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LATTICE STRUCTURE DESIGN OPTIMISATION FOR ADDITIVE MANUFACTURING USING FINITE ELEMENT ANALYSIS

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ABSTRACT

Additive manufacturing enables the manufacturing of complex forms such as lattice structures. Lattice structures are lightweight and have high-strength mechanical properties, which are suitable for requirements in the aerospace and automotive industries. The aim of this research is to propose an optimised lightweight lattice structure design method. The methodology used in this research consists of conducting finite element analysis on solid CAD models to observe the stress and strain distribution. From the results, an optimised lattice structure design method was proposed consisting of a guideline to choose the optimised lattice structure densities. The proposed design method optimises lattice structure designs by enabling the choice of different relative densities in certain areas of the lattice structure and further reduces its mass. In conclusion, current lattice structure designs for additive manufacturing can be further optimised and reduced in mass by defining optimised densities based on the stress and strain distribution. This outcome contributes to the design of lightweight high-strength parts in the aerospace and automotive industry to reduce fuel consumption and increase performances.

Keywords: Lattice structure, Additive Manufacturing, Mechanical Design, Optimisation, Lightweight Structure, Finite Element Analysis

1.0 INTRODUCTION

Additive manufacturing (AM) is a recent development based from the rapid prototyping technology which existed since the 20th century. The term 3D Printing and additive manufacturing was later introduced to replace the term rapid prototyping as the technology progressed and end-user parts can now be manufactured and is considered as a manufacturing process [1]. It is now possible using AM technology such as Electron Beam Melting (EBM) and Selective Laser Melting (SLM) based on a layer-by-layer manufacturing approach to manufacture parts such as lightweight lattice structures [2,3]. The demands for lightweight high strength parts is important, as it enables to produce lighter automobiles and aeroplanes, consequently, reducing carbon emissions and fuel consumption [4]. Due to new regulations to reduce pollution, designers and engineers are interested in integrating lattice structures in additive manufactured parts to produce lightweight products [5]. Figure 1 shows a CAD model of a uniform cubic lattice structure design.

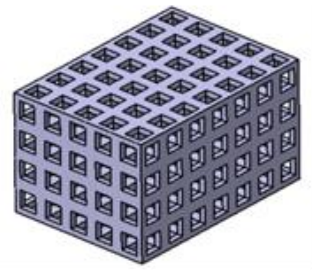


Figure 1 Uniform cubic lattice structure

Lattice structures are considered as a type of cellular structure and architectured material [6], where the geometry of the part is designed to optimise the mass of the structure [7]. Examples of cellular structures are stochastic metal foam, honeycomb structures and lattice structures [8]. Stochastic metal foams and honeycomb structures are widely used in various lightweight applications in various industries. These structures can be effectively manufactured and are cost-effective. The manufacturing of lattice structures using snap-fit [9] and die-casting methods [10] were previously difficult to manufacture and cost-ineffective. Consequently, causing reduced interest in lattice structures compared to stochastic metal foams and honeycomb structures. However, the breakthrough in manufacturing technology opens new horizons in free-form manufacturing and additive manufacturing is capable of effectively manufacturing lattice structures [11,12]. There is increased interest from researchers and engineers in integrating lattice structures in part designs to obtain lightweight high-strength parts [13]. Figure 2 shows a helical gear with periodic lattice structure manufactured using Electron beam-melting (EBM) machine ARCAM [14].

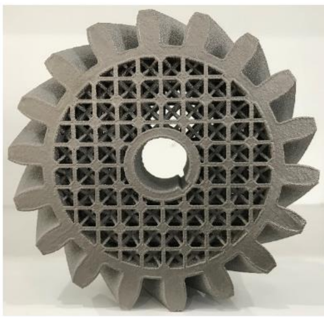


Figure 2 Helical gear with periodic lattice structure manufactured using Electron beam-melting (EBM) machine ARCAM [14]

Lattice structures have high-strength mechanical properties, which depends on the lattice type, density and orientation [15,16]. Previous design guidelines of lattice structures have been proposed. Azman et al. proposed a design guideline to integrate lattice structures in additive manufactured parts based on the use of homogenisation technique to choose suitable lattice structure configurations [17]. However, this design guideline is at an early stage and further improvements are required [18]. For example, in Figure 3, for the design volume given, where the stress distribution is not equal, hence the need optimise lattice structure designs. Recent research have explored the design and mechanical properties of uniform and gradient lattice structures [19]. The objective of this paper is to propose an optimised lattice structure design method to obtain lightweight high-strength parts.

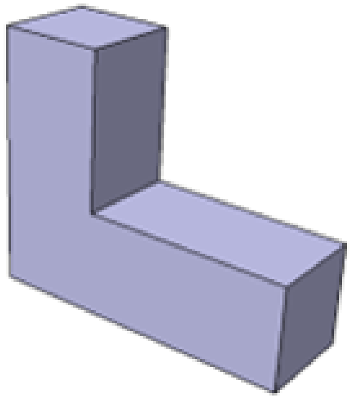


Figure 3 Design volume suitable for lattice structure design optimisation

2.0 METHODOLOGY

The work in this paper is based on the previously proposed guideline presented by Azman and aims to further optimise the method in defining partitions [17]. The methodology used in this research consists first of conducting finite element analysis (FEA) on solid CAD models to observe the stress and strain distribution of the solid model. From the results obtained, an optimised lattice structure design method is proposed consisting of a guideline to strategically define the partitions within the design volume consisting of different lattice structure relative densities. Through the partitions and densities proposed, mass optimisation can be achieved.

The next step consists of conducting finite element analysis on the lattice structure. Four computer-aided design (CAD) models were created: (1) solid structure (2) uniform lattice structure (3) optimised lattice structure 1, and (4) optimised lattice structure 2. The boundary conditions on each CAD model were applied with the same clamp and force. From the results of the finite element analysis, the stress and displacement distribution were observed. From the stress and displacement distribution, new partitions are defined by different volumes according the magnitude of the values. For example, in areas where it exists high stress, a higher density lattice structure is proposed, while in areas where it exists lower stress and displacements, lower lattice structure densities are proposed. New optimised lattice structures are then created, and the same finite element analysis conducted to verify that the new model respects the parts requirements.

The last step of the methodology consists of developing a new guideline to design the optimised lattice structure with different lattice structure densities. The guideline is presented in the results and discussion section of this paper. This guideline enables to further optimise the design of lattice structures and mass reduced, contributing to lighter products and reducing fuel consumption in the automotive and aerospace industry.

The proposed design method optimises lattice structure design by enabling the choice of different relative densities and patterns in certain partitions of the lattice structure and reduces its mass. For example, in areas where there is lower stress, a lower relative density is chosen, whereas in areas with higher stress, higher relative density is chosen.

3.0 RESULTS AND DISCUSSION

In this section, the results which is the proposed optimised design guideline is explained. Then a case study of the implementation of the design guideline is presented.

3.1 Proposed optimised design guideline

Figure 4 presents the new proposed guideline which was developed to optimise the design of lattice structures. It is a guideline to transform a solid structure model into an optimised structure of lattice composition. A solid model serves as the initial design of the concerned structure. The model provides the datum of stress distribution during the structural analysis stage. Therefore, it is important to have a well-defined model to undergo the optimisation.

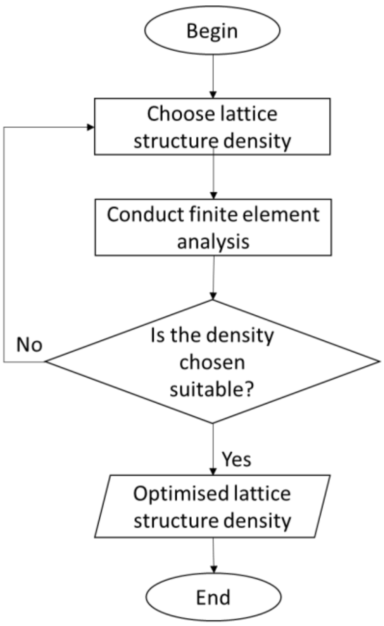


Figure 4 Proposed guideline to design the optimised lattice structure

The definition of the initial model must be clear with the tolerable and intolerable criteria during optimisation such as the acceptable displacement if a load is applied. In certain cases, the mass reduction is the main quality that needs to be controlled. Other aspects that should be considered are the magnitude of load, its direction and the functional surfaces and clamps which are classified as the boundary conditions.

The divisions of the partitions can be conducted by distinguishing the areas of high and low stress. The partitioning is then followed by modelling of the individual partitions using the most suitable lattice structure pattern and density. The structural analysis will then provide the data of maximum stress and displacement of the optimised model. There can be enhanced options if the data obtained from the first optimised model is not satisfying enough. A continuous refinement of the partitioning process can occur to produce more options of lattice structure design with enhanced properties. This will provide more flexible choices to the designers according to their preference in the product's function.

3.2 Case study: Implementation of the proposed design guideline

The case study conducted to implement the design optimisation guideline is presented in this subsection. First, the design volume and boundary conditions were defined. An 'L' shaped design volume was chosen with a clamp at the top surface (A) and a distributed force downwards applied on surface (B), as shown in Figure 5. The maximum displacement allowed it 0.2 mm. A finite-element analysis was conducted on the CAD solid model to observe its stress distribution.

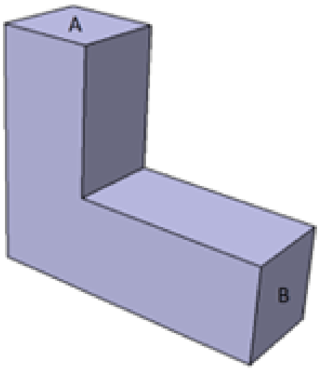
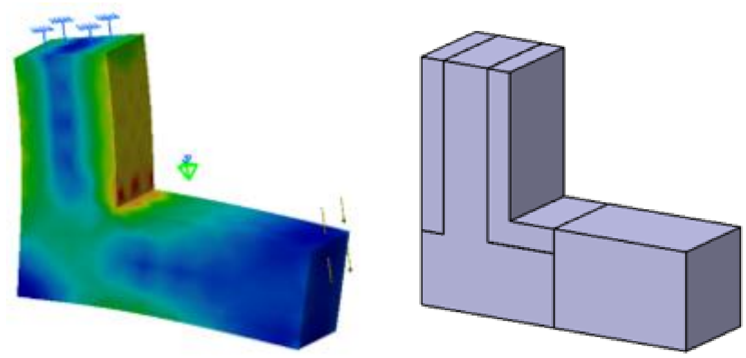


Figure 5 L shaped design volume

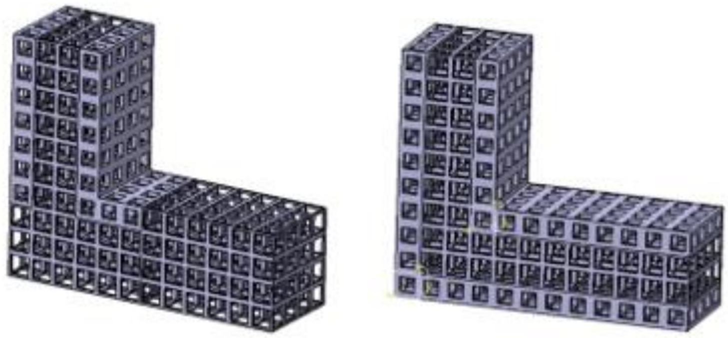
The next step consists of choosing the optimised density based on the stress distribution of the solid model. In this example, four densities and partitions were proposed. In areas consisting of lower stress, a lower lattice structure density is chosen, whereas in higher stress areas, higher densities are chosen. The border being the separation of the green (lower) and blue (higher) stress areas. The lattice structure model can be designed according to the stress distribution as in Figure 6(a) to obtain the structure as shown in Figure 6(b). In this example, a cubic lattice structure was chosen. The cubic lattice structure was designed and filled the design volume of the L shaped structure.



(a) (b)

Figure 6 (a) Stress distribution and (b) proposed partitions

In this research, Figure 7 shows two options of the lattice optimisation, where it has different partitioning cut than the previous one. From the results, conducted on both examples, the second option shows lower displacement and hence is the preferred option. There is an 11% mass reduction in the second option compared to a uniform lattice structured design while still respecting the part requirements of less than 0.2 mm.

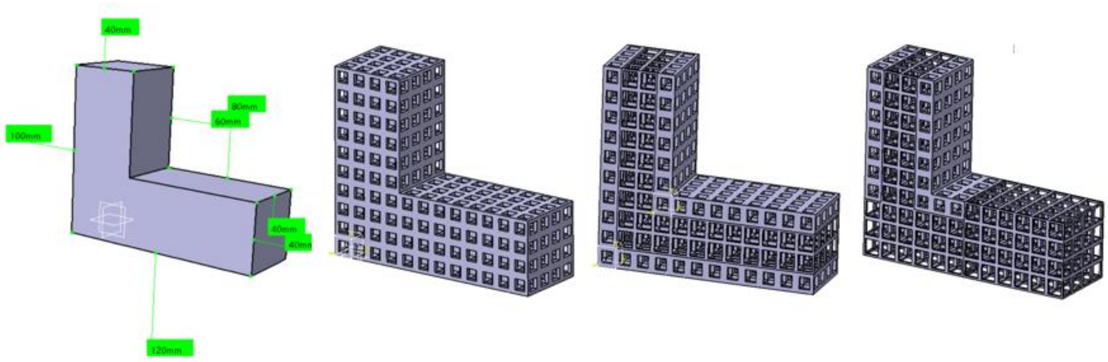


(a) (b)

Figure 7 Two different partition proposals

3.3 Discussion: Advantage of optimised lattice structure compared to uniform lattice structure

FEA simulations were conducted on the solid models and three lattice structure configurations: uniform and optimised lattice structure with different densities, as shown in Figure 8. All four CAD models have the same design volume, boundary condition and cubic elementary pattern. The solid structure consists of an L shaped solid dense structure within the design domain, as shown in Figure 8(a). Figure 8(b) shows a uniform lattice structure integrated within the design domain. Two optimised lattice structures with different partition options are shown in Figure 8(c) and 8(d).



(a) (b) (c) (d)

Figure 8 (a) Solid dense structure (b) Configuration 1 (Uniform lattice structure) (c) Configuration 3 and (d) Configuration 3 (partitioned lattice structure with different densities)

Table 1 shows the FEA results with the mass and maximum displacement of each structure. The partitioned option 1 and 2 have different partitioned densities. Each structure has a following mass: solid 1.470 kg, uniform lattice structure 0.452 kg, partition option 1 0.293 kg and 0.204 kg. The displacements obtained are 0.048 mm (solid), 0.106 mm (configuration 1), 0.174 (configuration 2) and 0.282 mm (configuration 3). From the results obtained, the integration of uniform lattice structure can contribute to a 69.25 % mass reduction with an increase to 0.106 mm of maximum displacement compared to the solid structure with 0.048 mm maximum displacement. Configurations 2 and 3 show that the mass can be further reduced within the acceptable limit of maximum displacement. Hence, enabling the optimisation of the lattice structures.

Table 1 Mass reduction and maximum displacements of each structure.

	Solid	Configuration 1	Configuration 2	Configuration 3
Mass (kg)	1.47	0.452	0.293	0.204
Mass reduction (%)	0	69.25	80.07	86.12
Maximum displacement (mm)	0.048	0.106	0.174	0.282

Figure 9 shows the mass reduction of each configuration compared to the solid dense model. Here it is observed that configuration 3 has the highest mass reduction compared to the uniform lattice structure (configuration 2) and partitioned lattice structure configuration 2.

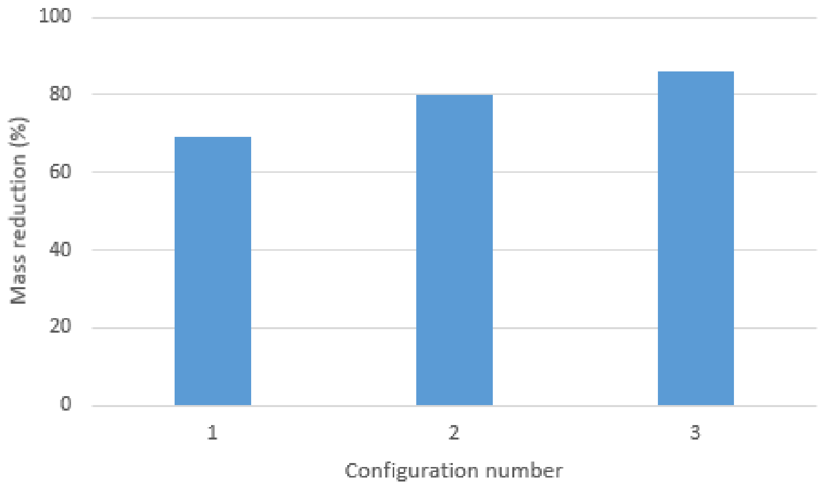


Figure 9 Mass reduction of each configuration compared to the initial solid dense model

The maximum stress is compared to the yield strength of the material Ti-6Al-4V, as shown in Figure 10. From the results obtained, configuration 3 is deemed to be sufficient as it is approximately 95 % below the yield strength for Ti-6Al-4V. The maximum stress is within the adequate stress and therefore it can be further optimised if required.

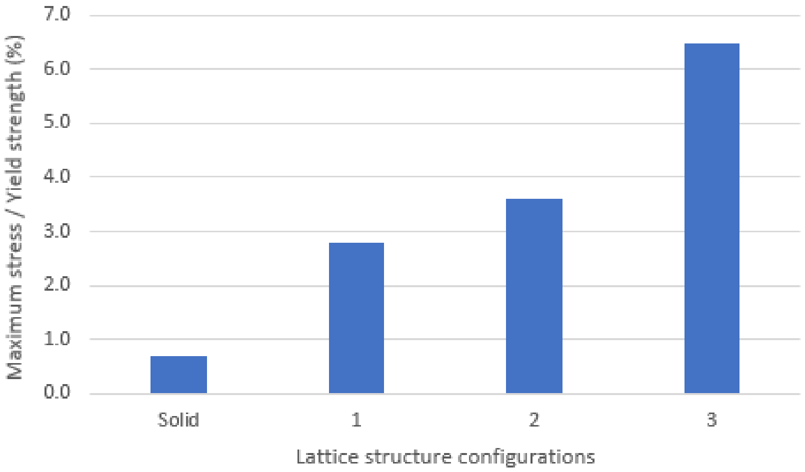


Figure 10 Maximum stress (MPa) compared to the Yield strength of the material

4.0 CONCLUSION

In conclusion, current lattice structure designs for additive manufacturing can be further optimised and reduced in mass by choosing the optimised lattice structure density based on the stress and strain distribution. This outcome contributes to the design of lightweight high strength parts in the aerospace and automotive industry to reduce fuel consumption and increase performances. The lattice structure design method is validated through a case study on a lattice structure part. In this research, the research objective is fulfilled where the produced guideline will be able to help designer in achieving structural optimization by exploiting the lattice structure advantages. The results indicate mass reduction as the main advantage of the optimisation work. It also has provided freedom for designers to manipulate the structure design according to its performance and functional purpose. This finding can initiate further studies regarding guidelines for more complex structures.

Acknowledgement

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