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Failure Behaviour of 3D-Printed ABS Lattice Structure under Compression

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Abstract: Lattice structure is a lightweight material that can be produced using the cutting edge additive layer manufacturing process or also known as 3D printing. Lattice structure material is a periodic cellular structure material that can be utilized in various applications especially as core material in sandwich structure configuration, where the ultimate aim is to be a lightweight material with load bearing capability. Researches are yet to be done to fully understand the behavior of lattice structure materials under several loading conditions such as tensile, bending and compression. The objective of this paper is to discuss the behavior of acrylonitrile-butadiene-styrene (ABS) lattice structure material that was produced using the layer by layer manufacturing, subjected to compressive load. Lattice structure specimens with dimension 20x20x20 mm^3 were designed with body centered cubic (BCC) unit cells for three sets of strut diameter size. The specimens were produced using fused deposition modelling (FDM) Cubepro 3D printer, with varying default parameters of layer thickness, print strength and print pattern. All specimens were subjected to compressive load until densification stage and the stress-strain curves of the material were plotted. The compressed specimens were observed under an optical digital microscope and a common failure behavior of 3D-printed ABS lattice structure material was highlighted. It was shown that the failure of compressed lattice structure was initiated at joint node areas due to bending tensile stress. It can be concluded that this polymer material showed hybrid between stretch and bending-dominated characteristics. This is a good indicator for lightweight material with load absorbing capability. An understanding in the failure behavior of ABS lattice structure material is enriching the knowledge on this material under stress-strain condition.

Keywords: lattice structure, 3D printer, compression load.

I. INTRODUCTION

The increasing applications of additive layer manufacturing or 3D printing in producing lightweight materials can be seen in recent years [1]-[5]. The capability of fabricating complex geometry with high precision, material savings and design flexibility are the main advantages of 3D printing [6]. With the development of 3D printing in the manufacturing industry, the production of lattice structure materials has become feasible.

Lattice structure material is a periodic cellular structure material which can serve the purpose of achieving lightweight parts with good mechanical properties [7]. It can be defined as a three-dimensional structure with struts and joints interconnected with each other. Lattice structure can be utilized in various applications with its diversity of part designs incorporated in its various cellular approaches within available manufacturing processes [8]. These designs are based on the design parameters that are available in the cellular design classifications which are associated with single unit sizes and shapes of the lattice structures, or also known as topological design. These topological designs can be classified into bending dominated or stretch dominated in which often associated with having greater relative strength. Bending dominated structure is suitable to be utilized in an energy absorbing applications [8]. Some of the famous topological designs that have been studied so far are body-centered-cubic (BCC) or octahedral, two-faced body-centered-cubic (F2BCC), tetrahedral, pyramidal, octet-truss, diamond, gyroid and many more [9]-[13].

Additive layer manufacturing has been steadily used for acrylonitrile-butadiene-styrene (ABS) such as in [14] and ABS lattice structure has also been realized from this polymer material such as in [15]. There are influences of 3D printing parameters especially the layer thickness of additive process on the performance of lattice structures [16]-[18]. For a mid-range pre-set up 3D printer, there are machine's default parameters which can significantly affect the produced lattice structure material [19]. On top of that, the load-bearing capabilities of these materials are seen as promising.

It is interesting that the ABS lattice structures can be successfully realized by using the 3D printer, and there was study reported that ABS lattice structure down to 1 mm strut diameter can be printed using the layer by layer FDM technique [20]. While other studies have reported on the response of this material under both tensile and compression loadings [15], this current paper reports specifically on the failure behaviour of ABS lattice structure material under compressive loading. Detail observation and explanation regarding the material's failure are important to assist future studies that are dealing with this material under similar type of loading.

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II. METHODOLOGY

A. Design and Fabrication

Lattice structure materials in cube specimens of 20x20x20 mm^3 were designed using SolidWorks and fabricated from acrylonitrile-butadiene-styrene (ABS) using fused deposited modelling (FDM) 3D printer. The cube specimens were having four layers of arranged body centered cubic (BCC) cells, where there were sixteen repetitive unit cells in each layer. Fig. 1 shows the schematic of lattice structure cube specimen.

Fig. 1. Schematic of lattice structure cube specimen.

The lattice structure materials were designed with three different groups of strut size, that were 1.2, 1.4 and 1.6 mm respectively. These groups of materials were manufactured using various default parameters of Cubepro 3D printing machine by 3D Systems Inc. There were three prominent parameters which were layer thickness, print strength, and print pattern. These prominent parameters were using three different levels respectively, as listed in Table- I. There were three different levels for all four parameters including strut diameter, and three specimen repetitions for each parameters combination. This has brought to altogether 243 specimens in total, being tested in this study, in order to normalize the effects of associated hidden parameters of the Cubepro machine, such as fill spacing and shell layer.

Table- I: Default parameters with different levels

	Default Parameters		
	Layer Thickness	*Print Strength*	*Print Pattern*
Various level combinations	70 µm	Solid (So)	Honeycomb (Hc)
	200 µm	Almost Solid (As)	Diamond (Di)
	300 µm	Strong (St)	Cross (Cr)

B. Testing and Characterization

Lattice structure blocks in this study were tested with compression test at a rate of 1.3 mm/min in compliance to ASTM D695-15 standard test procedure using Instron 5585 compression test machine. The lattice structures produced by the FDM technique were grouped in terms of its strut diameter size. The objective was to study the behaviour of this material with different parameters combinations when it was subjected to static compression load. All specimens were compressed up to densification stage, and the conditions of lattice structure materials were observed after they were compressed. The observation was done by using a portable optical microscope, as schematically shown in Fig. 2.

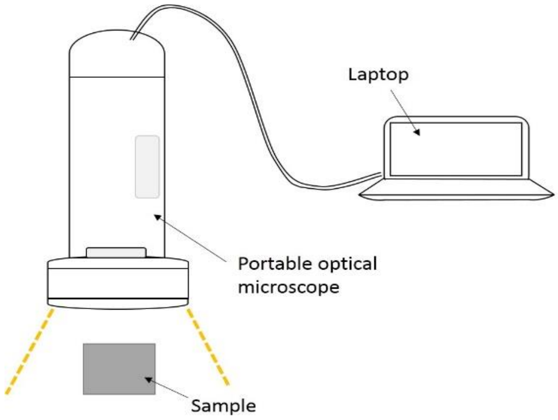

Fig. 2. Portable optical digital microscope.

III. RESULTS AND DISCUSSIONS

Fig. 3 (a), (b) and (c) show the stress-strain curves of the lattice structure samples with 1.2, 1.4 and 1.6 mm diameters of strut, respectively. The curves were comparable with the deformation pattern defined in [21]. Similar continuous pattern of stress-strain curves were observed, and in this study they were grouped according to their respective diameters of struts as in the figures.

As can be observed, there were two significant parameters that had influenced the results of lattice structures in this study which were layer thickness and strut diameter. By comparing all the graphs for each strut diameter, it can be concluded that the larger diameter of strut possessed higher compressive strength. There were three significant groups that have been highlighted by three different colours representing three different layer thicknesses. This confirms that the layer thickness had influenced on the properties of FDM 3D-printed lattice structure materials [16]-[18].

Curves in Fig. 3 show that all 3D-printed lattice structures were having similar flat plateau regions, which suggest that these materials were having the ability to absorb energy during compressive loading, although the curves were not really comparable to those of bending-nominated cellular material [8]. This type of curves was similar to that defined as stretch-dominated cellular as explained in [8], which is a good characteristic for lightweight application. Stretch-dominated behavior makes for the best choice of lightweight applications [10] meanwhile the bending-dominated behavior is most suitable to be utilized in an energy absorbing applications [8]. In regards to lattice structure behavior in this study, it can be concluded that the material is more suitable at the present time to be used in energy absorbing applications. The summary of compressive test results in this study is tabulated in Table- II.

Table- II: Summary of the ABS lattice structure compression test results

Diameter of strut (mm)	Layer thickness (µm)	Young's modulus (MPa)	Yield strength (MPa)
1.6	70	88.99 – 101.29	6.70 – 7.00
	200	49.86 – 67.58	3.50 – 4.00

	300	9.50 – 20.55	1.12 – 1.39
1.4	70	64.66 – 75.28	4.70 – 5.00
	200	26.43 – 34.58	1.75 – 2.10
	300	7.90 – 10.59	0.65 – 0.72
1.2	70	30.32 – 39.11	2.30 – 2.70
	200	12.33 – 15.14	0.90 – 0.95
	300	3.81 – 5.13	0.31 – 0.35

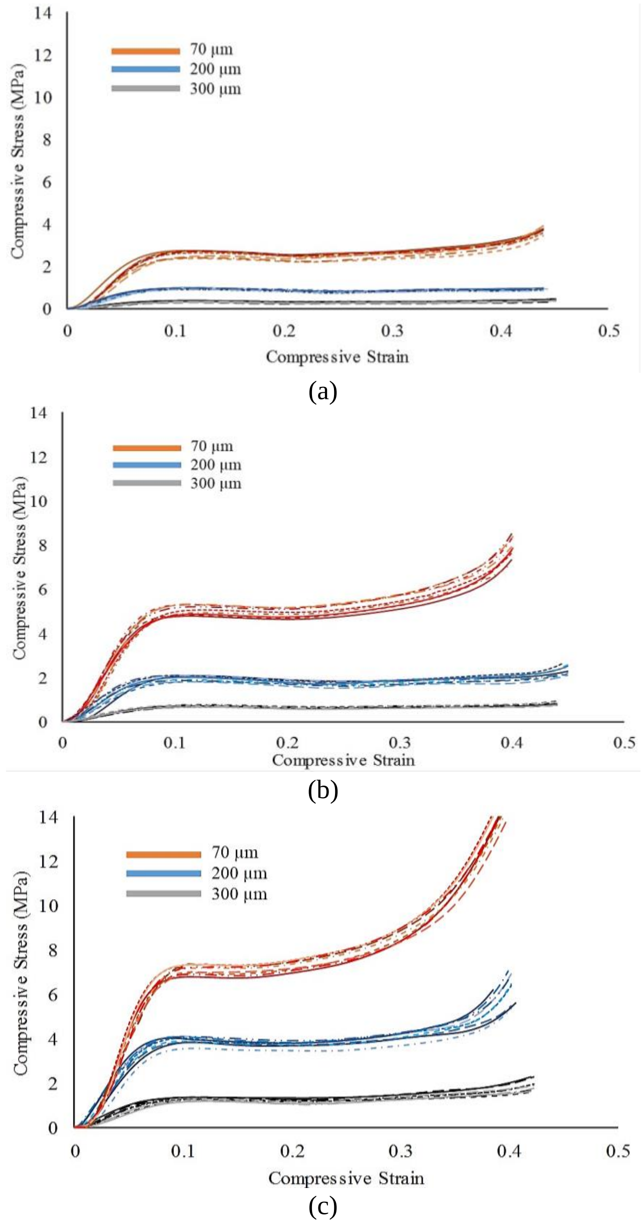

Fig. 3. Stress-strain curves for lattice structures with strut diameters of a) 1.2 mm; b) 1.4 mm; and c) 1.6 mm.

The compressed lattice structure blocks in this study exhibited similar failure behavior for all samples. Fig. 4 represents the typical crushed behavior of the lattice structure block after compression test. It can be observed that the lattice structure block failure was initiated from the middle area (during 25% crushed) of lattice structure block and dispersed to the upper and lower parts of the block simultaneously (during 50% crushed).

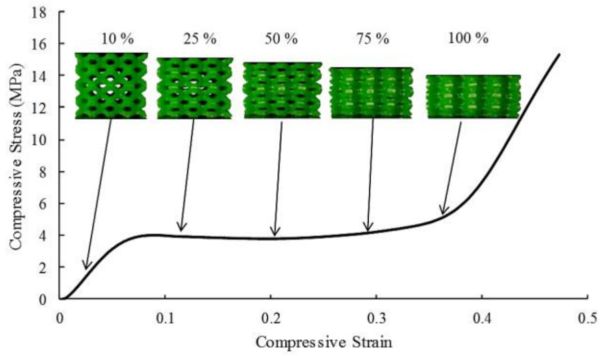

Fig. 4. Crush behaviour of FDM ABS lattice structure.

Fig. 5 shows the image of a compressed lattice structure block that can justify the failure that has taken place in contributing to the whole collapse of the lattice structure block. The failure occurred mainly at the node area with no significant evidence that it was originated from the struts. This can be due to the designed diameter of strut in this study which was rather thick as compared to that of microlattice material that was studied in [21]. It was reported in [21] that failure had occurred in their micro-lattice struts due to concertina effect during compressive loading.

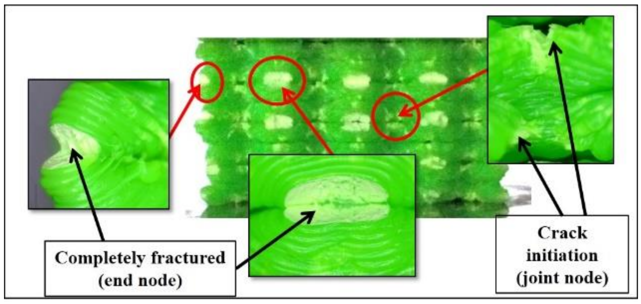

Fig. 5. Close up image of failed lattice structure block.

There were two types of nodes that can be discussed in this current study of FDM printed ABS lattice structure material, which were the joint node and the end node. The joint node denoted the nodes that were connecting the struts within lattice structure block, whereas the end node signified the nodes at the sides and edges of lattice structure block. The fractures that had occurred at these two nodes behaved differently and this can be seen in Fig. 5. The failure at the joint node began with crack initiation at the center of the node area and it had not entirely fractured at the densification stage.

Fig. 6 illustrates the failure mechanism in this area. Due to bending of struts during compressive loading, the area where struts and node had been joined, did experience tensile stress which caused the initiation of crack that was developed until a few layers before the propagation stopped at densification stage. On the other hand, different mechanism was found at the end node where the node had completely fractured. It can be seen from the end node failure behavior that the fracture was due to the delamination between the strut layers.

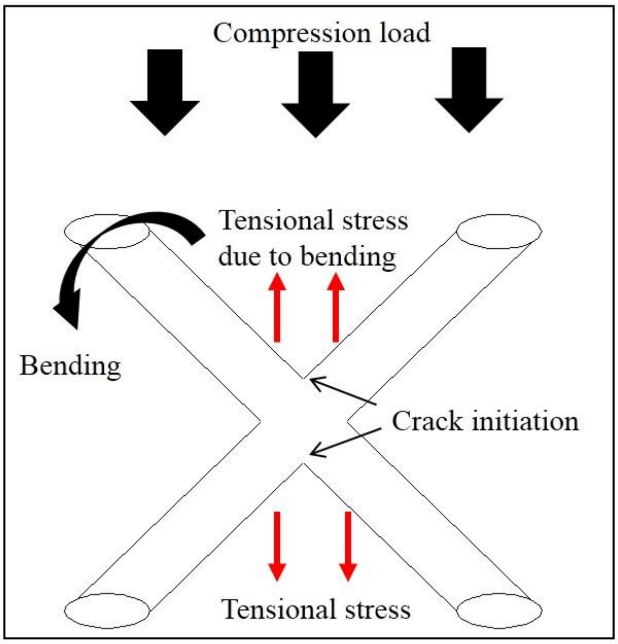

Fig. 6. Schematic representation of a failed lattice structure unit cell at the joint node area under compression loading

IV. CONCLUSION

The ABS lattice structure material deforms steadily under compression load, with continuous pattern of stress-strain curve. The failure starts at joint area between struts and nodes, where tensile stress exists, which causes the initiation of crack that propagates densification stage. The ABS lattice structure material that can be realized using the FDM 3D printer is seen to be a promising candidate for daily used impact absorbing material. Future related studies is underway to fully understand the failure mechanism and characterize the load bearing capabilities of the material.

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