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Effects of print orientation on the design of additively manufactured bio-based flexible lattice structures

Satabdee Dash[1], Axel Nordin[2]

Lund University
[1]satabdee.dash@design.lth.se
[2]axel.nordin@design.lth.se

Abstract

In upholstery applications, it is common to use polyurethane (PUR) foam when flexibility is desired. However, as PUR is a carbon-based material produced using toxic isocyanates, it is environmentally beneficial to replace PUR with bio-based alternatives. The challenge, however, lies in finding suitable bio-based replacement materials, capable of mimicking the foam-like functionality of PUR since many are stiff and brittle. Therefore, instead of relying on the inherent material property, this paper explores the possibility of producing flexible foam-like structures from bio-based materials with additive manufacturing (AM) employed as the manufacturing technique. As one of the key design constraints associated with AM is the intrinsic material anisotropy in the build direction, this paper focuses on the effects of print orientation on the compressive behaviour of structure which is indicative of flexibility. Three open-celled strut-based lattice structures are chosen for this purpose and the effect of these cell topologies on the compressive behaviour of structures is studied. The scope of this work includes structures printed using selective laser sintering (SLS) in a bio-based polyamide material (PA 1101). The results show that material failure and deformation behaviour are affected by print orientation, while the amount of plastic deformation is more influenced by the lattice cell topology.

Keywords: Additive manufacturing, print orientation, flexibility, lattice structures, sustainable design

1 Introduction

1.1 Background

Under a jointly funded project named STEPS (STEPS, n.d.), a Swedish furniture company (JI) has shown interest in investigating flexible structures for upholstery applications. Currently, polyurethane (PUR) foams are used extensively within the furniture industry since these elastomeric foams are ideal for cushioning applications due to their low stiffnesses (L. J. Gibson & Ashby, 1997). However, these fossil-based materials are undesirable from an environmental point of view and involve toxic chemicals during production (Gama et al., 2018). With industries transitioning towards sustainable materials, it is beneficial to switch to bio-based plastics, such as PA 1101 or other alternatives (Tenorio-Alfonso et al., 2020). For upholstery applications using PA 1101, it is a challenge to design parts that can mimic the function of PUR. Such foam-like flexibility can be achieved in a part either by relying on the material properties and/or by focusing on the structural arrangement. Since PA 1101 is a stiff material, from the structural perspective, one approach to utilize PA 1101 is to use cellular structures. These structures consist of unit cells formed by an interconnected network of solid struts and plates that are open- or close-celled and either stochastic or arranged in a periodic fashion (L. J. Gibson & Ashby, 1997). For the upholstery application, cellular structures should be engineered to exhibit the intended foam cushioning effect. Engineered cellular structures include lattice structures which form a class of metamaterials, i.e., owing to the micro-architecture, they can be viewed as a monolithic material with a specific set of effective properties (Scheffler & Colombo, 2005). They are hollow structures with a periodic arrangement of 3D unit cells, commonly employed as lightweight structures due to their high strength-to-weight ratio characteristics (Seharing et al., 2020).

One of the ways to manufacture lattice structures is by using additive manufacturing (AM) with selective laser sintering (SLS) being the commonly used AM technique to manufacture PA 11-grade plastics (Abou-Ali et al., 2020). AM or three-dimensional printing (3DP), first developed in the late 1980s (Vaneker et al., 2020) adopts a layer-by-layer material deposition approach for creating 3D parts (ISO, 2015). The ability of AM to create sophisticated parts with advanced attributes, such as novel materials, complex geometries, hierarchical structures, and functional assemblies (I. Gibson et al., 2010) has resulted in significant advancements in furniture, aerospace, manufacturing, and biomedical industries (Vaneker et al., 2020).

To leverage the design capabilities offered by AM, Bourell and Rosen (2009) coined the term Design for Additive Manufacturing (DfAM) which promotes the integrated practice of designing parts while considering their manufacturing using AM (Thompson et al., 2016). Being an inherently anisotropic process, AM adds material in a certain direction, resulting in parts that exhibit anisotropic behaviour governed by the microstructure produced during the layer-wise material deposition (Somireddy & Czekanski, 2020). Due to this design constraint associated with AM, the mechanical properties of printed parts (e.g., lattice structures) are dependent on the printing orientation. Apart from print orientation, lattice structures require designing a unit cell with appropriate size and topology, which are the primary determinants of the mechanical characteristics, and thus the lattice flexibility (Alghamdi et al., 2020). One of the important mechanical properties of these lattices that can serve as an indicator of the desired flexibility for upholstery is their compressive behaviour. This behaviour when investigated with respect to different print orientations can provide insights into flexible lattice structures, paving the path for an interesting area of research.

1.2 Research aim

As a step towards achieving flexible lattice structures employing bio-based materials through AM, this paper aims to investigate how print orientation influences the mechanical properties (compressive behaviour) of lattice structures during compression using three open-celled strut-based lattice topologies as discussed in Section 2.1.1. As motivated in the previous section, only parts printed using SLS in PA 1101 are considered within the scope of this study. Measurements are carried out to study the mechanical properties of the lattice structures during compression and the plastic deformation, and deformation behaviour along with any material failures are reported.

1.3 Literature review

Within the field of DfAM, there is a plethora of literature studying structural properties, several of these studies focus on the compliance aspect of employing lattice structures (Boley et al., 2019; Martínez et al., 2019; Nelson et al., 2016), aiming for lattice-based flexible structures. During the past few decades, the number of studies investigating lattice structures and their mechanical properties, both numerically and experimentally have increased significantly (Fleck et al., 2010; Karamooz Ravari et al., 2014; Karamooz Ravari & Kadkhodaei, 2015; Obadimu & Kourousis, 2021; Tancogne-Dejean et al., 2016; Wang et al., 2010; Xiao et al., 2015). However, none of these studies focus on their design while simultaneously considering the associated manufacturing constraints such as printing orientation-dependent-mechanical behaviour as seen in AM. Santorinaios et al. (2006) studied the crush behaviour of open cellular structures manufactured by stainless steel 316L using selective laser melting (SLM), whereas Karamooz Ravari et al. (2014) numerically investigated the mechanical properties of cellular lattice structures under compression which were fabricated by polylactic acid (PLA) filaments using fused deposition modelling (FDM). Another study by Abou-Ali et al. (2020) presented the compressive behaviour of triply periodic minimal surfaces (TPMS) lattice structures by PA 1102 using selective laser sintering (SLS). In addition to understanding the compressive behaviour of lattice structures, studies have also confirmed that print orientation has a significant influence on the mechanical behaviour of lattices (Garg et al., 2016; Gautam et al., 2018; Lee et al., 2007). Lee et al. (2007) experimentally investigated the compressive strength of printed cylindrical specimens with respect to the print orientation, Garg et al. (2016) studied the effect of print orientation on the surface roughness and dimensional accuracy of FDM printed parts and Gautam et al. (2018) investigated the effects of print orientation on the peak strength and effective stiffness of FDM-manufactured Kagome lattice structures. However, to the authors' knowledge, no studies have focused on the possibility of achieving flexible lattice structures by studying the effect of print orientation on the compressive behaviour of PA 1101 lattice structures manufactured using SLS.

1.4 Outline

This paper is divided into five sections. In Section 1, the research background and aim are introduced followed by an overview of the existing literature. In Section 2, the lattice topologies and their experimental investigation is described. In Section 3, the results of this work are stated, followed by Section 4, where these results are interpreted and discussed. In Section 5, the concluding remarks are presented.

2 Methodology

To investigate the effects of print orientation on lattice structures during compression, the scope of the study was restricted to pre-defined structural characteristics concerning the lattice topologies, unit cell size, lattice size, number of unit cells, and cell strut diameter as stated in Sections 2.1. The design and fabrication of these structures i.e., the details on geometrical modelling, manufacturing process, and selected material are explained in Sections 2.2. The mechanical testing and measurements for investigating the compressive behaviour of the chosen lattices are further explained in Section 2.3.

2.1 Structural characteristics

2.1.1 Lattice topologies selected for the study

Among the most commonly studied and reported lattice topologies (Obadimu & Kourousis, 2021), three open-celled strut-based topologies were considered for compressive testing. Strut-based topologies can exhibit either stretching-dominated or bending-dominated behaviour where the latter kind of topologies demonstrate a compliant force-displacement behaviour (Alghamdi et al., 2020) which is desirable for the upholstery application. One of the typical bending-dominated topologies with widespread research interest (Zhao et al., 2018) includes body-centered-cubic (BCC) and has been chosen for this work. In contrast, the other chosen topologies include vertical struts joining the corner nodes of the topology making them stretching-dominated, i.e., BCCZ (BCC variant) and FCCZ (face-centered-cubic or FCC variant). These structurally different topologies were chosen to study the compressive behaviour since the variants have directional properties due to the presence of vertical struts, as compared to BCC. The lattice structure configurations (front view) and their constituent unit cell designs are shown in Figure 1.

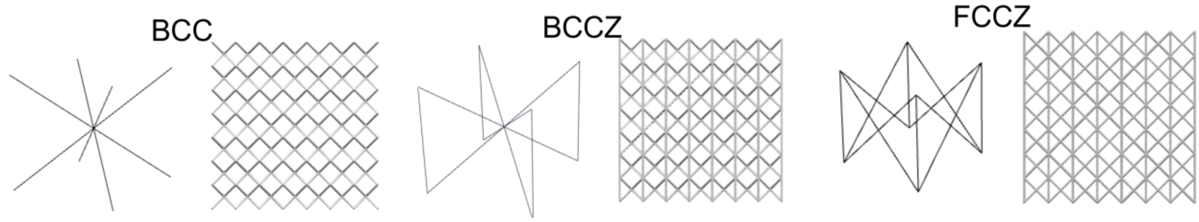

Figure 1. Unit cell designs (left) along with the front views of the lattices employing them (right)

2.1.2 Choice of unit cell size and lattice size

The number of unit cells per side in the lattice should be large enough to accurately represent the "bulk" behaviour, i.e., the boundary effects should not dominate the overall behaviour of the lattice. At the same time, a highly dense lattice will make it difficult to remove loose powder post printing. Therefore, as a trade-off, the number of cells per side was fixed to 7 and the lattice size was fixed to 35 × 35 × 35 mm (i.e., a unit cell size of 5 mm) which is in accordance with the periodicity required to sufficiently represent the bulk behaviour (Abou-Ali et al., 2020).

2.1.3 Choice of lattice strut diameter

As a first step towards investigating flexibility, it was decided to limit the testing of the lattice structures to one strut diameter. Preparatory experimental work concluded that the limits for the feasible strut diameters were in the range of 0.5 to 0.8 mm. A diameter of 0.8 mm resulted in structures that were easily compressible while being robust compared to those with 0.5 mm, hence, it was decided to print all structures with this diameter.

2.2 Design and fabrication

2.2.1 Geometrical modelling of lattice structures

Rhinoceros 3D was used along with Grasshopper 3D, an integrated visual programming language to design the unit cells of the lattices. Crystallon (Porterfield, n.d.), an open-source plugin for grasshopper along with Dendro (Ryein, n.d.), a volumetric modelling plugin was used for creating the lattice structures. The lattice structures (BCC, BCCZ, FCCZ) were created by periodically repeating unit cells in three (X, Y, and Z) directions resulting in seven-layer lattices. An example of the geometrical modelling using the plugins is shown in Figure 2.

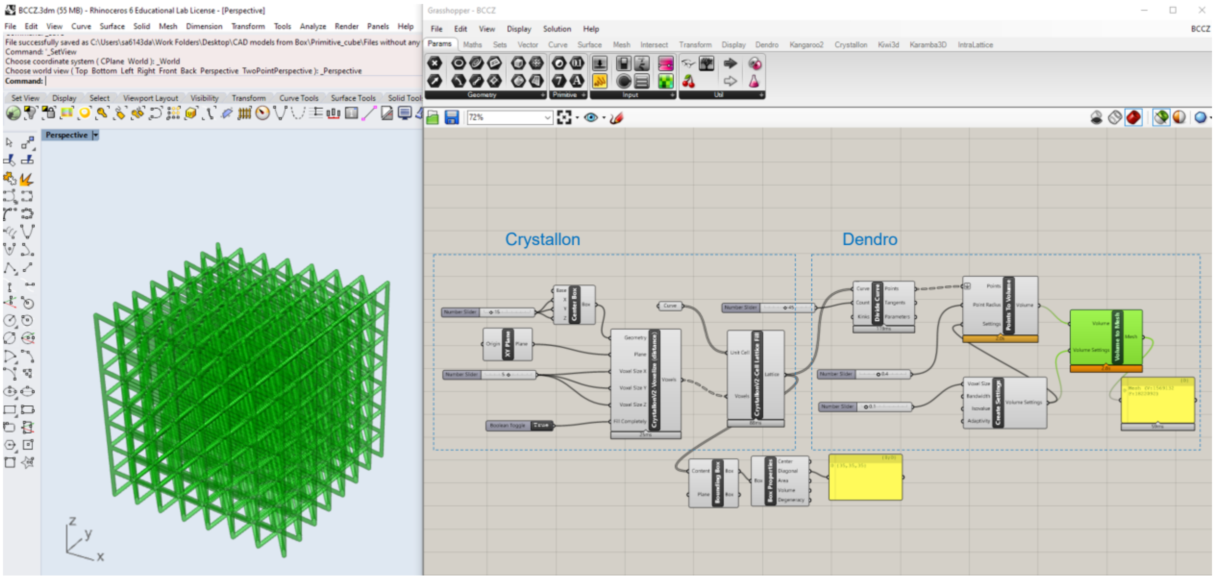

Figure 2. Geometrical modelling of BCCZ lattice in Rhino-Grasshopper interface using Crystallon and Dendro plugins

2.2.2 Additive manufacturing of lattice structures

The designed lattice structures were manufactured using SLS, a laser powder-bed fusion process on a Formiga P 110 SLS machine by EOS GmBH (Germany). A bio-based material, PA 1101 which is a whitish polyamide 11 powder made from renewable raw materials (castor oil) was employed as the base material. The material properties are shown in Table 1. The manufacturing process parameters used for SLS printing are shown in Table 2.

Table 1. Properties of PA 1101 (EOS GmBH, n.d.)

Properties	***Density (kg/m3)***	***Young's modulus (MPa)***	***Yield strength (MPa)***	***Poisson ratio***	***Melting temperature (20^0/min) (^{0}C)***
PA 1101	990	1600	48	0.4	201

Table 2. Manufacturing process parameters

SLS Parameters	***Laser type***	***Laser power (W)***	***Laser scan sped (mm/s)***	***Laser hatch spacing (mm)***	***Powder layer thickness (mm)***	***Powder bed temperature (^{0}C)***
Values	CO_2 laser 1060 nm	25	5000	0.25	0.1	185

Three samples, each for BCC, BCCZ, and FCCZ were printed each in a different orientation (XY, YZ, and XZ) as shown in Figure 3, resulting in a total of 9 samples (BCC XY, BCC YZ, BCC XZ, BCCZ XY, BCCZ YZ, BCCZ XZ, FCCZ XY, FCCZ YZ, and FCCZ XZ). Air jet

cleaning was employed for the removal of loose powder and other contaminations from the solid struts of lattice structures.
In Figure 3, plates of 1 mm thickness were added to the top and bottom of lattices to simulate the conditions during the actual upholstery application where they are designed in between thin plates that serve as boundary walls (Elmadih et al., 2019).

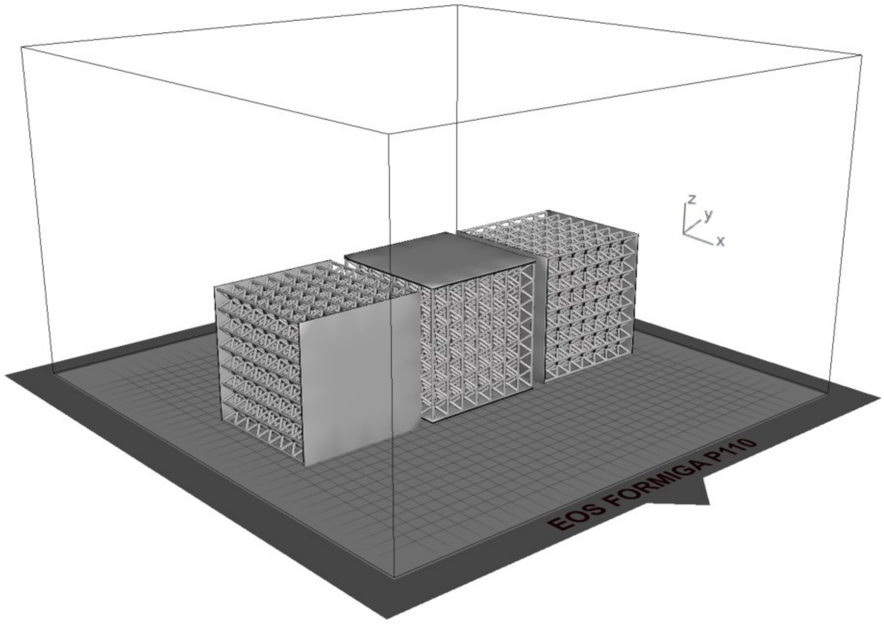

Figure 3. Printing of lattices in three different orientations: XY, YZ and XZ

2.3 Mechanical testing and measurements

When a lattice is under compression, it undergoes three processes: elastic deformation, energy absorption (plateau region), and densification (Syam et al., 2018). Therefore, to study the compressive behaviour of the manufactured lattices, uniaxial compressive tests were carried out. A simple experimental setup with bench vise was set up. The lattices were loaded onto the vise and held in place by the vise jaws against the top and bottom plates designed into the lattices. They were gradually compressed using the movable jaw against a gauge of 23.75 mm thickness (T_{gauge}) for performing the tests and for assessing the material failure and deformation behaviour. A video camera was employed during these tests to capture and record all the deformation stages. To exclude any effects of stress relaxation on the sample height, the lattices were left to rest for 24 hours before measuring the final height for the measurement of plastic deformation.

3 Results

3.1 Effect of print orientation on deformation behaviour

The deformation behaviour of the manufactured lattices under compression, printed in different orientations is shown in Figure 4.

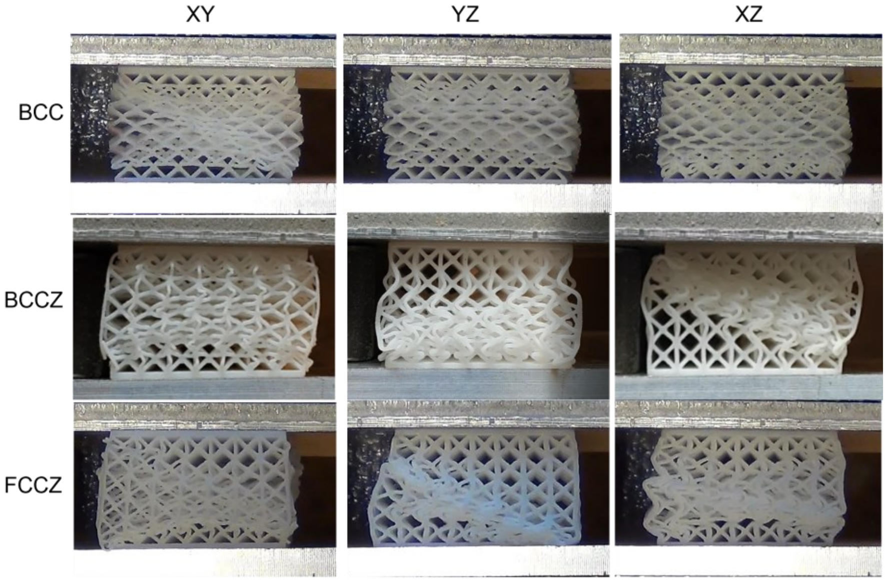

Figure 4. Deformed structures under uniaxial compression for BCC, BCCZ, and FCCZ lattices printed in XY, YZ and XZ orientations

For assessing the deformation behaviour, the gradual deformation pattern for the BCCZ lattices is presented in Figure 5. These patterns are shown at three different deformation stages: initial deformed stage, intermediate stage, and final deformed stage.

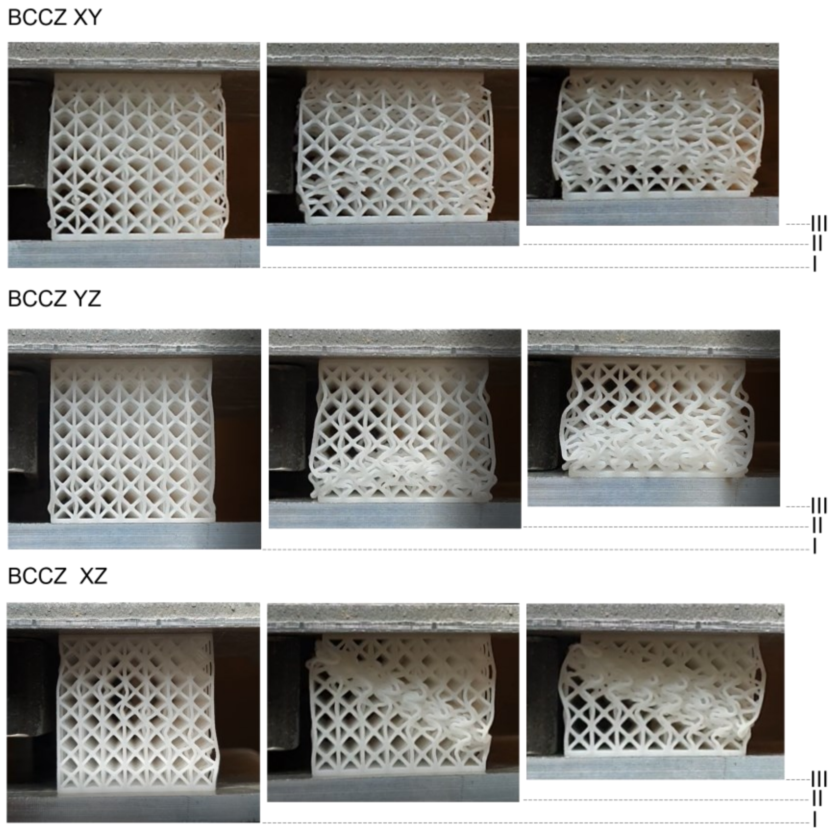

Figure 5. Deformation behaviour under uniaxial compression of BCCZ lattices printed in XY, YZ, and XZ orientations, presented at three different stages: (I) initial deformed stage (II) intermediate stage, and (III) final deformed stage

3.2 Effect of print orientation on plastic deformation

The results for plastic deformation in all the manufactured lattices are presented in Table 3, expressed using Plastic Deformation Percentage (PDP) as per Equation 1, where H_{ini}, H_{def} represents the initial height and the deformed height, respectively. T_{gauge} represents the thickness of gauge which corresponds to 23.75 mm as mentioned in Section 2.6.

$$PDP(\%) = \frac{H_{ini} - H_{def}}{H_{ini} - T_{gauge}} \times 100 \tag{1}$$

Table 3. Assessment of the influence of printing orientation on the plastic deformation for BCC, BCCZ, and FCCZ lattices

	BCC			BCCZ			FCCZ		
Print orientation	***H_{ini} (mm)***	***H_{def} (mm)***	***PDP (%)***	***H_{ini} (mm)***	***H_{def} (mm)***	***PDP (%)***	***H_{ini} (mm)***	***H_{def} (mm)***	***PDP (%)***
XY	37.15	34.92	16.64	36.92	35.03	14.35	37.47	34.10	24.56
YZ	36.70	34.50	17.00	36.74	34.19	19.63	36.80	33.58	24.67
XZ	36.65	34.60	15.90	36.30	33.85	19.52	37.00	33.33	27.70

4 Discussion

4.1 Deformation behaviour of the lattice structures

From the deformation results presented in Figure 4 and Figure 5, it is clear that there are major differences in behaviour between the structures. Importantly, the same structure shows different deformation behaviour depending on the print orientation, as seen when comparing the compressed state of BCCZ printed in different orientations in Figure 5. The deformed structures in full compression as seen in Figure 4, have two main modes of global deformation: along the loading axis (as in BCCZ YZ, also detailed in Figure 5) and along the diagonal axis (as in BCCZ XZ, also detailed in Figure 5). The deformation in all the BCC structures is along the loading axis, folding into neighbouring layers and out-of-plane. For BCCZ and FCCZ, the common deformation mode is along the loading axis, except for BCCZ XZ and FCCZ YZ where the structures deform diagonally as seen in Figure 4.

4.2 Material failure in the lattice structures

As seen in Figure 4, the print orientation strongly affected the amount of material failure in the struts for the BCCZ and FCCZ structures printed in the XY as compared to the XZ orientation. A possible explanation for this effect is that the vertical struts will be built along their lengths, with the compressive forces mainly transmitting through the layers when printed in XY orientation. In such cases, the intra-layer particle adhesion is not as good as that within the layers, thus leading to fragile structures. Based on the results, the best orientation is the XZ orientation as all three lattice types had no, or very limited failure when printed in this orientation.

Additionally, from Figure 4, it is seen that the structural arrangement (i.e., lattice cell topology) also has a clear effect on the amount of material failure, with BCC being the top-performing structure with no broken struts in any printing orientation.

4.3 Plastic deformation in the lattice structures

As seen in Table 3, there is a large difference in the amount of plastic deformation between the different structures. Interestingly, the print orientation does not have a strong impact. The BCC structure had the best overall performance, with all orientations having a PDP of approximately 16-17%, whereas the FCCZ structure had the worst performance on average, with PDP ranging from approximately 24-28%. As the different samples had slightly different starting heights, this was adjusted for in the calculation of the amount of plastic deformation using a PDP value, as shown in Table 3.

5 Conclusions and Future work

The motivation behind this work is to achieve flexible lattice structures employing bio-based materials through AM. To expand the knowledge within this area, this paper aims to investigate the effect of print orientation on the compressive behaviour of lattice structures. To this end, this paper presents results from the investigation of three lattice structures (BCC, BCCZ, and FCCZ) printed in three orientations (XY, XZ, YZ) using SLS in PA 1101.

The results show that the print orientation impacts the deformation behaviour and the amount of material failure, and thus serves as an important design factor for achieving flexible lattice structures for upholstery applications. The results show that the amount of plastic deformation is not strongly affected by print orientation and is more influenced by the lattice cell topology. The results further show that the BCC structure has the best performance in terms of both plastic deformation and material failure.

According to the results of material failure for all the lattices, it can be concluded that the XZ print orientation is suitable for reducing material failure. The XY printing orientation should be avoided for structures with vertical struts as the struts are more likely to break under compression. Although the results of this research uncovered the importance of print orientation in achieving flexible lattice structures, further research is needed to investigate the impacts of other lattice topologies, strut diameters, and materials on the compressive behaviour of these structures and to further evaluate the design implications. Further research is also needed into the effects of strain rate and fatigue in addition to the requirement of more test samples to fully investigate the deformation behaviour.

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