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Computational investigation of the post-yielding behavior of 3D-printed polymer lattice structures

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Abstract
Sandwich structures are widely used due to their light weight, high specific strength, and high specific energy absorption. Three-dimensional (3D) printing has recently been explored for creating the lattice cores of these sandwich structures. Experimental evaluation of the mechanical response of lattice cell structures (LCSs) is expensive in time and materials. As such, the finite element analysis (FEA) can be used to predict the mechanical behavior of LCSs with many different design variations more economically. Though there have been several reports on the use of FEA to develop models for predicting the post-yielding stages of 3D-printed LCSs, they are still insufficient to be a more general purpose due to the limitations associated with the lattice prediction behavior of specific features, certain geometries, and common materials along with showing sometimes poor prediction due to the computationally cheap elements out of which these models have been composed in most cases. This study focuses on the response of different LCSs at post-yielding stages based on the hexahedral elements to capture accurately the behaviors of 3D-printed polymeric lattices made of the Acrylonitrile Butadiene Styrene material. For this reason, three types of lattices such as body centered cubic, tetrahedron with horizontal struts, and pyramidal are considered. The FEA models are developed to capture the post-yielding compressive behavior of these different LCSs. These models are used to understand and provide detailed information of the failure mechanisms and relation between post-yielding deformations and the topologies of the lattice. All of these configurations were tested before experimentally during compression in the z-direction under quasi-static conditions and are compared here with the FEA results. The post-yielding behavior obtained from FEA matches reasonably well with the experimental observations, providing the validity of the FEA models.

Keywords: 3D printing; lattice structures; post-yield; finite element modeling; stress plateau; energy absorption

1. Introduction
Cellular material can potentially offer higher specific stiffness, specific strength, and specific energy absorption while offering lower specific heat and thermal conductivity than solid materials. Briefly, any combination of a solid material and air gaps or voids is considered as the fundamental definition of a cellular material, from which different categories emerged. First of all, the cellular material with stochastic distribution of unit cells is defined as a foam cellular material. The mechanical characteristics of the foam are difficult to control since it consists of unit cells of different sizes distributed arbitrarily in the 3D space,
Figure 1: Ashby and Gibson schematic of the compressive stress–strain behavior for lattice failure stages.

It is also worthwhile mentioning that both the cell topology (whether the struts are distributed in a vertical or horizontal direction within the unit cell) and the cell geometry (if the aspect ratio is higher or less than 0.3) can determine the deformation mechanisms of the lattice during compression, which in turn have a major influence on the mechanical properties (Maskery et al., 2016). The deformation of a lattice structure under mechanical load can be classified into being stretch dominated or bending dominated (Kadkhodapour et al., 2015; Köhnen et al., 2018; Leary et al., 2018; Macnachie et al., 2018). The stretch-dominated behavior results in the structure being stiffer and stronger for a given mass, while the bending-dominated behavior absorbs more energy during compression loading (Ashby, 2006; Köhnen et al., 2018; Leary et al., 2018; Kang et al., 2019). According to Ashby and others, in the compression of a cellular material there are three possible collapse regions: linear elastic, plateau region, and densification (Avallé et al., 2007; Habib et al., 2018; Köhnen et al., 2019) as shown in Fig. 1. For bending-dominated structures, the stress–strain response starts with a linear-elastic region (first region). When reaching the elastic limit, three possible collapse mechanisms (plastic yielding, fracture, or buckle) compete and the one that requires the lowest stress value dominates (Gibson & Ashby, 1997; Ashby et al., 2000; Ashby, 2005).

1. In the case of ductile cellular materials (plastic bending-dominated behavior), the struts deform plastically due to the bending moment and the second region of stress–strain response emerges, termed as a plateau region. During the plateau region deformation, the strain keeps increasing at almost constant stress till the opposite struts come in contact with each other to create the strain densification area (third region) during which a steep increase in the stress values occurs.

2. In the case of brittle cellular materials (bending-fracture-dominated behavior), the struts break as a result of bending moment and the collapse continues to create the plateau region with evolving instabilities till reaching the strain densification region.

3. In the case of elastomeric cellular materials (buckling-dominated behavior), the struts collapse by elastic buckling. In this regard, elastomeric cellular materials always fail due to the buckling. The rigid polymeric and metallic...
cellular materials might also undergo buckling before yielding when they have very small aspect ratios. Significantly, the buckling-dominated behavior shows more dependence on the aspect ratio, strut radius/strut length, than the topology of cellular materials.

For stretch-dominated structures, the stress–strain trace begins first with a linear-elastic region till the end of elastic limit. At this point, the struts might yield plastically either in tension or compression in the case of ductile cellular materials. This is called plastic stretch-dominated behavior. Very thin struts might also buckle in the case of metallic or rigid polymer cellular materials before they yield to create buckling-dominated behavior, as explained earlier. In addition, the collapse might be induced by a fracture of struts in the case of brittle lattice structures. This case is termed as stretch-fracture-dominated behavior. Thereafter, post-yield softening region created directly after the initial collapse as a result of plastic buckling or brittle collapse of struts, thereby shortening the plateau region. Then, the strain densification region begins when struts come in contact with each other (Gibson & Ashby, 1997; Ashby et al., 2000; Ashby, 2006). In addition, it was noticed that the boundary conditions have influence on the lattice behavior and mechanical properties (Shen et al., 2010; Smith et al., 2010; Gümruk et al., 2013). For instance, changing the boundary conditions from unconstrained to constrained ones by placing the lattice between two plates or skins helps improving the mechanical properties, especially for body centered cubic (BCC) lattice configuration. This is traced back to the fact that upper and lower struts of the sandwich lattice structure will be restricted from sliding horizontally, by this way inducing an enhancement in the mechanical properties and changing the lattice behavior. The latter was noticed to be wavy as a result of the local buckling that occurred in the constrained layers (Shen et al., 2010; Smith et al., 2010; Gümruk et al., 2013). Besides, various applied loads, whether compression, tension, bending, or shear, could lead to different stress–strain responses of lattice structures (Gümruk et al., 2013). The deformation mechanism depends not only on the lattice topology and relative density but also on the shape of lattice strut cross-sectional area. In other words, changing the cross-sectional area of lattice struts has an effect on the deformation mechanisms and mechanical properties even if the lattice topology and relative density are kept the same. As was reported in the literature (Queheillalt & Wadley, 2005a; Queheillalt & Wadley, 2005b; Huang et al., 2017), using lattices with hollow, semicircular, or U-like shape cross-sectional areas instead of the solid ones helps improving mechanical properties as a result of increasing the second moment of area and the associated inelastic buckling resistance.

Over the years, the numerical models have been used to observe how Young's moduli and the mechanical properties can vary or change due to the influence of the topologies and boundary conditions (Mazur et al., 2016). To develop FEA models to capture the entire three failure stages under compression, it is necessary to use appropriate fracture criteria in the post-yielding region. In this regard, numerical simulation is preferred for many studies because it is low cost and practicable (Besson, 2010; Karamooz et al., 2021; Liu et al., 2021). In terms of getting higher accuracy of numerical techniques, the higher order formulation and small time frame can improve the quality of the results (Cook et al., 2002; Adam & Premnath, 2019). According to Smith et al. (2013), Luxner et al. (2005), Ozdemir et al. (2017), Al-Saedi et al. (2018) and Raja et al. (2021), there are many limitations in developing accurate FE models in similar works by other researchers, which can be summarized as follows:

1. First of all, generating an efficient element type of a good quality and formulation to build lattice models that could accurately capture the post-yielding behavior or the entire stress–strain tendency under compression is nontrivial work and usually requires user intervention to be achieved, especially for hexahedral elements (Tadepalli et al., 2011; de Oliveira & Sundnes, 2016).

2. Second, the size of lattice structure whether it consists of a single unit cell or higher number of unit cells has a major effect on the number of elements out of which the model is composed and the associated computational cost or time. To put this in consideration, increasing the lattice size or number of unit cells leads to increasing the number of elements required to build the lattice models and, hence, increasing computational time as well as making the associated model computationally expensive. Thus, the size of lattice structure imposes more limitations on the associated finite element model (FEM).

3. Third, the feature or topology and the geometrical parameters of lattice structures have significant influence on the accuracy of FEMs created to mimic the real deformation behavior of lattices under compression. To elucidate that, the reproduced stress–strain curves of lattices under compression provided by Gibson and Ashby consist of three essential regions (linear elastic, plateau stress, and strain densification) (Ashby et al., 2000; Ashby, 2006) and show different trends based on the deformation mechanisms, whether bending or stretch dominated, which in turn depend on the lattice topology and relative density. In other words, it should be taken into account that the degree of accuracy and the level of complexity of the created models depend on whether it is required to predict the deformation behavior of low-density, high-density, bending-dominated, stretch-dominated, or various lattice structures of different densities and features together as a more general purpose.

4. The last one is that the created lattice models also depend on the material type. To clarify this point, the material type shows a major influence on the second region of reproduced compressive stress–strain curve provided by Gibson and Ashby (Ashby et al., 2000; Ashby, 2006). In the case of ductile materials like metals, the struts yield plastically at the beginning of the second region, thereby showing smooth plateau region that can be captured easily by the developed models. However, the struts or cell edges start breaking, fracturing and showing fragments when the material is brittle, by this way showing fluctuations in the plateau stress region with including stress drops and rises, which are difficult to be captured by the FEMs. As such, the accuracy and difficulty of the created FEMs depend on whether it is demanded to model lattice structures made of metals, polymers, or both as a general purpose.

The researchers from the literature faced the limitations mentioned above during their investigations about the FEMs of the compressive crushing behavior of lattice structures. For instance, Smith et al. (2013) tried to model the full compressive behavior of two types of lattices (BCC and BCC-Z) made of metal (316L stainless steel) with various relative densities between 0.035 and 0.159 using the ABAQUS software. A single unit cell corresponding to each configuration was simulated under quasi-static compression using two types of elements (two nodes-based beam and eight nodes-based brick elements). First of all, the beam element is well known in reducing the computational time, but it cannot capture the real geometry and stiffness.
of the lattice due to not considering properly the multiple volumes at the strut joints and the constraints in the areas around the strut junctions where the material is accumulated (Luxner et al., 2005). Also, the contacts between the struts were not defined in the formulation of beam elements, so the associated models cannot predict the strain densification region. Furthermore, the beam elements show a better prediction of the behavior of BCC feature than that of BCC-Z. This belongs to the fact that the compression behavior of BCC-Z (stretch-dominated) is different from that of BCC (bending-dominated). Indeed, BCC-Z behavior exhibits a kind of fluctuation (drops and rises) in the stress–strain curve that is difficult to be predicted by the beam elements since their formulation is missing the capability of element deletion that occurs when the strut failure happens. In other words, the beam element model shows a better capability for predicting BCC behavior than that of BCC-Z since the former behavior is smooth during the plateau stress region while the latter tendency includes stress peaks and drops, thereby showing that the prediction accuracy of the created model depends on the lattice topology. In general, with increasing the relative density, the beam element models show a discrepancy in the results of predicting the lattice behavior due to magnifying the error associated with the fact the beam elements cannot capture real geometry and stiffness of the lattice. In addition, modeling a single unit cell in order to reduce the computational cost is not always working efficiently. It means that the full compressive behavior of a lattice cannot be always observed and understood clearly based on modeling a single unit cell of a similar shape to the entire lattice due to the effect of the boundaries and the lattice topologies. For example, the mismatching in the results of beam element model raised up and became significant with increasing the number of unit cells for BCC-Z feature, by this way showing a clear deficiency comparing with the experimental work. To this end, Maskery et al. (2016) also created FEMs based on 3D-brick element to simulate the full compressive crushing behavior of BCC and BCC-Z, but this time worked only on a single unit cell to reduce the computational cost and the element deletion is still not included in the element formulation, thereby resulting in a discrepancy in the results, especially for the BCC-Z configuration in particular and the lattices of higher relative densities in general.

A similar work (Ozdemir et al., 2021) was conducted for modeling the compressive post-yielding behavior of two types of lattices (diamond and re-entrant cube of 0.137 and 0.166 relative densities, respectively) made of metal (Ti6Al4V alloy) based on LS-DYNA. Beam elements were adopted in the created lattice models instead of the quantum solid elements and single layer of lattice was used instead of the overall lattice structure to void obtaining highly computational cost. This time, the contact and element deletion were involved in the formulation of beam elements to provide a better prediction of the lattice behavior. Though, there was still discrepancy when comparing the FEM prediction with the experimental work, the results of the models are considered fair enough. However, it is important to point out that the developed FEMs are limited to a metal (one type of material), certain relative densities since both values (0.137 and 0.166) are almost close to each other, stretch-dominated behavior (both configurations show the same dominated behavior), and single layer of lattice (instead of lattices with multilayers where the effect of boundaries is negligible). Consequently, the developed models are not considered a more general purpose and might not be able to predict accurately the full compressive behavior of other lattice configurations, which is definitely not the main goal of these models.

In addition, another study was carried out by Al-Saedi et al. (2018) for modeling the deformation behavior of uniform and gradient F2BCC lattice structures of 0.185 relative density with \(6 \times 6 \times 6\) layers made of a metal (Al-12Si). To reduce the computational cost, only \(1 \times 1 \times 6\) layers of the uniform and gradient lattice structures were modeled under quasi-static compressive loading based on 3D solid tetrahedral element (four-node). Through comparing the results of FEMs with the experimental work, it was noticed that the developed models cannot predict well the deformation behavior of the lattice structures, especially for the uniform F2BCC. Also, it is clear to see that these models cannot capture any kind of stress rises and drops for both uniform and gradient F2BCC lattices, thereby showing an evident deficiency in predicting the deformation behavior. Besides the inaccuracy of the predicted deformation behavior, the created FEMs were limited to a certain material, relative density, specific feature. In addition, the behavior of one lattice column cannot be exactly similar to that of the overall lattice. Hence, these models cannot be regarded as general-purpose models.

The state of art presented in the current investigation is to overcome the limitations mentioned above through creating more general-purpose FEMs to predict accurately the full compressive deformation behavior of various lattice structures using efficient mesh element type.

1. First of all, to ensure providing accurate results along with precise prediction, 3D-brick elements of eight-node hexahedron type that include the contact and deletion as essential part of the formulation were adopted here to mesh the FEMs. These types of elements were created in a direct way with the help of the lattice structure designer (LSD) tool, which was created for that purpose based on Python programming and worked under ABAQUS plug-ins. Significantly, this tool helps saving a lot of human time and efforts through conducting both design and analyses of various lattice structures.

2. Second, the created FEMs were used to predict the compressive deformation behavior of three lattice structures with various features (BCC, TetH, and Pyr), several relative densities (0.17, 0.541, and 0.203, respectively), and different deformation mechanisms (bending-dominated and stretch-dominated).

3. Third, the full deformation behavior of entire lattice built with \(5 \times 5 \times 4\) layers cell was modeled and the results were compared with experimental work of lattices having the same number of layers. This is much better than modeling a single unit cell, single layer, or single column and comparing the results with an entire real lattice.

4. Last, the 3D-printed lattice structures of the current research were made from ABS material. This material is not a ductile material like all other materials used in previous investigations. Indeed, ABS material tends to behave as a brittle material, whose stress plateau region fluctuates (stress rises and drops) and is not smooth in most cases comparing with that of ductile material. So, the prediction of this region in the brittle materials is usually much more difficult than the corresponding one of the ductile materials. As a result of that, if the created models are able to predict the deformation behavior of lattices made of brittle material, this means they will definitely be able to predict that of ductile material. Actually, the created models were tested to predict the behavior of metal lattice and the results were in good agreement with the experimental work from the literature. The latter was not presented here, but it will be introduced separately as a future work.
To clarify the scope of the current research, providing efficient FEMs to predict the post-yielding behavior of various 3D-printed polymeric lattice structures subjected to a quasi-static axial compressive loading is the main goal of this study. Comparison of lattice structures has been addressed in other studies (Sangle, 2017; Al Rifaie, 2017). Five lattice configurations (BCC or Diamond, BCC with vertical struts, Tetra, Tetrahedron, and Pyramid) were fabricated based on 3D printer using ABS materials and tested experimentally under quasi-static compression to evaluate their mechanical behavior and find out the one of best performance, especially regarding energy absorption (Sangle, 2017). Also, a similar work has been done on other features to investigate the effect of strut distributions on lattice behavior and to reveal the lattice feature of best resilience and toughness (Al Rifaie, 2017). The comparison here was carried out between the results of FEMs and the experimental work, only for the purpose of validation. This was the scope of our paper.

Up to this point, even though many researches have been applied for the purpose of simulating the post-yielding stages and progressive damage, there is still shortage in developing accurate finite elements models to capture the post- Yielding behavior and studying the failure mechanisms of ABS Plyometric lattice structure configurations. Consequently, this study focuses on the computational modeling of three types of the most common practical 3D polymer printed LCSs and the deep analyses of the post-yielding behavior of these lattice types under compression. The three types of lattice structures are body centric cubic (BCC), tetrahedron with horizontal struts (TetH), and pyramidal (Pyr).

### 2. Design, Fabrication, and Testing

For the purpose of developing a model based on FEA to capture the post-yielding compressive behavior, three different lattice designs have been adopted in the current research. First of all, BCC is the most familiar feature in lattice generation that can be manufactured well based on different 3D printers using various materials along with diverse geometrical parameters. In addition, due to the relative simplicity of BCC lattice feature and the associated fabrication capability using various materials, the lattice designers consider this configuration as a starting point or reference in order to compare the mechanical behavior of the designed lattice topology. The second feature is Pyr. Indeed, it has been selected as a next step in the current research to explore the capability of the proposed FEM to predict the post-yielding behavior of what can be simply described as BCC configuration developed through adding four horizontal struts at the base. This means that the sensitivity of the proposed model to the change in the feature of BCC lattice and its ability in capturing the associated post-yielding behavior can be evaluated by simulating the deformation behavior of Pyr. Finally, working on a lattice feature that is totally different from BCC lattice configuration is important to prove the functionality and efficiency of the proposed FEM in predicting the post-yielding compressive behavior of various lattice configurations. Consequently, TetH has been used in this study as a final step.

According to Sangle (2017) and Al Rifaie (2017), three types of 3D-printed lattice configurations were fabricated and tested under compression load. The configurations were (a) BCC, (b) tetrahedron with horizontal struts, and (c) pyramidal as shown in Fig. 2. The unit cell dimensions of BCC are 5 mm × 5 mm × 5 mm with a relative density of 0.17, while the TetH and Pyr unit cells have a strut length of 5 mm for the base with a height of 5 mm corresponding to relative densities of 0.541 and 0.203, respectively. The entire lattice dimensions were designed to be 25 × 25 with a height of 20 mm. Strut diameter for all three types of LCSs is 1 mm. In this regard, the selection of the lattice dimensions was basically for the purpose of comparing the results of the developed models with the previous experimental findings of lattice structures having the same dimensions as the ones of the FEMs, by this way verifying the accuracy of the models created in this study. In
addition, the lattice dimensions of the current investigation or the experimental work from the literature were chosen significantly based on the number of unit cells higher than $3 \times 3 \times 3$ to reduce the effect of the boundaries on the lattice mechanical characteristics (Abdulhadi & Mian, 2019; Abdulhadi, 2020). This is an important criterion when selecting the dimensions of the entire lattice structure. In other words, the lattice dimensions and the unit cell dimensions out of which the lattice is composed should all be manipulated and fitted together very well to build the entire structure of the lattice with a number of cells higher than $3 \times 3 \times 3$. Finally, it is important to indicate that after validating the results and considering the effect of boundaries, the created computational models could be further used for predicting the post-yielding behavior of printed lattice structures with various dimensions.

After designing the LCSs in SolidWorks, a fused deposition modeling-based 3D printer Stratasys uPrint SE plus having a nozzle diameter of 2.54 μm was used to fabricate all three lattice structures with 300°C extruding temperature, 77°C chamber temperature, and 0.254 mm layer thickness (Sangle, 2017; Al Rifaie, 2017). The printer used production-grade thermoplastic (ABSplus-P430) provided by Stratasys (Stratasys, 2019). Three samples for each configuration were printed and tested under the quasi-static compression for 12 mm overall displacement.

3. Finite Element Modeling

The elements in the ABAQUS library have been enhanced and developed according to family, degree of freedom, number of nodes, formulation, and integration (Simulia, 2016; Fadeel et al., 2021). Smith and others (Smith et al., 2013; Karamooz & Kadkhodaie, 2015; Al-Saedi et al., 2018) have proved that the tetrahedron and hexahedron mesh elements have the capability to run 3D simulation of LCSs. In this regard, it was proven that the brick elements or hexahedron ones are more efficient than the tetrahedral elements due to their higher degree of freedom and higher order of formulation (Cook et al., 2002; Tadepalli et al., 2011; de Oliveira & Sundnes, 2016; Abdulhadi & Mian, 2019). Also, it is necessary to adjust the number of the elements through applying the convergence analyses to ensure obtaining accurate results in a reasonable time. Since the finite element modeling that includes the fracture criteria is very sensitive to the element type, the formulations of the elements have to be chosen and validated carefully (Gedik et al., 2011; Man & Van Mier, 2011). According to the Simulia 2018 (Simulia, 2016; Abdulhadi & Mian, 2019), several standard geometrical shapes such as cuboid, prism, pyramid, cuboid with angular cut, etc. can be meshed automatically with hexahedron elements in ABAQUS (Simulia, 2016). Otherwise, ABAQUS generates free mesh with tetrahedron elements as default. To solve this issue, it is required to decompose the geometry into meshable ABAQUS standard structural shapes by using a lot of tedious manual partitioning that is needed and known as geometric decomposition (Simulia, 2016).

Figure 3 shows the discretized models for BCC, TetH, and Pyr LCSs. Therefore, the hexahedron element type of C3D8R was applied to all the configurations and, thereafter, the number of elements was selected according to the convergence analysis (Abdulhadi, 2020). To explain that, this analysis was used here as a criterion to ensure that the created FEMs will provide accurate results. It was conducted based on reaching a convergence in the values of lattice elastic modulus after varying the number of elements several times. For instance, the convergence analysis of the BCC lattice configuration was made based on varying the number of hexahedron mesh elements out of which the BCC lattice model was created and estimating the corresponding value of the lattice elastic modulus. In essence, it was found that the lattice elastic modulus values approached each other with increasing the number of elements. In this case, the convergence error or the differences in the modulus values reached to insignificant values, which is less than 2%, when the number of elements became 220 000 or higher as shown in Fig. 4. A similar procedure was applied for all other configurations to ensure that the number of elements will not have a significant influence on the accuracy of the results.

The clamped–clamped boundary conditions for the top and bottom faces of all the FEA models were applied through two extreme unyielding planes. The bottom plate was fixed while the top plate was displaced downwards to match the experimental displacement rate. Also, the maximum applied displacement in FEA was simulated well to match the experimental maximum displacement. Since explicit finite element modeling was used, the displacement loading was applied through the top rigid plate by moving it down gradually with the strain rate of 0.0002/sec until a displacement of 12 mm was reached.

The material properties required to be selected as model material in FEA are shown in Fig. 5. According to this figure, the elastic stage can be captured at the part (a–b) (Simulia, 2016). Young’s modulus and Poisson’s ratio are required for isotropic linear elastic materials. The plastic stage can be captured based on the part (b–c) that requires the plastic strain and yield stress (Simulia, 2016). Regarding the progressive damage criteria, the part (c–d) can be defined and logged based on the appropriate damage criteria identified through experiment as explained in reference (Fadeel et al., 2018).

The material properties were identified based on the experimental observation and stress–strain curves. The density was identified as 792 kg/m³. The other mechanical properties, such as modulus of elasticity, plasticity, yield point, and failure strength, were experimentally measured using separate

Figure 3: The entire (a) BCC, (b) TetH, and (c) Pyr LCSs meshed by using geometry decomposition.
compressive and tensile tests for the printed samples (Fadeel et al., 2018). For the elastic stage, the Young modulus was plugged as 861.5 MPa, and the Poison ratio was 0.35. For the plastic stage, it has plugged multiple points between yield strength of 25.77 MPa (corresponding to the plastic strain of zero value) and ultimate failure strength of 33.32 MPa (corresponding to the plastic strain of 0.0455 mm/mm). In this regard, Hooputra et al. have developed an efficient model for simulating the plastic deformation and failure based on ductile and shear damage criteria (Hooputra et al., 2004). According to Simulia, the required criteria were fracture strain, stress triaxiality η, shear stress ratio θs, and strain rates ε′ (Simulia, 2016). The fracture strains can be obtained from the stress–strain curves based on the reference (Fadeel et al., 2018), while the strain rates were considered to be the experimental loading rate of 0.0002/s. The stress triaxiality η can be determined from equation (1) (Simulia, 2016).

\[
\eta = -\frac{p}{q} = -\frac{1}{3} \frac{(\sigma_1 + \sigma_2 + \sigma_3)}{q},
\]

where \(\sigma_1\), \(\sigma_2\), and \(\sigma_3\) are the principal stresses. The shear stress ratio θs is calculated from equation (3) (Simulia, 2016).

\[
\theta_s = \frac{(q + K_s p)}{\tau_{\text{max}}},
\]

where \(K_s\) is the material parameter and \(\tau_{\text{max}}\) is the maximum shear stress and can be found from equation (4) (Simulia, 2016).

\[
\tau_{\text{max}} = \frac{\sigma_1 - \sigma_3}{2}
\]

Consequently, it is worthwhile mentioning that the Python GUI code was developed to proceed with all challenging tasks that are impossible or difficult to be implemented manually based on ABAQUS. The LSD tool was developed to do many tasks such as creating and decomposing the lattice geometry, meshing, building the lattice configuration patterns (linear or polar), assigning the boundary conditions, and defining the materials for the developed models. The notepad++ was used to script the LSD program under the ABAQUS plug-ins. In this regard, the LSD flow chart has been designed as shown in Fig. 6, and the associated LSD interface was created as explained in Fig. 7 (Fadeel, 2021). Accordingly, all the configurations have been simulated efficiently and their affiliated results have been obtained accurately for the entire stages of the lattice compressive behavior in general and post-yield progressive damages in particular. Detailed procedure of using and running the LSD tool based on ABAQUS is available in YouTube for user reference (Fadeel, 2020).

4. Results and Discussions

The current FEMs have successfully provided the essential information for the elastic–plastic stages. Besides, the progressive damages were clearly captured for all configurations. Also, the load-displacement plots were obtained from the FEMs and experiments for the BCC, TetH, and Pyr LCS configurations. Significantly, the FEMs proposed in the current research for predicting load–displacement trends show the capability to capture relatively well the entire deformation behavior of LCSs during compression. To explain that, Table 1 shows the comparison between the experimental and simulation results based on the lattice Young’s modulus, yield stress, and peak load. To this point, it is obvious that the FEMs have provided acceptable simulations for the progressive damages and post-yielding behaviors.
4.1. Progressive failure analysis

The stress–strain plots were computed for each configuration by dividing the applied compressive load with the cross-sectional area of the specimen to create the engineering stress and the displacement associated with the applied load was divided by the specimen height such that the corresponding strain will be produced. For the BCC configuration, four layers of the BCC cells were denoted as L1 for layer 1 and L2 for layer 2 till L4 for the layer 4 as shown in Fig. 8. For stage I, the yield point was captured at the strain of 9.995% and the corresponding stress was 0.806 MPa as shown in Fig. 9. According to the stress contours for the sections x-x and the front view, the maximum bulk stress was observed at the middle of the internal faces of the lattice and the stresses in lattice struts exceeded the yield stress of the bulk material. The next, for the stage II, when the strain reached 12.0%, the plastic plateau stage was developed, and the
Table 1: Comparison of FEA results with the experimental work along with associated errors.

| LCS  | Young's modulus (MPa) | Lattice yield stress (MPa) | Peak load (N) |
|------|------------------------|---------------------------|--------------|
|      | Average | FEA     | Error  | Average | FEM     | Error  | Average | FEM     | Error  |
| BCC  | 13.46   | 14.19   | 5.14%  | 0.807   | 0.813   | 0.74%  | 515.5   | 470.29 | −9.61% |
| TetH | 143.679 | 151.61  | 5.23%  | 5.13    | 5.13    | −0.01% | 3372.12 | 3361.2 | −0.32% |
| Pyr  | 69.91   | 85.06   | 17.81% | 2.55    | 2.95    | 13.42% | 2013.2  | 1825.3 | −10.29%|

Figure 8: BCC configuration with layer designations.

corresponding stress dropped slightly to 0.752 MPa. Because of the plastic plateau, the fatal deformation started in the regular struts at L2. Thereafter, at stage III, when the strain reached 15.2%, the abrupt failure occurred because of exceeding the failure point of the bulk material and then the layer L3 completely collapsed, and the stress dropped to 0.534 MPa. Hence, at stage 4, the configuration started building new resistance from the debris of L2 in a combination with the other layers, and this assembly continued resisting elastically until 24.10% (stage IV) strain and the corresponding stress rose up to 0.804 MPa. Up to this point, multiple progressive failure stages occurred till reaching the final stage, which was at 60% strain. Obviously, at this stage the strain densification regime initiated where the lattice structure will behave approximately as solid material (see Fig. 9).

For the TetH configuration, two types of layers were defined. First set was for the horizontal struts, which were denoted as HSL1 to HSL3 and second sets of layers were denoted as L1 to L4 for tetra layers (Fig. 10). In this regard, L2 was observed to be in an opposite direction to L1 and L4 is opposite to L3. For stage I, the linear elastic behavior was observed until the strain of 0.3% and the corresponding stress of 4.548 MPa was reached, which was almost before starting the plastic plateau stage as shown in Fig. 11. After that, stage II at the strain value of 6.10% and the corresponding stress value of 5.133 MPa started. At this stage, the maximum stress was observed at the internal sides of the struts as shown in section x-x. This was because the extrema stresses and fatal deformation occurred in the struts and the failure happened at the joints between the horizontal and diagonal struts as shown in the stage III. For stage III, the abrupt failure started due to the fracture of the horizontal struts and the corresponding strain reached 18.20% and the stress dropped down to 2.643

Figure 9: BCC configuration with (a) stress–strain curve, (b) isometric view showing front side and section X-X, and (c) different strain levels at both the front side and section X-X.
For the other stages, the struts will deform and continue resisting elastically and plastically until the strain densification took place in the final stage at a strain value of 60% (see Fig. 11). For the Pyr configuration, four layers of the LCS were designated as L1 to L4, and every layer was opposite to the others (Fig. 12). For stage I, the elastic deformation occurred until the strain of 3.11% with corresponding stress of 2.553 MPa as shown in Fig. 13. The next stage, stage II, came right after the plastic plateau stresses at the strain of 6.610% and the corresponding stress of 2.894 MPa. Then, abrupt failure happened due to the damage initiation in the middle struts. Because of that, a huge drop in the stress to a value of 0.705 MPa occurred during stage III at a strain value of 9.0% as shown in Fig. 13. For the next stages, fluctuations in the stress–strain curve were observed accompanied by slight variations in the stress level due to the strut’s deformation, which will continue till the beginning of strain densification for the final stage as shown in Fig. 13.

To ascribe the deformation mechanism of all three configurations, it is important to mention that the specific testing method and boundary conditions are quasi-static axial compressive loading with constrained boundary conditions. They are made of ABS polymeric material, and each configuration has a relative density different from the other. As mentioned earlier, the lattice deformation mechanisms are related to the ensued stress–strain responses. First of all, the general stress–strain trend of BCC lattice is similar to the one provided by Gibson and Ashby for bending-dominated structure except that it is wavy with several peaks and valleys, by this way reflecting the brittle aspects of the material. Based on the contour plots of the sections and side views, it is evident that the middle struts undergo bending till breaking, thereby inducing an initial or first collapse for the whole middle layer. For this reason, it is possible to say that BCC lattice undergoes fracture-bending-dominated behavior under the conditions considered in this study. Regarding TetH, the stress–strain response is similar to the one of Gibson and Ashby for stretch-dominated structure. Also, it shows one peak and post-yield softening after the initial collapse, where it occurs due to the resisting of the middle horizontal struts to the axial tensile loading till fracturing. Consequently, fracture-stretch-dominated behavior can be ascribed to this feature under the adopted conditions. The behavior of Pyr could approximately be fracture-stretch-dominated, where the first collapse is induced by breaking the middle horizontal struts subjected to tensile loading. However, this feature shows instabilities and weak behavior comparing with that of TetH. In addition, there is a rapid drop after the initial collapse including post-yield softening, and it cannot carry loading again for a while and, thereafter, minor peaks show before the strain densification.

Any lattice feature might have bending-, stretch-, or buckling-dominated behaviors depending on different loadings and boundary conditions, structural parameters, and material type. To explain that, the deformation mechanisms corresponding to the same lattice topology, unit cell size (X, Y, and Z), and material type could change from one dominant behavior to another beyond certain relative density through changing the strut...
diameter. Besides, the cross-sectional shape of lattice struts has an evident influence on the lattice mechanical behavior, even when the lattice relative density and other parameters are the same. In addition, the cellular structures made of rigid polymer and metal materials may undergo buckling before yielding if the slenderness ratio is high. In addition, buckling will depend on material type; for example, the elastomeric cellular materials always suffer from elastic buckling. Changing the boundary conditions from unconstrained to constrained also affects the lattice behavior and mechanical properties, especially for BCC configuration. Additionally, loading types will influence the deformation mechanisms and stress–strain responses of any lattice topology. The above information is important for lattice designers and can be further investigated in separate research with the help of the FEA model developed in this study.

4.2. Specific energy evaluation

The plateau stress and useful absorbed energy are essentially used to evaluate the quality of the computational models (Habib et al., 2018). The useful absorbed energy can be defined as the area under stress–strain curve till the end of plateau regime or the beginning of strain densification where the end of plateau stress is located. To identify the useful absorbed energy, it is required to find the efficiency and based on which the plateau stress can be computed. In general, absorbed energy can be expressed as the area under the stress–strain curve corresponding to a strain interval (ε) and it can be calculated from equation (5) (Habib et al., 2018). Then, the efficiency will be estimated from the ratio between the absorbed energy and the ideal energy absorbed with ideal peak stress and it can be found from equation (6). The end of plateau region is to be theoretically identified at the same location of the maximum efficiency (Habib et al., 2018).

In addition, the plateau stress can also be found using another way by dividing the energy absorbed within a certain strain interval between ε_y and ε_cd by the strain difference associated with this interval (ε_cd − ε_y) (Habib et al., 2018). Thus, equation (7) will be used to compute the plateau stress, where ε_y refers to the initial crash strain and ε_cd indicates the strain at the end of the plateau region. For example, in BCC lattice configuration according to Fig. 14a, the maximum efficiency was captured at the strain of 0.567 value that corresponds to the end of the plateau regime with 0.86 MPa stress. Based on the value of the latter, the corresponding maximum absorbed energy was found to be 0.392 J/mm³ as it can be noticed in Fig. 14b. Similarly, the stress and efficiency with the strain as well as the absorbed energy with peak stress for both the TetH and the Pyr have been explained in detail through Figs 15 and 16, respectively.

\[
W = \int_0^{\varepsilon_y} \sigma(\varepsilon) \, d\varepsilon \\
E = \int_{\varepsilon_y}^{\varepsilon_{cd}} \frac{\sigma(\varepsilon)}{\varepsilon_{p}} \, d\varepsilon \\
\sigma_{pl} = \frac{\int_{\varepsilon_y}^{\varepsilon_{cd}} \sigma(\varepsilon) \, d\varepsilon}{\varepsilon_{cd} - \varepsilon_y},
\]

where \(\sigma_p\) is the peak stress at the interval strain \(\varepsilon\).

Figure 13: Pyr configuration with (a) stress–strain curve, (b) isometric view showing front side and section X-X, and (c) different strain levels at both the front side and section X-X.
Based on the energy efficiency and the plateau comparisons, the FEMs adopted in the current investigations are valid and efficient for capturing the post-yielding behavior of different lattice configurations based on rational values of the variance coefficient between the FEMs and the experimental works cited from the literature (Sangle, 2017; Al Rifaie, 2017). According to Table 2, the variance coefficient of the plateau stress was 17% for BCC configuration that has been drawn based on the difference between 0.86 (MPa) as a value extracted from the finite element modeling and 1.01 (MPa) measured from the
experimental work. Regarding the absorbed energy and the strain at the plateau of BCC configuration, the variances were 13% and 2%, respectively. In the same manner, the results of the other configurations (TetH and Pyr) show acceptable agreements; therefore, these FEMs can be used to conduct further investigations and analyses on other configurations and lattice designs in the future. To this end, the variance coefficient values of the three lattice configurations were summarized in Table 2 for the plateau stress, absorbed energy, and plateau strain.

5. Conclusions

The finite element-based modeling has provided precise simulation for the post-yielding compressive behavior of the adopted lattice configurations, thereby showing good agreement with the experimental work.

1. Due to the reasonable agreement between the experimental work and FEAs for different lattice configurations, it can be concluded that these models can be useful for further studies such as developing new lattice designs and conducting optimizations with least amount of expenses and human effort.

2. The FEMs have shown latent behaviors that are impossible or complicated to be captured experimentally at this level of details. Since FEMs were validated based on the post-yield stages and the associated parameters, these models can be valid and can work effectively to understand the progressive failure damage of various lattice designs and the effect of horizontal and vertical struts on lattice compressive mechanical behavior. Due to the difficulties in capturing the failure moments at each stage, these models have been used to identify the deformation behavior of the lattice configurations whether bending or stretch dominated based on the detailed analyses that have been explained at each stage of the lattice failure. The BCC has shown multiple progressive damage states at various stages of deformation, whereas the TetH and Pyr have shown single peak before abrupt failure, signifying a single failure mode. This is because both TetH and Pyr have a combination of horizontal and diagonal struts in which the horizontal ones resist the axial deformation until the applied loads reach 3361.2 and 1825.3 N, respectively. Once they broke, all the diagonal struts will fail abruptly because they cannot resist the bending due to the associated longer strut length. Therefore, the deformation behavior of TetH and Pyr can be described as “stretch” dominated. However, the absence of the horizontal struts in the BCC configuration makes its behavior as “bending” dominated.

3. The absorbed energy and the efficiency analyses have revealed that the BCC configuration has the lowest energy absorption with a value of 0.392 W, while the highest has been attained by TetH lattice with a value of 1.58 W. The Pyr configuration has an intermediate energy absorption with a value of 0.91 W. Lattice energy absorption depends mainly on the plateau region, which in turn depends on the plateau end and average or ideal stress plateau. The highest ideal stress plateau of TetH enhances its capability of absorbing more energy even though its plateau end has a small value compared with the other configurations. Indeed, the highest value of plateau stress belongs to the highest relative density of TetH as compared with the other configurations.

4. The Gibson–Ashby model can be useful to understand the mechanisms of the failure; however, the finite element simulation can help to capture the failure stages and can provide greater insight into the progressive failure process. It has been noticed that polymeric BCC lattice under compressive loading with constrained boundary conditions corresponding to a specific relative density has a wavy behavior of several peaks and valleys. This gives an indication that the lattice material behavior is more brittle. Besides, it has good load bearing capability after each layer collapse along with maintaining almost the same peak loads. For TetH, one peak can be seen from the stress–strain response with post-yielding softening after the first collapse. Then, the load starts increasing slightly till reaching the densification region, by this way showing a ductile-like material trend. Finally, the Pyr feature fails abruptly after the first peak along with post-yield softening. The material fails to carry loading again for a while followed by an increase in load till a second short peak after which the densification starts.

5. Based on the FEMs developed in this study, the influence of the structural parameters, material types, boundary conditions, and applied loadings on the deformation mechanisms could be investigated thoroughly. This in turn would show the role of such parameters in transition from one dominated behavior to another and help realizing the physics behind such a problem.

6. The dependence of the normalized mechanical properties on the material type and lattice topology will be a good subject for future study. In this case, a large data set is required based on using both various relative densities and different material types corresponding to several lattice configurations. Also, of course, the developed FEMs in the current research will be handy to achieve this massive work efficiently.

Conflict of interest statement

None declared.

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