

Finite Element Analysis Study on Lattice Structure Fabricated Recycled Polystyrene from Post-used Styrofoam Waste.

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Abstract. Lattice structure design widely applicable for 3D printed components. This research investigated the lattice structure with different shape and relative density using Finite Element Analysis (FEA) simulation. The material used for the lattice structure was the recycled polystyrene made from post-used Styrofoam. The research assessed the mechanical behaviour of lattice structure with either triangular prism and square prism with FEA simulation and numerical mathematical modelling, such as stiffness to-mass ratio, maximum von Mises stress and effective Young's modulus. The finding FEA shows a good agreement with result from numerical mathematic modelling. The FEA results show lattice structure with triangular prism exhibited lowest value of maximum von Mises stress with maximum stiffness-to-mass value compared to lattice structure square prism. The finding from this work provided an early prediction on mechanical properties of lattice structure fabricated from recycled polystyrene.

1 Introduction

In this modern age, additive manufacturing (AM) is an advanced manufacturing method used in developing prototypes, parts of end-use, and tools for production line. AM is widely adopted by many industries such as aerospace, automotive and medical industries, due to its many benefit, such as shorter product development cycles, able to create component with complex geometry, and reduced fabrication cost and lead time [1-2]. Component with cellular pattern usually fabricated using AM process due to its unique capacities in fabricating part with complex geometry which cannot made by traditional manufacturing process [3]. The Fuse Deposition Modelling (FDM) technology is one of the AM process that widely used because low cost, reliable and easy handle. The materials used for FDM usually are thermoplastic materials, such as polylactic acid, acrylic butadiene styrene (ABS) and recycled plastic [4-5]. From literature, there is a research studied the

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mechanical properties of cellular pattern made by FDM process using ABS material [6]. The study related to cellular pattern made from thermoplastic material using FDM is relatively rare, especially for recycled plastic materials.

Styrofoam also called as expanded polystyrene is type of polymer foam that widely used in industry as packaging material due to its light weight, good heat insulative and cushioning properties [7-8]. Although Styrofoam poses a great property for packaging application, but the disposal of Styrofoam causes a pollution to the ecosystem [9]. The research by Ng et al. [5] found that the Styrofoam waste can be converted into recycled polystyrene (PS), then turn into FDM filament. They found the part printed with rPS filament was about 52% higher stiffness compared to part printed with commercial high impact polystyrene filament, and the strength was slightly lower. The research related to usage of rPS filament was rarely found in any open-source literature. Hence, this study was underway in order to explore the potential of the rPS filament for cellular structure application.

The design of cellular patterns in modern term is called lattice structure. The application of lattice structure in AM is used to enhance the strength-to-weight ratios, decrease the printing time, and increase the energy absorption of the 3D printed component. For lattice structure design, there are two main types of lattice structure, such as stochastic lattice structures which are random structure and non-stochastic which are pattern structure such as honeycomb structures, sandwich panels, triangular prism, square prism and hexagonal prism [10]. Lattice structures are important for industries such as automotive as 10% of weight deduction of the parts which can reduce the fuel consumption of vehicles up to 8% [4]. Nowadays, the Computer Aided Design (CAD) modelling software is typically aimed to designing a part with lattice structure. Then, the FEA simulation allows researcher to evaluate the mechanical behaviour of the lattice structure before fabricating into a real part. Niu et al. [6] studied the mechanical properties of specimen with lattice structure with lattice parameter and prism shape using FEA simulation. The authors found the lattice structure with optimum stiffness-to-weight ratios by using FEA simulation. Hence, the present study also investigates the mechanical properties of lattice structure made from rPS filament using FEA simulation.

This research use FEA simulation to evaluate the mechanical properties, such as effective young modulus, maximum von Mises stress and stiffness-to-weight ratios of the lattice structure made from rPS filament.

2 Methodology

2.1 Lattice structure modelling

Figure 1 shows two types of unit cells, including square prism and triangular prism were designed using strut at the edges. In this search, SOLIDWORKS® 2020 software was used to generate the 3D model of lattice structures. First, a single unit cell of lattice structures was created with square prism and triangular prism as displayed in Figure 1. The unit cell parameters were shaped by length, L , thickness of strut with square cross-section, t , and the height, h . The first single layer of unit cells was obtained by assembling in an in-plane direction by n times, where the distance was equal to the L and t between unit cells. The layer of unit cells was then assembled n times in an out-plane direction, where the distance was equivalent to the h of unit cells.

The method of creating the 3D model for the lattice structure was referring to Niu et al. [6]. The large-scale lattice structures were created with a dimension of 20 mm × 20 mm × 50 mm as illustrated in Figure 2. The square prism and triangular prism lattice structures

were constructed with the relative density (RD) ranging from 20% to 40%. Table 1 shows the geometry parameters of each group of lattice structure with square prism unit cell and triangular prism unit cell. The Relative density (RD) was derived by following Eq.1.

$$RD = \left(\frac{\rho^*}{\rho}\right) \times 100\% \tag{1}$$

Where ρ is the density of the block, ρ^* is the effective density of the lattice structure which can be obtained in SOLIDWORKS[®]. For this research, the thickness of the struts, t , length, L and the height, h were following Table 1.

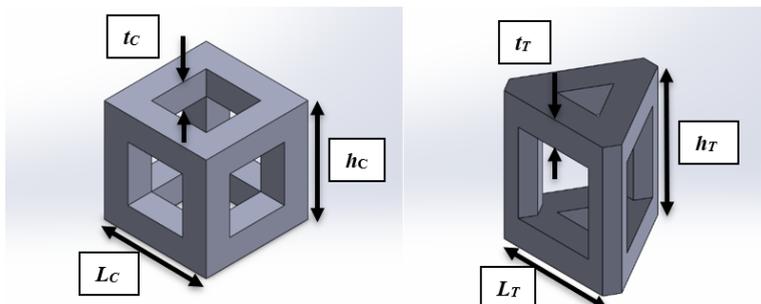


Fig. 1. Square prism (left) and triangular prism (right) unit cells.

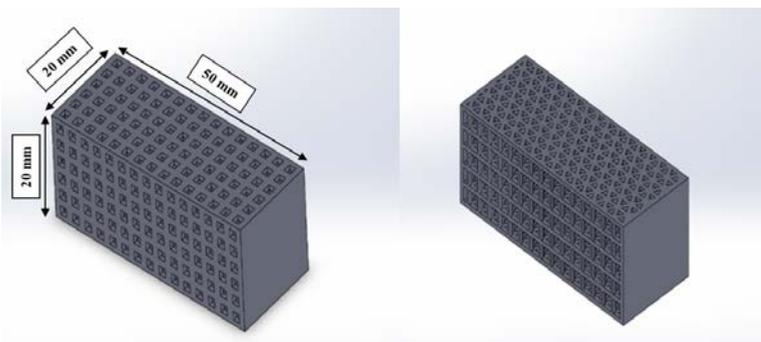


Fig. 2. Block with square prism lattice structure (left) and triangular prism lattice structure (right).

Table 1. lattice parameters of square and triangular cells with the different RD.

Cell Shape	L (mm)	t (mm)	h (mm)	RD (%)
Square	4.75	1.10	4.73	20
	4.75	1.48	4.63	30
	4.75	1.84	4.54	40
Triangular	4.75	0.92	4.77	20
	4.80	1.20	4.70	30
	4.85	1.50	4.63	40

2.2 Finite Element Analysis

The rPS made from post-used Styrofoam waste was used the material for this research. The mechanical data was obtained from study reported by Ng. et al. [5]. The elastic modulus of rPS was 1720 MPa and poisson ratio was 0.35. The density of rPS was 1.045 g/cm³. For simulation, ANSYS[®] 2020R2 version software was analysis the mechanical

properties of the lattice structure, including maximum von Mises stress and maximum total deformation. In this research, the 3D models were assigned with tetrahedron element method as displayed in Figure 3. Then, mesh size was controlled to keep the skewness of model less than 1. The lattice structure block was analysis for its mechanical properties under tension and bending load. From Figure 4, the left end of the lattice structure block was set as fixed support, and the force was applied on the opposite side of the block. In the axial tension analysis, the force, F was applied perpendicular to the selected reference face. In the bending analysis, the force was applied in two directions, including, i) parallel to the height of the lattice structure, h_L force, F_P and ii) perpendicular to the height lattice structure, h_L force, F_V (as displayed in Figure 4). The force applied in all cases was set to 200 N.

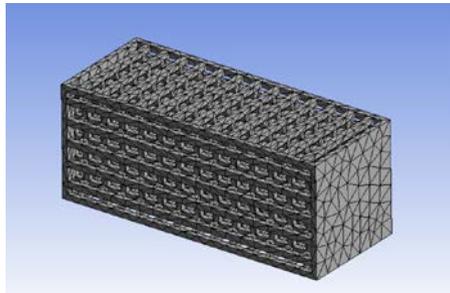


Fig. 3. 3D mode with tetrahedrons mesh method.

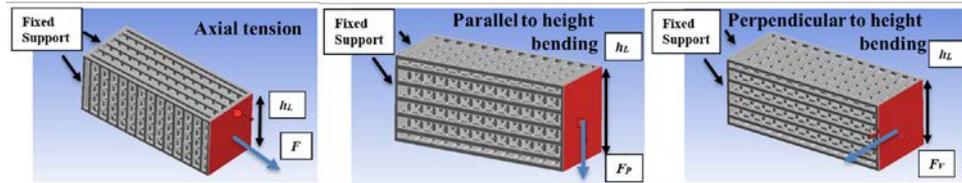


Fig. 4. Boundary condition and different direction of applied force.

3 Result and Discussion

The effective Young’s modulus, E^* was calculated using Eq. (2). Where, σ was the normal stress, ϵ was the axial strain, F was the axial force and A was the cross-sectional area, ΔL was the elastic tensile elongation and L_{Total} was the total length. In the bending analysis, two loading conditions were applied and classified as vertical Force, F_V parallel to the height of the lattice structure, h_L and perpendicular Force, F_P perpendicular to the height of the lattice structure, h_L . The d_V was the maximum total deformation obtained from FEA result. The d_V^* was the predicted displacement based on effective Young modulus, E^* and $\sigma_{V,max}$ was maximum von Mises stress in vertical direction.

$$E^* = \frac{\sigma}{\epsilon} = \left(\frac{F}{A}\right) \div \left(\frac{\Delta L}{L_{Total}}\right) \tag{2}$$

The evaluated stiffness-to-mass ratio value, R_V was used to assess the mechanical properties of the lattice structure and demonstrates the capabilities of these two types of lattice structure with different relative density. The stiffness-to-mass ratio, R_V can be derived from Eq. 3. Where, m^* was the weight of lattice structure which can be calculated from relative density.

$$R_V = \left(\frac{F_V}{d_V}\right) \div m^* \tag{3}$$

Figure 5 displays the effective Young’s modulus, E^* of lattice structures with square prism and triangular prism unit cells. The effective Young’s modulus, E^* increases when the relative density increases for both types of unit cells. When the relative density increased, there would be more the material need to build the lattice structure. As the unit cell size was maintained as close as possible, the increment of strut thickness resulted into higher relative density, thus it poses a beam like structure to be bulky. Furthermore, the lattice structure with triangular prism exhibited higher effective Young’s modulus compared to lattice structure with square prism unit cell.

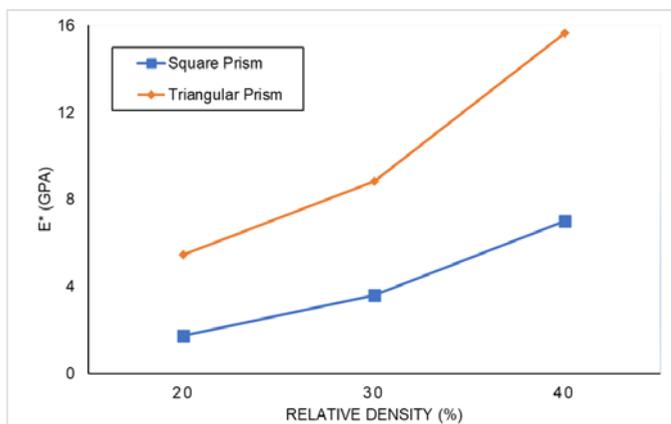


Fig. 5. Effective Young’s modulus, E^* against relative density (RD) for two lattice structures.

Figure 6 shows maximum von Misses stress, σ_{max} of lattice structures with square prism and triangular prism under perpendicular bending force, F_V and parallel bending force, F_P . The increase of relative density resulted in the decrease of maximum von Misses stress. As mentioned earlier, the increases of the relative density resulted in the increase of strut thickness of the unit cells. The increase of overall strut thickness also increases the relative cross section of the block. Thus, the bending stress developed in the block would be decreased as well. Furthermore, the lattice structure with triangular prism unit cell under perpendicular force exhibited lowest maximum von Misses stress compared lattice structure with lattice structure with square prism, even though the lattice structure with triangular prism has smaller struct thickness. In opposite, the lattice structure with triangle prism show highest von Misses stress when lattice structure under parallel bending force. This was because the triangular unit cell gives a good support by stabilizing the forces while only reduces non-load bearing materials by the isolation of struts in the vertical direction as the forces were equally distributed on the triangular struts resulting lowest maximum von Misses stress as the forces does not concentrate in a specific location on the block. Similar observation also found by other researchers [6, 10-12]. As compared between lattice structure with square prism and triangular prism, the lattice structure with square prism exhibited a minimal stress under perpendicular and parallel bending force. This can be explained by the rectangle regularity and symmetry in all the face in the square prism unit cell. Thus, the stress developed on the structure show less different in different direction of bending force.

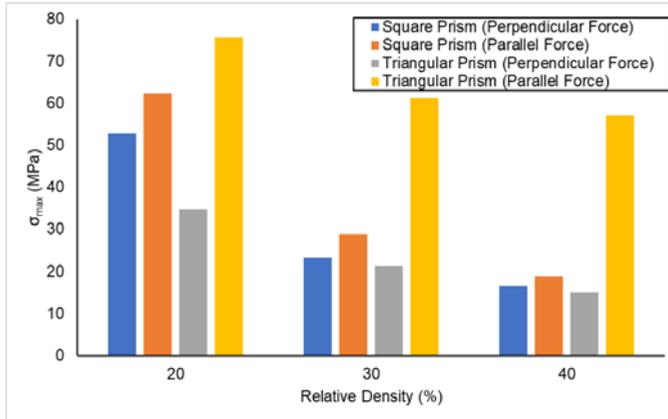


Fig. 6. Maximum von Mises stress (σ_{max}) of lattice structure with square prism and triangular prism in difference direction of applied bending force.

Figure 7 displays the stiffness-to-mass ratio of lattice structure with square prism and triangular prism unit cells under perpendicular bending force, F_v and parallel bending force, F_p . The value of stiffness-to-mass ratio, R shows a proportional relation with the relative density (RD) for lattice structure with different prism shape under different direction of bending force. The FEA results show that the lattice structure with triangular prism unit cells had a higher value of stiffness-to-mass ratio compared to lattice structure with square prism unit cells under different load condition. Overall, the lattice structure with triangular prism unit cell was the better option for building lightweight conformal lattice structures when compared to lattice structure with square prism unit cells.

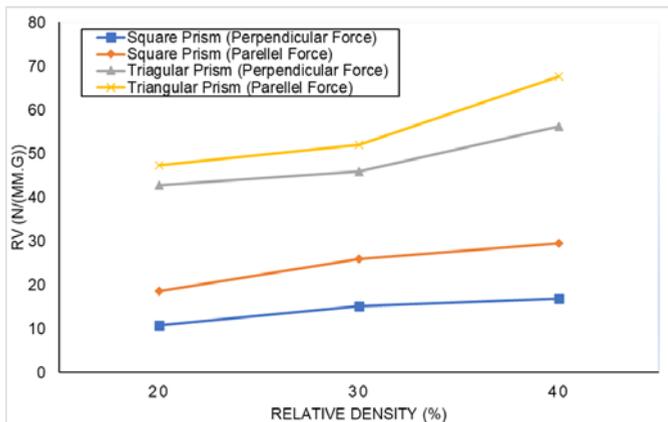


Fig. 7. Stiffness-to-mass ratio of lattice structure with different prism shape and relative density.

4 Conclusion

Lattice structures are used to design lightweight component while maintaining or improving the structural integrity of an object. This study was investigated the mechanical properties of lattice structure with square prism and triangular prism as well as different relative density. The effective Young’s modulus of lattice structure was increased with increase of relative density. Overall, the lattice structure with triangular prism unit cells had a higher effective Young’s modulus, E^* , lower value of maximum von Mises stress and

better stiffness-to-mass ratio compared to lattice structure with square prism unit cells. Future work can be carried out to fabricate the lattice structure using recycled PS filament via FDM process. Then, the experimental finding will be compared to this simulation result.

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