PRELIMINARY STUDY ON THE NATURAL FREQUENCY OF ADDITIVELY MANUFACTURED BCC LATTICE STRUCTURE WITH HOLLOW STRUTS

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ABSTRACT

Lattice structure has drawn much attention to researcher due to its vast advantages such as lightweight and high strength to weight ratio. This study presents the preliminary study on the effect of hollow struts of body-centered-cubic (BCC) lattice structure on the natural frequency values vibration characteristic. The samples in this study were made by using fused deposition modeling (FDM) additive manufacturing into cubic and bar samples for compression and vibration test respectively. As expected, through compression test, it was found sample with highest solid strut diameter produced the highest stiffness value followed by hollow strut of the same strut size with 2 mm wall thickness and lastly solid sample with smaller strut diameter size. Meanwhile from vibration test it was found sample with hollow strut produced comparable natural frequency values as sample with highest strut diameter size despite of smaller stiffness. These results suggest that in order to have higher natural frequency values, hollow struts lattice is preferable as it can produce similar natural frequency values with adequately less mass which in the end can reduce cost and material consumption.

KEYWORDS: Lattice Structure, 3D Printing, Additive Manufacturing, Natural Frequency & Compression

Received: Jun 10, 2020; **Accepted:** Jun 30, 2020; **Published:** Jul 21, 2020; **Paper Id.:** IJMPERDJUN2020399

1. INTRODUCTION

Lattice structure is one type of cellular structure made up of interconnected network of plates or struts that exist in many forms ranging from natural to human made (Gibson et al., 1999). Lattice structures was initiated from the approximation approach of the foam cellular structures (Hasan, 2013). Lattice structures is periodic structure that are constructed from periodically repeating unit cells and can be considered the improved version of foam structure as it eliminates the uneven mechanical performance of foam structure (Ashby et al., 2000; Ashby, 2006; Cheung et al., 2013). Besides that, lattice structure is also isotropic unlike that of honeycomb's anisotropic behavior as the strength of honeycomb structures is drastically declined when the force exerted is in plane to the honeycomb structures (Cricri et al., 2013).

Early days of fabrication of the lattice structure was through the conventional manufacturing techniques such as investment casting, hot press method, wire lay-up etc. (Wadley, 2006; Zhang et al., 2012; Lou et al., 2014; Li et al., 2015; Yin et al., 2011). These methods although still work, it can severely restrict the design freedoms of lattice structure due to its principles and limitations. The emergences of additive manufacturing techniques since 1980's pioneered by stereolithography (SLA) technique, enables higher degree of design freedom where the cell size design parameter now can be made into wider range from large to micro scale lattice structures (Hasan, 2013). The exploration on the potential of lattice structures can be done by greater extent as additive manufacturing opens up new opportunity due to its higher degree of design freedom, various materials availability from polymers, metals

and alloys based and wider range of size availability from macro to micro which is nearly not possible with the use of the conventional manufacturing techniques (Chua et al., 2007; Adam et al., 2014; Ngo et al., 2018).

The exploration on the behavior of lattice structures are usually done through either variation of design parameters or printing process parameters of additively manufactured lattice structure. This is because of the high influence of different design such as topological designs, unit cell's size, variable wall thickness of hollow struts lattices etc. as well as different printing process parameters such as layer thickness, pattern, infill density etc. have different effect on the performance of lattice structure (Azmi et al., 2018). Queheillalt et al., (2005) studied diamond "textile" lattice truss structures with hollow struts and found that to be significantly stronger than their solid truss counterparts. This is because hollow struts have higher second area moments than solid struts. Besides that, Queheillalt et al., (2005) explored the compressive strength of pyramidal lattice structures with hollow struts/trusses made by using the lay-up process conventional manufacturing technique. They found that the compressive strength of a hollow lattice with a relative density of 2.8% was approximately twice that of a solid pyramidal lattice of similar relative density. A more recent study by Wang et al., (2018) then explored the lattice structure with hollow struts of variable wall thickness manufactured using additive manufacturing and improved the design efficiency by developing a new generative design method where the wall thickness of struts are varied to obtain the optimal materials distribution by means of a mapping method, which avoids complex topology optimization. Therefore, preliminary study was conducted to see the behavior of the lattice structure produced by using fused deposition modeling (FDM) additive manufacturing on natural frequencies values in the dynamic vibration testing as well as compression test.

2. EXPERIMENTAL PROCEDURES

2.1 Sample Fabrication

Two solid and a hollow struts lattice structure samples based on body centered cubic (BCC) topological design with unit cell size of 160 x 40 x 20 mm in the 8 x 2 x 1 configuration were made for vibration testing by utilizing the CubePro FDM 3D printer. Meanwhile, cubic sample of 20 x 20 x 20 mm in the 2 x 2 x 2 configuration were made compression test. The default process parameters' combination of 200 μm layer thickness, solid print strength and diamond print pattern were used for all cubic samples. The sample details as tabulated in Table 1. All samples were made from acrylonitrile butadiene styrene (ABS) material density, $\rho = 1.05 \text{ g/cm}^3$. Figure 1 shows the illustration of tessellated lattice structure, one-unit cell lattice structure and the outer and inner diameters of the struts.

Table 1: Cubic lattice structure sample details

Sample	Layer thickness (μm)	Print strength	Print pattern	Outer diameter (mm)	Inner diameter (mm)
4 mm	200	Solid	Diamond	4	0
5 mm	200	Solid	Diamond	5	0
5'3 mm	200	Solid	Diamond	5	3

Figure 1: An illustration of tessellated lattice structure, one-unit cell lattice structure and the outer diameter (D) and inner diameter (d) of the struts

2.2 Compression Test

Cubic samples were compressed using universal compression test machine, the Instron 5585 following ASTM D695-15 as guideline. The schematic diagram of compression is shown in Figure 2. The compression test was carried out by applying axial compression at speed rate of 1.5 mm/min until densification of the samples occurred. The readings acquired from the test were recorded using Blue Hill software. Three compression tests were carried out for sample and the average force and displacement were used in the plot of force against displacement.

Figure 2: Schematic diagram of the compression machine

2.3 Vibration Test

Vibration experiments were carried out to find the natural frequency values of each lattice structure bar. The experimental set-up for vibration measurement consisted of Dataphysics Quattro as signal generator and analyzer, impact hammer and accelerometer sensor to measure the vibration amplitude. Each bar sample was clamped to a solid test rig at one end. A schematic layout of the experimental setup is shown in Figure 3.

Figure 3: Schematic diagram of the vibration set up

3. RESULTS AND DISCUSSIONS

3.1 Compression Testing

The results of the compression tests for each strut diameter were averaged and plotted into force against displacement graph. Figure 4 shows the force-displacement plots of averaged results of compression for each cubic sample. The values of mass and stiffness for each sample then tabulated into Table 2. For the ease of understanding, area moment of inertia of a cross sectional area of single strut is also calculated and tabulated in Table 2 where for sample 5'3, the area moment of inertia is calculated by simply subtracting the moment of inertia of inner diameter from outer diameter. Figure 5 shows the cubic sample undergoes compression. Meanwhile Figure 6 illustrates the cut-up version of Figure 4 which shows the linear part of the graph where the gradients of the linear part provide the stiffness.

Figure 4: Force-displacement plots for compressed cubic samples

**Figure 5: Cubic sample undergoes compression showing (a) sequential struts collapse
(b) complete struts collapse before densification**

From Figure 4, it can be seen at low displacement region, linear elastic behavior was shown where the gradients of each plots provide the stiffness. The linear elastic region ended when plastic collapsed. The plots followed by fluctuated curves where the lattices destruct in a sequence as the struts layer collapses, each with its own linear elastic region up to densification region due to collapsed cells being forced into contact leading to huge jump in stiffness (Maskery et al., 2017). Based on the cut up linear part in Figure 6, it can be seen that the 5 mm sample has the highest gradient followed by 5'3 mm sample and lastly 4 mm sample.

Figure 6: Illustration of cut-up linear-elastic part from force-displacement plots

Table 2: Mass, calculated area moment of inertia and stiffness of samples. Calculated area moment of inertia is calculated for cross sectional area of a single strut

Sample	Mass (g)	Calculated area moment of inertia, I ($\times 10^{-11} \text{m}^4$)	Stiffness (kN/m)
4 mm	9.71	1.2566	190.638
5 mm	14.84	3.0680	519.534
5'3 mm	11.51	2.6704	368.227

From Table 2, the values showed that the 5 mm cube sample exhibit 92.62% higher percentage different in stiffness when compared to 4 mm sample and just 34.09% higher stiffness when compared to sample 5'3 mm. This result gives insight that sample 5'3 has higher strength to weight ratio as compared to 4 mm sample as it produced 63.55% higher percentage different stiffness with only 16.97% higher percentage different in mass. The trends of stiffness are

consistent with the calculated area moment of inertia of a cross sectional area of single strut. The trend of stiffness is similar with other study conducted by Syam et al.,(2018) where lattice samples with higher moment of inertia has higher stiffness values.

3.2 Vibration Testing

The accelerance FRF and bode plot graphs for sample with 4 mm, 5 mm and 5'3 mm were plotted using MATLAB software and shown in Figure 7, Figure 8 and Figure 9 respectively. The first two natural frequency values were also tabulated into Table 3. It can be seen on all three Figure 7, Figure 8 and Figure 9, that the bode-plot has sharp phase shift 90° angle at resonant frequency.

Figure 7: FRF graph and bode plot for sample 4 mm

Figure 8: FRF graph and bode plot for sample 5 mm

Figure 9: FRF graph and bode plot for sample 5'3 mm

Table 3: Vibration test results and mass of lattice cube samples

Sample	Mass (g)	Natural Frequency (Hz)	
		1st Mode	2nd Mode
4 mm	19.566	40.0	225.0
5 mm	29.799	55.0	315.6
5'3 mm	23.115	55.0	321.0

Based on Table 3, it can be seen that the 5 mm sample exhibited similar first mode natural frequency values with sample of 5'3 mm struts and slightly lower second mode natural frequency to that of 5 mm sample. Meanwhile, as expected sample with 4mm strut exhibited the lowest both first and second modes natural frequency values. Equation (1) shows the formula of natural frequency where ω_n is the natural frequency (Hz), k is the stiffness (N) and m is mass (kg).

$$\omega_n = \sqrt{\frac{k}{m}} \quad (1)$$

Based on equation (1), the mass of the lattice structure cellular material bar samples is supposedly inversely proportional to the natural frequency (i.e. an increase in mass will lower the natural frequency). However, the from sample 5'3 mm and 4 mm showed otherwise. Thus, this suggests that despite an increase in mass of the lattice structure from sample 5'3 mm and 4 mm, the stiffness component of the lattice structure is more significant compared to the mass component of the lattice structure cellular material bar samples. Nonetheless, despite having higher stiffness for sample 5 mm, the natural frequency values are comparable to that of 5'3 mm as it is lighter. These results suggest that in order to have higher natural frequency values, hollow struts lattice is preferable as it can produce similar natural frequency values with adequately less mass which in the end can reduce cost and material consumption.

4.CONCLUSIONS

Through the hollow strut design parameter with (2mm wall thickness), comparable natural frequency to that of solid strut counterpart can be achieved. This shows that the variable wall thickness design parameter has significant influence to the natural frequency values. Although from the compression test, the hollow sample 5'3 produced less stiffness. However, due to smaller mass value, similar natural frequency can be achieved. The results suggest that in order to have higher natural

frequency values, hollow struts lattice is preferable as it can reduce cost as well as material consumption for sustainability.

ACKNOWLEDGEMENT

The authors acknowledge the financial support from Zamalah Scheme, Universiti Teknikal Malaysia Melaka.

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