring materials such as nacre, nail, beaks, and shells, are increasingly being adapted in several engineering applications owing to their enhanced properties. Natural cellular structures provide better crash worthiness due to higher toughness than other alternatives. Man-made honeycombs, inspired by natural cellular structures have garnered increased attention owing to their unique mechanical behaviour. Cellular structures with repeated units with a negative PR are referred to as hierarchical structures. They collapse under the application of compressive loads and expand under tensile loads, contrary to other materials. Foam-like auxetic structures were first synthesized in late 1980s [1]. Later, hierarchical structures were seen to exhibit crashworthiness, and many different geometries of such nature have been reported in the literature [2-10].

Hierarchical auxetics are commonly used in aerospace and automotive industry owing to their crash-worthiness characteristics. In the event of a collision, they absorb the kinetic energy of the vehicle by collapsing and can also reroute the vehicle post-collision. They exhibit such behaviour as a result of their geometry, which when subject to a load, twists and folds onto itself, thus resulting in negative PR. Auxetic nanostructures are used in biomedical applications like

targeted drug delivery, applications in solar energy harvesting and space travel, which require materials with high strength-to-weight ratio. The AM has been used to manufacture 3D hierarchical auxetics, made of either metals or plastics since material is deposited layer by layer onto a platform. This provides great freedom in design of such structures and provides opportunities to design unique geometries which can find applications in many fields of engineering. Structures such as re-entrant hexagonal honeycombs [6, 11-13], chiral/rotational structures [14-16], double arrowhead (also known as re-entrant double-V) honeycombs [5, 13, 17], and the recent double-U honeycombs [18] can be synthesized using AM with great accuracy.

Many studies have been conducted by tweaking the parameters of hierarchical structures to maximize the energy absorption in quasi-static and impact loading applications. The best geometry is selected using Finite Element Analysis (FEA) based on the energy absorbed and stress distributions [18-34]. In any given type of geometry of the repeating unit, optimization study must be conducted to determine the best possible configuration for the intended purpose. Recently, Yang et al. [18] conducted FEA studies and experiments on a DUH structure, which utilizes sine curves, and showed that this configuration performed better in terms of energy absorption and stress concentration zones than the traditional DVH structure. This suggests that curviness can reduce the manufacturing damage with an added advantage of enhanced auxetic behaviour. However, the option of adding curviness to the traditional DVH structure itself has not been investigated yet.

In the present study, we incorporate rounded corners in the DVH geometry to create a novel auxetic structure, named as DRVH structure, and study its behaviour using an FEA study. The advantage of this form is that, for a given size of single cell, changing only the radius of the rounded edged would lead to multiple geometries which can be selected based on the applications. Our preliminary finite element analyses shows that DRVH performs better than the DUH geometry. More analyses and experimental studies will be conducted in future work.

Materials and Methods

The FEA studies are conducted on DUH and DRVH auxetic structures. The DUH structure considered in the present study is the same as reported by Yang et al. [18]. The DRVH structure is created by adding roundness at the junction of members in the traditional DVH structure. The design is explained in section 2.1 and the FEA study in section 2.2.

Design of hierarchical structure

The design parameters, namely, H1, H2, L, B (side of square cross-section) are kept the same for DUH and DRVH, as mentioned in [18] to ensure a true comparison of geometries. The new parameters introduced in DRVH are radii R1 and R2, which for the present study are kept at 3 mm each, as indicated in table 1. Figure 1 shows the line diagrams associated with these geometries.

Table 1: Design parameters for auxetic cell.

Parameter	Value (mm)
L	10
H1	18
H2	6
B	1
R1	3
R2	3

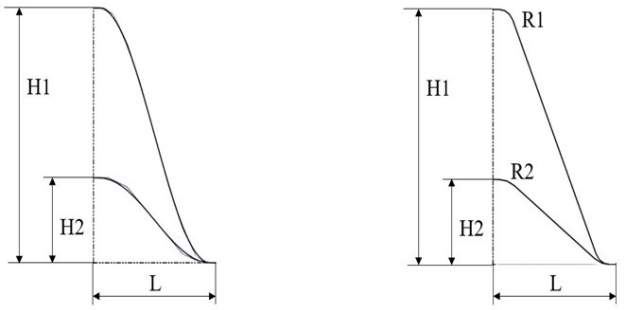

Figure 1: Schematic sketch of DUH (Left) and DRVH (Right).

Figure 2 shows the repeating cells and the 2 x 2 x 3 lattice (2 cells in x, 2 in y, and 3 in z) for DUH and DRVH structures, and the 2 x 2 x 3 lattice is used for comparison of the two geometries.

Finite element analysis

Material model

Yang et al. [18] utilized a rate independent elastic-perfectly plastic material model for SS316L for their FEA study, which was conducted on a DUH lattice of 4 x 4 x 6 cells. The material properties used were: Young's Modulus (E) = 205000 GPa; PR = 0.3; Yield stress (S) = 500 MPa. In the present study, to facilitate a true comparison of the DRVH and DUH geometries, the same material model was used.

Validation

Yang et al. [18] performed a quasi-static compression study on DUH auxetic lattice of 4 x 4 x 6 cells using ABAQUS/Explicit. The structure was kept between two rigid

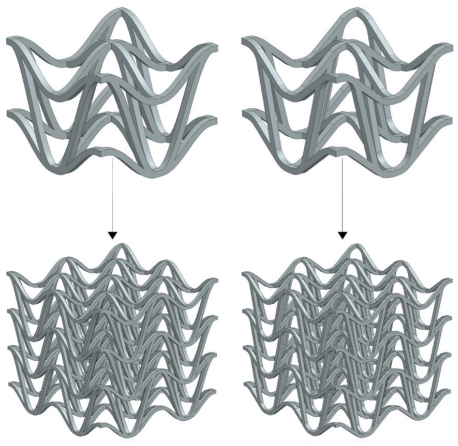

Figure 2: DUH geometry (Left) vs DRVH geometry (Right).

plates, keeping the bottom plate fixed and the top plate given a velocity of 10mm/min and moved by 60 mm during the simulation. The structure was meshed using 8-noded hex elements of an average size of 0.33 mm. The contact between the plates and the lattice was defined as frictionless and hard. To validate and reproduce results presented by Yang et al. [18], the same geometry, simulation parameters, average mesh size, and element type were utilized. The results of this simulation were found to be in agreement with Yang et al. [18]. The force-displacement characteristics are presented in figure 3. This validated the simulation procedures which were then applied to 2 x 2 x 3 lattices.

Simulation setup and parameters

ABAQUS/Explicit is utilized in the present work due to its well-established capability to solve complicated non-linear problems involving self-contact. The lattice structures were placed between two rigid plates, keeping one fully fixed and the other given a fixed velocity (0.166 mm/s for quasi-static and 100,000 mm/s for impact). The contacts were modelled as hard and frictionless with self-contact allowed. To achieve a structured mesh using 8-noded hex elements, the geometry was partitioned into simpler sections, which were meshed with the medial axis method, keeping option to "minimize mesh transition" turned on. Hex elements were chosen over tetrahedral elements as even though the elements reduce domain approximation error for complex geometries, they suffer from problems of skewness and aspect ratio problems. The average mesh size was kept at 0.3 mm, determined from a mesh convergence study (Figure 4) comparing 0.5 mm, 0.3 mm and 0.2 mm, which showed that the change in the force-displacement characteristics was less than 6% and the computational time increased by over 3 times while comparing mesh sizes of 0.3 and 0.2 mm. The DUH quarter model had a total of 22,834 elements, while the DRVH quarter model had 23,432 elements.

Simulations were performed for a time of t = 120 s for quasi-static and t = 0.0002 s for impact case. A quarter model was utilized keeping in mind the symmetry of the structure. The meshed model is presented in figure 5. Comparisons were drawn based on energy-time and force-displacement plots.

Results and Discussion

FEA results

In both quasi-static and impact loading case, the parameters examined are the displacements and force-displacement curves for both geometries. Based on the results conclusions are drawn about the auxetic nature and the extent of energy absorption in all the cases. The displacement plots are used to determine which structure retained more of its auxetic nature in the impact study. It is observed that the DUH structure loses some of its auxetic behaviour at a higher rate of crushing, and hence the collapse of the structure is affected. This may lead to a relationship between PR and crashworthiness, which will be explored in the future work. Although a similar occurrence is observed in DRVH, it seems to retain more of its auxetic nature, as is evident from figure 6. Rapid rate of crushing deforms the regions near the moving plate, leaving the structure below relatively stress free as the stress wave propagates

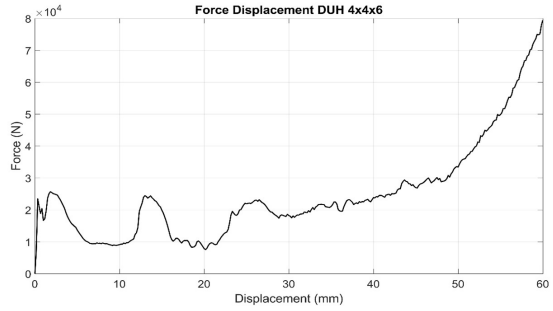

Figure 3: Force displacement characteristics of 4 x 4 x 6 DUH lattice (validated against [18]).

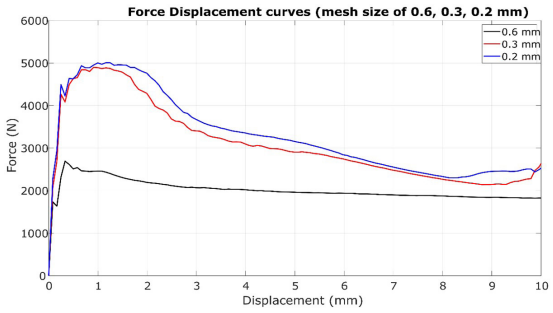

Figure 4: Mesh convergence study with element sizes of 0.6 mm, 0.3 mm, and 0.2 mm.

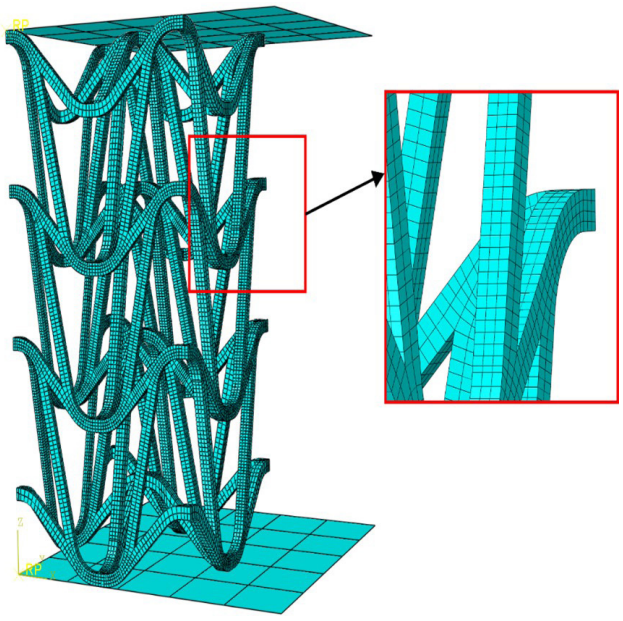

Figure 5: Meshed quarter model (average element size 0.3 mm).

through the structure. Figure 6 shows the comparison between the deformed structures (displacement magnitude plots) of the two geometries for the same amount of displacement of the top plate (20 mm) under quasi-static simulation.

It is noteworthy that behaviour of both structures is different under quasi-static and impact loading, thus, the rate of loading significantly affects the deformation behaviour of the auxetic structures.

It is to be noted that as loading rate is increased, the ap-

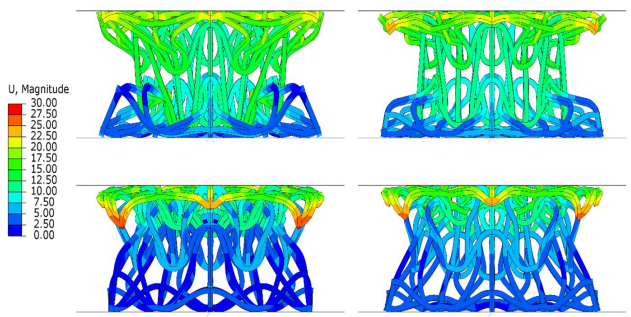

Figure 6: Deformation plots: DUH (quasi-static (Upper Left), impact (Bottom Left)); DRVH (quasi-static (Upper Right), and impact (Bottom Right)).

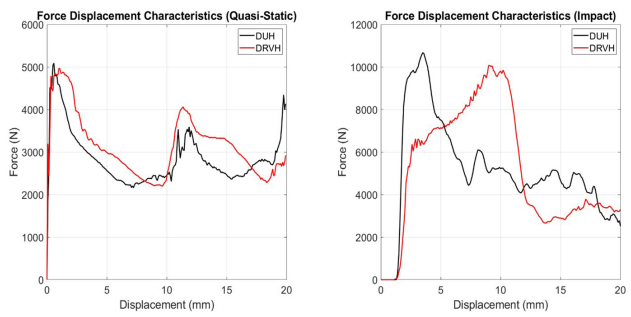

Figure 7: Force displacement characteristics: Quasi-static (Left) and Impact (Right).

parent auxetic nature of the lattice reduces, which is evident by visually inspecting the extent to which the lattice structure has collapsed. The lower cells of the structure near the fixed end have deformed to a greater extent in quasi-static loading than in impact loading condition and the maximum deformation occurs in the region closer to the moving plate for impact loading. This highly localized deformation influences the extent of collapse of the structure. The member of DRVH unit cell (Figure 1) contains both straight and curved regions. Even at the final stage of deformation during impact loading (Figure 6), the straightness of DRVH members remains visually unchanged in the unit cells near fixed end. This deformation characteristic of DRVH auxetic structure provides better absorption of impact energy than DUH design. The combination of straightness and roundness of DRVH members thus proves to be more beneficial than DUH structure.

Comparison of energy absorption

Force-displacement plots obtained for quasi-static and impact simulations of DUH and DRVH geometries are shown in figure 7. The area under curve for DRVH is higher that of DUH in case of quasi-static loading, which implies that DRVH structure is better than DUH structure in the aspect of energy absorbed during quasi-static loading. Energy absorbed by DRVH structure is 62658.83 N-mm, compared to 56804.01 N-mm with DUH design, which is an improvement of 10.3%.

In impact loading, the energy absorbed by DRVH structure (103800.62 N-mm) is slightly higher than that of DUH structure (102312.45 N-mm). Both structures show a decline in the reaction force as displacement increases. The force-displacements plots in quasi-static loading and impact loading are quite different. Further investigation is required to check if a change in loading rate leads to a notable change in force-displacement plot.

The characteristic bump in the quasi-static loading curve of DRVH design looks sharper than the one in the impact loading curve (Figure 7), which is attributed to the differences in the resulting contact interactions between the individual unit cells. Our preliminary analyses reveal that stress wave caused during impact loading propagates through DRVH lattice gracefully, while simultaneously keeping the deformation of unit cells near fixed end significantly low. It is difficult to draw conclusions on the general behaviour of DRVH auxetic structure without conducting further study on the effect of loading rates on its deformation behaviour. Future work will be carried out by running experiments and more analyses on DRVH auxetic structure.

Conclusions

We have improved the traditional DVH auxetic structure by incorporating a smooth/curved geometry in its unit cell, which we call DRVH. Our preliminary FEA show that DRVH design performs better than the recent sinusoidal DUH lattice reported by Yang et al. [18] in the aspects of deformation pattern and energy absorbed through the course of deformation, as evidenced by the values of energy absorbed for the same lattice size in the FEA results. The following are our key findings, which will be investigated further by conducting experiments and more analyses.

- DRVH structure performs better than DUH structure during quasi-static compression; a 10.3% improvement is seen in the energy absorbed.
- The combination of straightness and roundness of DRVH members helps not only to reduce stress concentration but also to enhance auxetic behaviour.
- Stress wave caused during impact loading propagates through DRVH lattice gracefully while simultaneously keeping the deformation of unit cells near fixed end significantly low, thereby providing an opportunity to improve the static collapse stress.

Acknowledgements

None.

Conflict of Interest

The authors of the study have no conflict of interests.

Credit Author Statement

Samarth Acharya: Conceptualization, Experimentation, Writing - original draft preparation; Sharvil Bartake: Writing - review and editing; Rajesh Kumar: Writing - review and editing; N. Iniyan Thiruselvam: Conceptualization, Writing - original draft preparation, Supervision. All the authors read and approved the manuscript.

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