FAILURE MODE ANALYSIS OF KAGOME LATTICE STRUCTURES

GAUTAM RINOJ
Singapore Centre for 3D Printing, School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore.

SRIDHAR IDAPALAPATI
Singapore Centre for 3D Printing, School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore.

STEFANIE FEIH
Singapore Institute of Manufacturing Technology (SIMTech), 71 Nanyang Drive, Singapore 638075, Singapore

ABSTRACT: Ultralight weight structures are today's essential need in aerospace, marine and automotive industries. Strength and stiffness optimization of load bearing structures is made possible with the evolution of additive manufacturing technologies through shape or topology optimization. Further composite materials and sandwich constructions reduce the design weight. To fully realize the lightweight structure, core designs with low density and high strength are necessary for sandwich panel design. In this study, the performance of the 3D Kagome truss core structure in compression loading is experimentally investigated. These bio-inspired core structures are fabricated by Fused Deposition Modelling (FDM) with Acrylonitrile butadiene styrene (ABS) ABSplus® material for experimental validation purposes. The geometrical parameters of the Kagome structure in terms of its slenderness ratio are varied to study the switch of failure mechanism from yielding dominant behavior to buckling. The effective stiffness of the truss found from finite element modeling and based on experimental results are compared, and the reasons for their discrepancy are explored. The modulus of the Kagome unit-cell is found to be linearly related to its relative density. The result show that with the increase in the slenderness ratio (*l/r*), the strength of the Kagome structure decreases.

Keywords: Fused deposition modelling, Kagome structures, yielding and buckling, finite element analysis.

INTRODUCTION

Lightweight structures are the common need in the aerospace, marine and automotive industries. Sandwich structures are used in weight critical applications which have the features of low weight with high strength and high energy absorption. The core structure plays a crucial role in defining the performance of the sandwich structures. Different honeycombs as well as other open core structures are used. The manufacturing limitations of conventional techniques for producing different complex structures are solved by the introduction of additive manufacturing technologies. With the advancement of additive manufacturing, different design possibilities of core structures have come to reality. With that, the recent studies in different core truss and lattice structures have increased in tremendous amount.

There are different types of lattice structures that are being studied. Shen et al. (2009) investigated the mechanical properties on different lattice structure configuration and found that the compressive properties are better with the one having the vertical strut. Gümrük et al. (2013) studied the static mechanical behavior and found out that the imperfections in processed structure

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are more detrimental to the mechanical behavior in shear loading than compression and the shear test showed no repeatability. Markkula et al. (2009) studied the compressive behavior of different ABS plastic lattice structures produced by fused deposition modelling. They found the optimum slenderness ratio for the studied structures and demonstrated that strut reinforced tetrahedral performed best among the studied structures.

The performance of Kagome truss structure has been studied by different research groups. Hyun and Torquato (2002)found that the 2D Kagome structure was structurally efficient with further desirable properties like heat dissipation characteristics, ease of fabrication, etc. Hyun et al. (2003) also simulated the Kagome and tetragonal truss core panel and predicted that the Kagome has the greater load bearing capacity and is superior in terms of core panels than tetragonal structure. The main reason for this is that Kagome structure behaved isotropically after yielding, and has strain hardening and was more resistant to plastic buckling in compression and shear. Wang et al. (2003) proved this simulated finding with experimental results and validated that Kagome structure outperforms tetrahedral and pyramidal cores. Lee and Kang (2010) explored the compressive behavior of wire woven bulk Kagome truss core with the variation in diameter, strut length and number of layers. They found that with increase in layers, strength decreases gradually. They also found that compressive strength and energy absorption capacity of Kagome structure outperformed other cellular structures such as aluminum foams, egg box structures, etc. Ullah et al. (2014) investigated the deformation and failure of Kagome truss core structure in compression and shear and successfully predicted their behavior through finite element simulations. They also found that Kagome structure performed better than honeycomb structure in terms of specific strength for compression and shear.

In this work, the compressive behavior of Kagome structure fabricated by fused deposition modeling with different slenderness ratio is studied. The effect of the variation in the slenderness ratio on the elastic modulus and compressive strength is measured experimentally and compared with numerical simulations. The imperfections in the fabricated structures have great effects on the mechanical properties.

EXPERIMENTAL DETAILS

Design and fabrication

Kagome cell structure is formed by the pair of tetragonal structure lying vertically inverted with each other as shown in Figure 1. The geometric parameters governing the given Kagome core structure are its height (h), diameter of the strut (d), and the internal angle (θ). Internal angle is the angle made by the struts with the face sheet. In this study, the height of the structure is 35 mm whereas internal angle is 55^0.The Kagome core structures with four different truss diameters (precisely 1.2 mm, 1.5 mm, 2mm, and 2.5mm) with the face sheets of 4 mm were modeled in a CAD package.

ABSplus® plastic is used as the material and the structure is fabricated through fused deposition modeling (FDM). First, the three-dimensional Cad model is created in the SolidWorks and the .STL format file is send to Stratasys Dimension Elite for the fabrication. The orientation of parts during the printing also plays the vital role in the mechanical properties. The parts are fabricated with the faceplate normal to build platform as shown in Figure 1. Layer resolution of 0.178 mm with the solid part fabrication with surrounded support material parameters are set in the machine before the start of the fabrication.

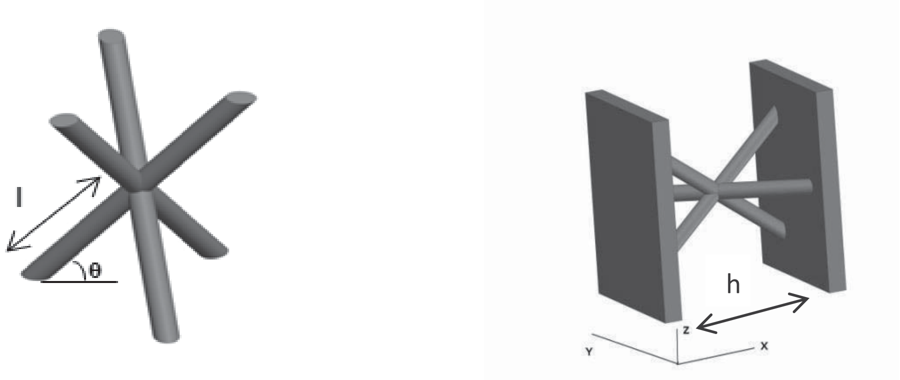

Figure 1: Kagome truss unit cell and orientation of structure in build platform

Mechanical testing

The compression tests on single Kagome truss core are carried on the Simazdu universal testing machine (UTM) using a 10kN load cell. The tests are carried out under displacement control at the crosshead speed of 0.1 *mm/min* to obtain the compression behavior. Before the compression test, the faceplates are made smooth and parallel through polishing on emiry paper. The extension during the test is measured using a video extensometer. The tests are carried out on different samples with different diameter in other to find the compressive behavior with different slenderness ratio.

Numerical simulation for compression testing is carried out using commercial finite element package Abaqus® version 6.14. The material properties modulus of elasticity *E=2200 MPa* and Poisson's ratio of 0.35 were used.

RESULTS AND DISCUSSION

The measured force (F) versus displacement data is converted into compressive stress ($\sigma = F/A_{face}$) versus compressive strain $(\varepsilon = \Delta h/h)$ for the unit cell. A_{face} is the effective cross sectional area supported by Kagome unit cell and is given by $2\sqrt{3}l^2$ where l is half the total length of strut. The compression strength and the modulus of elasticity were calculated using the force and cross head displacement respectively.

Figure 2 shows the compressive stress vs strain diagram with the different truss radius. It is clearly seen from the graph that the strength and the modulus increase with the increase in radius of the truss. From the graph, it is seen that the different failure behavior of the Kagome lattice structure occur with the change in radius hence the slenderness ratio (l/r). The core with radius 1.2 mm fails by buckling without reaching the yield whereas the one with higher radius has reached the yield and maximum strength and failed after the yielding. So, with increase in the radius (i.e. decrease in slenderness ratio), the strength, modulus of elasticity increases with the expense of increase in weight. The struts also fails by buckling before reaching its yield point with high slenderness ratio whereas low slenderness ratio struts fail by yielding.

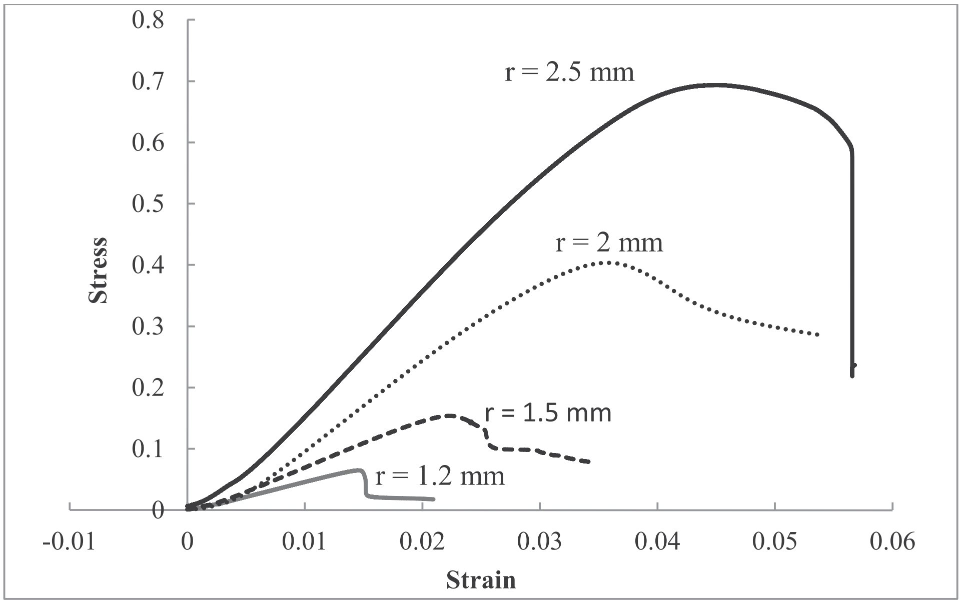

Figure 2: The compressive behavior of Kagome structure with variation in radius of truss

The Kagome cell compressive Young's modulus in terms of cell relative density $\bar{\rho}$, solid cell wall material Young's modulus E_s and truss angle θ is given by (Ullah et al. (2016)):

$$E_{cell} = E_s \bar{\rho} \left(\sin^4 \theta\right) \tag{1}$$

Table 1 lists the relative density of designed Kagome truss structures used in the study both analytically and the measured ones, respectively. In Table 1, there are two different relative densities. One is obtained from the calculated unit mass cell with the help of volume and density whereas the other is obtained from the measured mass. Note that the measured relative density is lower than the analytically calculated value. There is variation in diameter as well as printed truss have several stairs like structure due to the inclination of the truss in Kagome structure. The part produced are not perfectly solid thus has less mass than expected reducing the relative density.

Table 1: Relative density of the Kagome unit truss obtained from calculated and measured cell mass

Truss radius (mm)	Calculated unit cell mass (g)	Calculated Relative density ($\bar{\rho}$)	Measured unit cell mass (g)	Measured Relative density ($\bar{\rho}$)
1.2	0.603	0.0105	0.320	0.0056
1.5	0.942	0.0164	0.539	0.0094
2.0	1.675	0.0291	1.023	0.0178
2.5	2.617	0.0455	1.595	0.0277

Figure 3 shows the relation of stiffness of the truss cell with the relative density. In Figure 3(a), predicted analytical stiffness and numerical simulated results are plotted against the calculated relative density whereas Figure 3(b) shows the graph of analytically predicted and experimentally obtained stiffness in relation to measured relative density from Table 1.

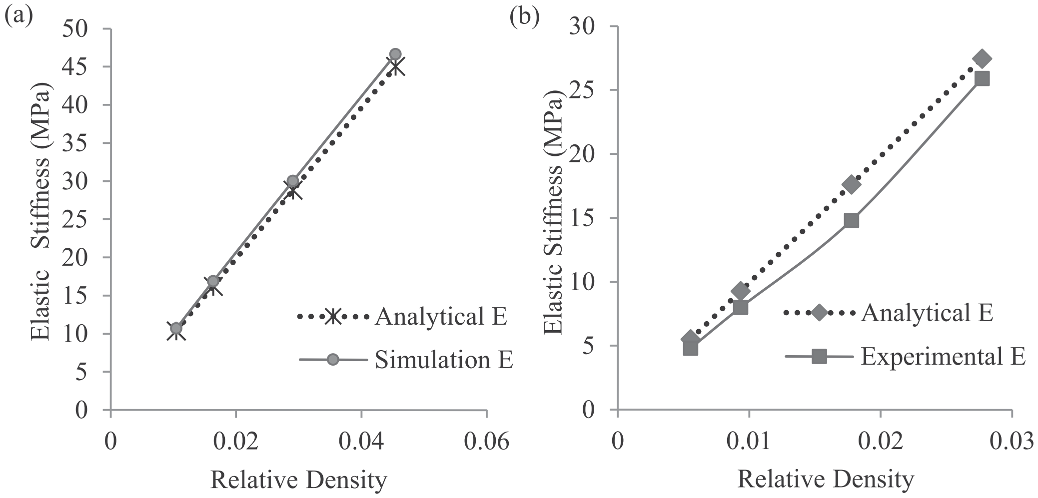

Figure 3: Comparison of elastic stiffness (a) analytical and simulation value and (b) analytical and experimental value

The analytically predicted with calculated mass and numerically simulated results are nearly equal as depicted in Figure 3(a). But there is a significant difference in between numerically simulated result and the experimental results (see Figure 3(a) and (b)). The numerical results are more conservative as they assume fully solid and uniform diameter. This resulted in the high stiffness value but in reality the structures fabricated were not fully solid and also not perfect with variation in diameter due to stairs effect while printing. But analytical solution obtained after the measured mass and the experimental results are similar. The elastic modulus is linearly dependent to the relative density as given by equation (1) and verified through the experimental measurements and numerical simulations for the Kagome structure. The variation in the diameter and the imperfection has vital effect in the modulus and strength in the additively manufactured parts (Ravari et al. 2014).

CONCLUSION

In this work, Kagome structures with unit cell with different truss radius are fabricated in FDM and their compressive behavior is investigated. With the increase in radius (decrease in slenderness ratio) the compressive strength and the Young's modulus of the structure increases. Similarly, the failure behavior also changes from the buckling mode to yielding. As the calculated mass and the measured mass of the core structures differ, relative density too differ thereby the different simulation and experimental results are obtained. However, the analytical prediction and experimental solutions are similar with the measured mass. Henceforth, the proportional relation of elastic modulus with relative density is verified numerically and experimentally.

Future works include the investigation for precise slenderness ratio with which the structures change their failure behavior from buckling to yielding. Also, the investigation of mechanical behaviors with multiple units as well as multilayer structure will be carried out.

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