Numerical and Experimental Studies on the Deformation of Missing-Rib and Mixed Structures under Compression

Cong Tang, Lisa Li, Li Wang, Vince Zevallos Herencia, and James Ren*

Herein, the deformation and properties of cellular structures of missing-rib (MR) model and mixed structures (MSs) are studied experimentally and numerically. Samples with different beam angles and lattice patterns 3D printed with thermostatic elastomer (TPE) are tested in uniaxial compression. Parametric finite element models are developed and used to simulate structures of different sample dimensions and lattice patterns with a particular focus on beam–wall contacts. Structures with different sizes and aspect ratios, beam angles, and lattice patterns are comparatively studied. The numerical results show a good agreement with the experimental data on samples of various sizes/patterns. The main deformation modes and key stages of the corner edge–wall contact and structure deformation are presented, and the key mechanism is analyzed.

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1. Introduction

Auxetic materials are an active research area with many potential applications.[1–8] There are many mechanisms/structures that have been developed to generate negative Poisson’s ratio behaviors, including re-entrant structures, chiral structures, rotating rigid/semirigid units and angle-ply laminates.[7–15] These established mechanisms and the capacity of designing Poisson’s ratio through controlled heterogeneity have opened up the possibility of developing material systems with targeted Poisson’s ratios. The unique properties of auxetic structures lead to a wide range of applications, such as novel fasteners, biomedical applications, energy-absorbing devices, acoustic dampers, membrane filters with variable permeability, personal protective equipment, smart implant, actuators, and sensors.[12–16] These applications targeted require a detailed understanding of deformation of auxetic structures at both local cell level (beam bending, rotation, buckling, and contact) and macroscales (e.g., sample deformation) to balance the mechanical requirements as well as the functional properties.[17–27] In addition, the stability of Poisson’s ratio and auxeticity under different loading modes and strain levels is also important.

The deformation of porous materials under a compression load is more complex than simple uniaxial tension loading. The deformation of different auxetic structures under compression has been increasingly studied,[28–37] such as negative Poisson’s convex-concave foams,[8] re-entrant unit cell,[31–34] disordered auxetic metamaterials,[35] cellular frameworks,[36] arrowhead structures,[29] and missing-rib (MR) auxetic structures.[29–37] Yang et al.[29] studied the behavior of auxetic structures under compression using both static model and dynamic finite-element (FE) modeling. The results show that auxetic materials could be effective in reducing the shock forces. The properties, such as stiffness, Poisson’s ratio, and efficiency in shock absorption were found to be dependent on the structure and material combinations. Dong et al.[31] studied the compressive mechanical properties of the metallic auxetic re-entrant honeycomb. The work found that the modeling results were affected by the number of cells used in the FE model. Wang et al.[33] compared the characterization of composite 3D re-entrant auxetic cellular structures made from carbon fiber-reinforced polymer and single materials. The composite re-entrant auxetic structure showed the potential to significantly increase the specific stiffness of the structure. Remennikov et al.[34] studied the quasi-static compression and drop hammer impact tests of sandwich panel with re-entrant honeycomb design. The results suggest that sandwich panels with a re-entrant honeycomb core have a strong potential for enhancing the performance of lightweight impact-resistant protective systems. Apart from research on single mechanism structures, several works have been reported, exploring the use of mixed structures (MSs), which combined auxetic structures of different mechanisms.[32,38–43]
These have opened up opportunities in designing more complex materials with auxetic behaviors. In all these cases, the use of auxetic structures shows significant potential benefits on the functional performances, such as improved impact energy, stiffness, and acoustic properties. Factors, such as sample size, may directly affect the material deformation and stability of the key properties (e.g., auxeticity) for some structures, in particular, in compression. This is an important issue for the design, manufacture, and performance prediction of auxetic structures or MS systems. Furthermore, if the auxeticity effects are induced by instability in porous materials or lattice structures, the instability or contact at cell level may influence symmetric structures at a macroscale, thus directly affect the deformation process of the cell and shape of the deformed samples as well as the properties and their stability, including Poisson’s ratio and auxeticity. MR auxetic structures have attracted many research attentions recently. Many of the applications are intended for application under in-plane compression loads, and it is important to establish a detailed understanding on the deformation process, in particular, the contact between the edges and cell walls at high strains for normal MR and MSs, which are directly relevant to the mechanical behaviors and the stability of the cell and overall sample deformation. MSs could offer opportunities to further enhance the freedom in structures design. It is important to establish the detailed deformation mechanisms, properties, and stabilities.

In this work, the deformation of MR auxetic structures and MSs is studied experimentally and numerically. The first part of the work is focused on experimental and numerical modeling of MR structures of 3D printed thermoplastic elastomer (TPE) samples. Parametric numerical models have been developed and correlated with testing data on structures of different beam angles, sample sizes, and aspect ratios. The modeling results are also compared with other published experimental data of a different material. The key edge–wall contact stages in samples of different sizes and its effects on the structure deformation were investigated and analyzed. The deformation of auxetic structures with different beam angles is established with a particularly focus on the corner edge–wall contact and the deformed shapes at the full contact stage under compression. The deformation of mix structures with alternating columns of different directions is studied experimentally and numerically; Poisson’s ratio and its stability are established. The influence of corner edge and beam–wall contacts on the overall structural deformation, critical strain range for auxeticity, and stability of the structures is discussed.

2. Structures, Experimental, and Modeling Approaches

2.1. Structures of MR Models with Different Angles and MSs

Figure 1 shows some typical structures studied experimentally and numerically. Figure 1a is a normal MR auxetic structure with a beam angle of 90°. Figure 1b is a typical MR auxetic structure with a beam angle of 60°. In the work, models with different beam angles have been studied (e.g., 60°, 70°, 80°, and 90°). Figure 1c is an MS (designated as MS-1) consisting of alternating single column of MR model at opposite direction. As shown in the figure, cell columns in green are regular MR cells, and columns in blue are opposite MR cell. Figure 1d (designated as MS-2) is an MS of two columns of MR model at opposite direction. Samples of different sizes, including much larger samples, are systemically studied to establish the deformation mechanisms, and the effective stable Poisson’s ratios with a particular focus on the cell wall/edge contact, localized deformation, and structure/shape stability. Figure 1e is a typical example structure of wider samples. The example shown in Figure 1f is with a 10-10 lattice pattern. In the FE model, a Python program is developed, which is able to automatically vary the key parameters, including the beam length (l), thickness (t), sample size, and depth (out-of-plane sample dimension) as well studying the effect of mesh size, friction,
and material models. Use of the Python program allows the mapping of potential effects of sample dimensions and sizes on the deformation process, deformed patterns, and key properties, such as Eng. stress–strain data, Poisson’s ratio, and their stabilities.

2.2. FE Model and Materials

The main material used in 3D printed samples presented in this work is TPE plastics, Young’s modulus is 22 MPa, and Poisson’s ratio is 0.3. The property was based on standard compression and tension tests, double checked by Shore D hardness tests and an MT2000 microbending tests (Deben Vertical 3/4 Point Bending Stage). The uniaxial compression test was performed on a tension/compression machine with series of sensitive load cells. The displacements are monitored by a linear variable displacement transducer (LVDT). The deformation field is captured by a high-resolution video camera. Samples are also printed with stainless steels through metal additive manufacturing. The majority of the 3D printed samples have a beam length of 10 mm and a beam/wall thickness of 1 mm. This large beam length–thickness ratio offers a flexible structure to experimentally study beam/wall deformation and the contact between different edges and cell walls over a large strain range (Figure 2). A particular focus is on observing the initial contact between the corner edge and the opposite cell wall (termed corner edge–wall contact), and the overall structure after full beam–wall contact is formed. The corner edge–cell wall contact is a special feature due to a unique structure of MR models in comparison with other cellular structures. The wider sample presented in Figure 1c (with 7-3 cells) is different, which is adapted from published work to cross-examine the validity and accuracy of the FE modeling approach with experimental data from published source.

Samples of different depths (out-of-plane dimension) up to 100 mm (typically, 30, 50, and 100 mm) have been studied to preserve clarity. Approach-1 used the 2D solid model with the out-of-plane depth controlled through a plane-strain thickness condition (Abaqus User’s Manual 2017); Approach-2 used a full 3D solid model, whereas Approach-3 used a shell model (section of the model is presented in Figure 2). The shell model (presented in Figure 2) is able to produce results matching the full 3D model up to a strain level past the full beam–wall contact stages with much less demand on computational resource and time. Most of the numerical modeling are based on FE model with as-testing full boundary conditions of a uniaxial compression test, whereas additional representative volume element (RVE) approach-based analysis has also been performed on selected samples as a comparison. The boundary and loading conditions for the FE model with a full boundary condition are schematically shown Figure 2. In the model, a uniaxial velocity (V2) load (1 mm s⁻¹, the same as the test) is applied on the top loading surface, and an encastre fix condition (U1 = U2 = U3 = UR1 = UR2 = UR3 = 0, all degree of freedoms are fixed) is applied on the bottom surface. U1 is lateral in-plane displacement, U2 is vertical displacement, and U3 is the out-of-plane displacement. URs 1–3 are the rotational degrees of freedom. Figure 2 also shows a typical meshing scheme used in the FE analysis. The element type used in the simulation is S4R, which is a four-node, quadrilateral, stress/displacement shell element. Detailed mesh sensitivity tests have been conducted. For compression tests with a particular focus on the contact and deformation pattern, the mesh sensitivity is crucial, in particular, for the post-contact stage. In the mesh sensitivity tests, the convergence of the simulation is depicted through the reaction force and the deformed shape of the beams. The final mesh size selected is 1 mm, which gives a ratio of an element size of 1, and sufficiently accurate results within the strain range and contacting stage are studied. A similar meshing condition has been used in other published works of cellular structures.

Self-contact is defined with a fitted plastic–plastic friction coefficient of 0.35 being used in the model. In the simulation, force–displacement is recorded, the deformation of the structures under compression is analyzed, and central point of the outermost left–right columns is recorded for calculating Poisson’s ratio from the captured images. The process excluded the two points immediate next to the fixed and loading end to reduce the uncertainty with the boundary effect. This gives the overall Poisson’s ratio of the structure studied and provides a mean for studying the sample size (cell number) effects on Poisson’s ratio.

3. Results and Analysis

3.1. Deformation of Normal MR Structures with a Beam Angle of 90° (MR-90)

Figure 3 compares the engineering (Eng.) stress–strain data of a normal MR model with a beam angle of 90° (MR-90) from the experiments and numerical modeling. The stress is the overall force divided by the effect area of the sample; the strain is
calculated by the overall displacement divided by the original height of the sample. The deformed structure at different stages is presented in Figure 4. As shown in Figure 3, the numerical data showed a good agreement with the experimental stress–strain curve. The experimental data are based on the average of three test data. There are some scatter of the data at higher strains, but, in general, the numerical result followed the trend of the testing data well. Point 1 is the initial unreformed stage, point 2 represents the initial corner edge–cell wall contact stage, and point 3 represents the point when all the corner edges are in contact with the cell walls in the sample. Point 4 is the further deformation of the locked/contacted structure. As shown in Figure 4, the simulated deformation patterns resemble the images from the test for all the key stages, including the initial corner edge–wall contact (Figure 4b,f), and the location of the contact is highlighted in red dotted circle. The structure when full contact is formed (Figure 4c,g) also showed a reasonable resemblance. The stage post the full corner edge–wall contact also shows a reasonable agreement between the modeling and the test, but this is not the main focus of this report, as it is subject to more complex modeling and testing with different materials.

The results show that the relatively smaller sample size with a 4-4 lattice pattern is effective in capturing the key deformation stages. The simulation and testing also show a skewing in this case. This is probably a specific feature for the MR type of structures. To study this feature, both numerical results and experiments have been conducted on a wider and shorter sample with a lattice pattern of 7-3 (Figure 1e). The results are presented in Figure 5. Figure 5a shows the Eng. stress–strain for the wider sample processed with the same material and processing method in this work. The sample consists of 7-3 cells; the beam length is \( \approx 9.57 \) mm, the wall thickness of 1.5 mm, the thickness of the sample is 30 mm, and the overall height of the sample is 82.5 mm. The dimension is selected to assess the potential effect of the sample aspect ratio on the beam–wall contact and change of the stress–strain due to the contacts. As shown in Figure 5a, the testing data and the numerical results show a reasonable agreement. Figure 5b shows the comparison between numerical modeling results with the published force–displacement data of a different material. The beam–wall thickness is 1.5 mm, and the out-of-plane sample thickness is 50 mm.[34] The overall sample height is the same as in Figure 5a of 82.5 mm. The material used is nylon with Young’s modulus of 597 MPa, Poisson’s ratio of 0.33, and a density of 1140 kg m\(^{-3}\). Both elastic and elastic-plastic models have been evaluated based on the stress–strain data provided,[34] and there is no significant difference in the modeling results within the strain range studied. Only the results with an elastic model are shown in Figure 5b to preserve clarity; further details on the effect of different material models can be found in the previous study.[48] The FE modeling data are in a reasonable agreement with the published data in terms of the key stages. In Figure 5a,b, the overall shapes and key stages of the stress–strain curves are similar to the key stages of the 4-4 structure presented in Figure 4. The wider model showed more significant plateau stages (circled in Figure 5b) than the 4-4 model in Figure 3. The deformation at later stage showed certain diversion, which is subject to future studies, but the overall trend of the stress–strain curve over the contact stages is similar among these three sets of data (Figure 3 and 5a,b). Figure 5b uses force–displacement data to preserve the original data.[34]

Figure 3. Numerical (solid line) and experimental (open symbols) Eng. stress–strain data of MR-90 (4-4) sample.

Figure 4. Deformation and contact in the structure at different stages (Figure 3). a) Point 1 (FE), b) Point 2 (FE), c) Point 3 (FE), d) Point 4 (FE), e) Point 1 (Test), f) Point 2 (Test), g) Point 3 (Test), and h) Point 4 (Test).
A key point of focus, the strain for reaching the first slope increase point on the stress–strain curves among these samples, is similar, which is observed to be correlated with the first corner edge–wall contact in all the cases. The association of this on the overall Poisson’s ratio and its stability is to be analyzed based on data of different structures and sizes in the discussion section.

### 3.2. Deformation of MR Structures with Different Beam Angles

Figure 6 shows typical simulation and test data of MR auxetic structures with different beam angles. For each model, the beam length is the same (l = 10 mm), so the sample size is reduced as the angle is changed from 90° to 60°. From geometry analysis, when the angle changes, the distance between the corner edge and the opposite wall is changed accordingly for a fixed beam length and thickness, and this directly affects the contacting situations. Experimental tests have been performed on the sample with an angle of 60°, which is presented together with the testing data of normal MR model with an angle of 90° (open symbols).

In general, the FE modeling and experimental data show a good agreement. As shown in the close-up view (dotted box), in the initial stage, the stress for the model with a higher beam angle is higher, and the slope of the stress–strain data decreases as the angle is varied from 90° to 60°. This is due to the fact that the beam is tilting more in the structure with a smaller beam angle, and it is much easier for the wall to bend. The data clearly show that the critical strain for reaching the corner edge–wall contacting point for lower angled structure (for example, the 60° model) is much lower due to the geometrical effect, and the stress increased significantly once the full corner edge–wall contact stage is formed. The typical deformed structure captured from the test and FE simulation is shown in

![Figure 6. Simulation and experiment results of structures with different beam angles. a) Eng. stress–strain data of MR auxetic structures with different beam angles (4-4 model). The symbols are experimental data, and the solid lines are FE data (beam length = 10 mm, wall thickness = 1 mm, and out-of-plane sample thickness = 30 mm). b) Deformed structure with the corner beam in full contact with the opposing wall (beam angle = 60°) (experimental). c) Deformed structure with the corner beam in full contact with the opposing wall (beam angle = 60°) (FE model). d) Deformed structure of model (70° beam angle). e) Deformed structure of model (80° beam angle).](image-url)
Figure 6b,c. Comparing this with feature for the 90° model (Figure 4 and 5), there is less bending of the wall for the 60° structure at the full corner edge–wall contact stage. The results (Figure 6b,c) also show that the full contact (or locked) structure has more corner edge–wall contacting points than that for the 90° structure (Figure 4 and 5). This is probably the main reason for the much stiffer stress–strain data for the 60° structure after contact. As shown in Figure 6d–f, the shape of the cells and the number of contacting points change as the beam angles are increased and less contact points are formed, which would directly affect the stiffness of the structure.

3.3. Deformation of the MSs

Figure 7 compares the Eng. stress–strain for the MSs (MS-1 and MS-2) with the normal MR structure (MR-90). As shown in data, the slopes of the initial stages are similar between these structures up to a certain strain level. However, the localized contact situation is much different. As shown in Figure 7b(i–iii), at a strain of ≈20%, the corner beam–wall contact starts to form for the normal MR model (Figure 7b(ii)); however, no contact is formed for the MS at this stage for the MSs (Figure 7b(ii, iii)). The connecting point between the columns with different angles restraints the rotation of the unit, which changes the strain to reach the corner edge–wall contact, as well as the formation of the contact. Another significant difference is the in-plane deformation between the three structures. The MS-1 and MS-2 structures are much more stable than the normal MR model. Both MS-1 and MS-2 exhibit clear inward lateral displacement (U1) under compression, suggesting that the structure has maintained the auxeticity of the MR model.

Series of FE models had been developed with much larger sample sizes to further establish the effect of the MS on Poisson’s ratio and the stability of the sample shapes. Some typical examples are shown in Figure 8. As shown in Figure 8a, the critical strain range for a stable Poisson’s ratio corresponds to the corner beam–wall contact point (as marked by the dotted line in Figure 8a). The stress–strain curves for MS-1 and MS-2 are similar between the 4-4 and 10-10 models, but there is a clear difference between the 4-4 and 10-10 for the normal MR models (MR-90). Figure 8b plots Poisson’s ratio of the structures. Also, plotted (open symbols) on Figure 8b are the experimentally measured Poisson’s ratios. As shown in Figure 8b, there is a slight difference in the value of Poisson’s ratio, but all structures are in the negative Poisson’s ratio domain at small strains. The effective Poisson’s ratio of the MS-1 is similar/identical to the value for the normal MR model (MR-90), but the critical strain within which Poisson’s ratio is stable is much higher. Poisson’s ratio of MS-2 is even lower, indicating a stronger auxeticity, and the stability range of Poisson’s ratio for MS-2 is similar to that for MS-1, much higher than the normal MR model. Figure 8c compares the deformed shape of the MS and normal MR structures (10-10 structure) at a strain level of ≈20%. At this strain level, the MR-90 has lost its stability of the auxeticity, the MR-90 model shows a clear unstable deformation, and Poisson’s ratio becomes unstable. While both MS-1 and MS-2 have maintained a relative stable structure, the contour of the lateral displacement (U1) is indicative of clear auxeticity. This may also have contributed to the difference in data from sample sizes. The image also shows that the large sample (10-10) could not form a fully contacted structure. The top and bottom sections formed a full contact pattern (box in dash line). This may have contributed to the difference in stress–strain data between the 4-4 and 10-10 normal MR structures. This suggests that the MS offers similar Poisson’s ratio/auxeticity level with better shape stability and less sensitivity to the cell numbers under compression.

4. Discussion

The experimental and corresponding numerical data showed that the contact between the corner edge and the opposite wall in the MR model played a significant role in the deformation mode of the structure and the Eng. stress–strain curve. Models with a larger beam length to thickness ratio (l/10) and a relatively soft material provided an effective experimental setup to study the deformation mechanism in detail. The work on samples of different sizes reveals that once the corner edge–wall contact is initialized, the stress is increased slightly, and once a full contact position is formed, the structure becomes much stiffer. Figure 9 presents the initial corner edge–wall contact for different structures and sample sizes (4-4 and 10-10 lattice pattern). There is a clear difference between the three structures. For the MR-90 models, the corner edge–wall contact starts at a diagonal corner. This is due to the shear point and the intrinsic angle of the structure. While for the MSs of different sizes as shown in Figure 9c,d for MS-1 and Figure 9e,f for MS-2, the position of the initial contact is different, and the contact was at different orientations due to the rotation of the cells. This probably has contributed to the improvement of the shape stability.

For auxetic structures, the stability of Poisson’s ratio and the auxeticity is also very important. The work shows that the critical
strain for a stable Poisson’s ratio is associated with the starting of the corner edge–wall contacting points. Figure 10a shows Poisson’ ratio of MR-90 with different cell numbers. In all the cases, Poisson’s ratio at lower strain levels is negative, reflecting an auxetic behavior. In general, the value of Poisson’s ratio is close, but there are still difference in the values. When a small number of cells is used, the absolute value is relatively low. When the number of the cells is further increased, Poisson’s ratio value becomes close to the RVE prediction. Poisson’s ratio is similar to other reported values.[32] Despite the difference in Poisson’s ratio values, the critical strain for stable Poisson’s ratio among the samples of different sizes is only slightly increased as the number of cells is increased. The effect of the cell number effect agrees with the observations by others.[31,52–54] The influence of the edge might be associated with constraints of the edge on the operative deformation modes, including potential shear-induced deformation. In simulation and experimental studies on the tensile behavior of tetrachiral honeycombs,[53,54] it was found that the auxeticity of the system decreases upon increasing the number of repeating units in the system. This behavior was found to be associated with the tendency of the tetrachiral systems to undergo shear deformation upon uniaxial loading, which is blocked by the edge effects at the regions where the geometry is being fixed. Similar process on the shear deformation can be observed under compression load as well. Further work will try to quantify the contribution of such a mechanism on the auxeticity of MR models under uniaxial compression.

Figure 11 shows Poisson’s ratio of the MSs of different sizes. Poisson’s ratio values are all in a similar range. Poisson’s ratio for MS1 is similar to the normal MR model, whereas Poisson’s ratio for MS-2 is lower, and there is limited effect from the sample sizes (cell numbers). In every case, the critical strains for a stable Poisson’s ratio of the MSs are higher than the normal MR model (Figure 8b). For compression loading, out of shape in-plane deformation has also been observed by other experimental and numerical works in compression tests of MR and other auxetic structures,[30,31,52,58,59] which may have an adverse effect on the design uncertainty and shape control processes. So, the improvement on the stability with structures MS-1 and MS-2 could be a beneficial advantage to the structure design and development depending on the application. Also, plotted on Figure 11 are Poisson’s ratios calculated by RVE approach. The decreasing trend of Poisson’s ratio is similar to that from the FE models of the full boundary model for both MS-1 and MS-2. This is probably benefited from the stability of the two MSs.

The contact, sample size/cell number effects, and Poisson’s ratio stability are particularly important for compression loads, as for some applications, a relatively smaller number of the cells is required, whereas for other applications, a large lattice system might be involved. Different theoretical analysis and single cell approach works have been conducted on estimating Poisson’s ratios in tension or compressions.[49–52] The upper bound based on the rigid-rod rotational spring model showed that the upper Poisson’s ratio bound of a 90° MR is around −0.45,[52] indicting a clear auxeticity, which supports the stable auxetic behavior observed. However, this work was focused on the overall deformation of samples with different-sized structures, and Poisson’s ratio is calculated based on the averaged displacement of the

Figure 8. Stress–strain, Poisson’s ratio, and deformed shape of the MSs. a) Eng. stress–strains of different structures simulated with different cell numbers (4-4, 6-6, and 10-10). b) Comparison of Poisson’s ratio MSs and normal MR auxetic structures. c) Deformed shape of the MS and normal MR structures at 20% strain (the color band for U1 is applicable to all the figures (i–iii)). i) Deformation of MR-90. ii) Deformation of MS-1. iii) Deformation of MS-2.
center point of the outer column. This method was used in previous works, and Poisson’s ratio obtained with the average displacements also reflects the overall sample behavior and closer to applied situations. Poisson’s ratio reported for the MR model is in agreement with the experimental data in this work, also close to other recently published works. The work used a high beam length-to-wall thickness ratio, and this offered a case to study the initial contact patterns in detail and to evaluate the deformation, properties, and stability of MSs associated with MR structures. Future more quantitative work will systematically investigate the effect of angle and beam length on the deformation of different complex material systems at higher strains with the support of digital image correlation to be able to quantify the complex deformation at even higher strains. Auxetic behaviors

Figure 9. Initial corner edge–wall contact position and deformed shapes (U1: lateral displacement). a) Initial contact pattern of 4 × 4-MR-90. b) Initial contact pattern of 10 × 10-MR-90. c) Initial contact pattern of MS-1-4 × 4. d) Initial contact pattern of MS-1-10 × 10. e) Initial contact pattern of MS-2-4 × 4. f) Initial contact pattern of MS-2-10 × 10.

Figure 10. Poisson’s ratio of normal MR structure (MR-90) determined from different sample sizes and RVE.

Figure 11. Poisson’s ratio of mixed MR models (MR-1 and MR-2) determined from different sample sizes and RVE models.
may exist at different scales at macrolevel as well as atomic and microlevels. The development of 3D additive printing and joining technologies has opened the path to produce complex structures with both plastics and metals, in particular, stainless steels and titanium alloys. Future work will consider the elastic–plastic material behavior that could influence the contact and deformation of MR structures at higher strain levels.

5. Conclusion

In this work, the deformation of MR auxetics and MSs was studied experimentally and numerically. Experiment and numerical modeling work of 3D printed models of different sizes and beam angles were studied. The FE results were correlated with testing data of structure with different beam angles, size, and aspect ratio as well as other published data. The stress–strain and Poisson’s ratio of normal MR model and MSs are established. The deformation of mix structures with alternating columns at different orientations is studied experimentally and numerically, and Poisson’s ratio and its stability strain ranges and shape of the samples. The work shows that deformation and instability of auxeticity of MR structure are associated with the corner edge–wall contact. The mixed model showed different beam–wall contact patterns, which contributes to the much higher critical strain of stable auxeticity and overall shape stability.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

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