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CAD TOOLS AND FILE FORMAT PERFORMANCE EVALUATION IN DESIGNING LATTICE STRUCTURES FOR ADDITIVE MANUFACTURING

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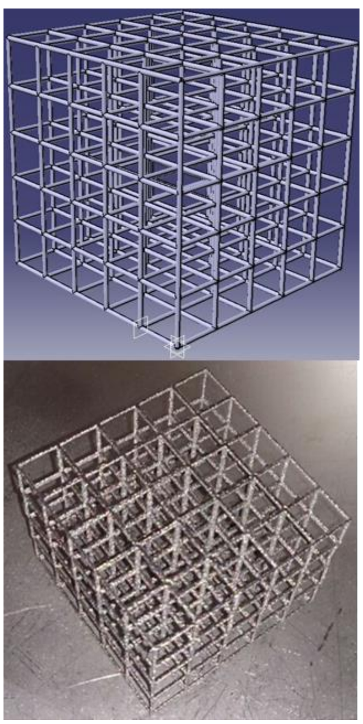
Graphical abstract



Abstract

Additive manufacturing has opened the door to the creation of lightweight lattice structures. However, present Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) software are unsuitable for these types of structures. The objective of this research is to examine the performances of current CAD and CAE software to design lattice structures and to demonstrate their limitations and propose requirements for future developments. A performance evaluation of a case study for lattice structure designs was conducted. The criteria used for the evaluation were CAD human-machine-interface, RAM consumption, data exchange between CAD, CAE and CAM tools and finite element analysis (FEA) duration and file sizes. The CAD tool was incapable of executing a repetition function for octet-truss lattice structures of 150 x 150 x 150 mm dimensions or larger and the software stopped working. For 70 × 70 × 70 mm octet-truss lattice structure, the FEA computation file size reached 36.6 GB. The CAD file size of a 200 x 200 x 200 mm octet-truss lattice structure reached nearly 290 MB. In conclusion, this study exposes the performance inadequacy of current CAD and CAE tools and CAD file formats to design lattice structures for additive manufacturing parts.

Keywords: Lattice structures, additive manufacturing, computer-aided design, lightweight structures, mechanical engineering design

Abstrak

Penciptaan struktur ringan menjadi lebih mudah dengan pembuatan tambahan (AM) melalui penggunaan struktur kekisi. Bagaimanapun, alatan perisian reka bentuk terbantu komputer (CAD) dan kejuruteraan berbantu computer (CAE) tidak disuaikan untuk jenis struktur ini dan tidak dioptimumkan untuk mencapai potensi hebat yang ditawarkan oleh teknologi baru ini. Kajian ini bertujuan untuk menilai prestasi CAD dan CAE untuk menghasilkan struktur kekisi, mengkaji batasannya dan mencadangkan penambahbaikan masa depan. Penilaian prestasi melalui kajian kes untuk merekabentuk struktur kekisi telah dijalankan. Kriteria yang digunakan untuk penilaian ini adalah antara muka manusia-mesin, penggunaan ingatan capaian rawak (RAM), pertukaran data antara perisian CAE dan CAM dan durasi simulasi kaedah unsur terhingga. Perisian reka bentuk terbantu komputer (CAD) tidak dapat melaksanakan fungsi pengulangan untuk struktur kekisi oktet kekisi 150 x 150 x 150 mm atau lebih besar. Bagi struktur kekisi oktet 70 × 70 × 70 mm, saiz pengiraan FEA mencapai 36.6 GB. Saiz struktur kekisi oktet 200 x 200 x 200 mm mencapai hampir 290 MB. Kesimpulannya. Kajian ini menunjukkan bahawa alat CAD dan CAE semasa dan format fail CAD tidak mempunyai prestasi yang mencukupi untuk mereka bentuk struktur kekisi untuk pembuatan aditif (AM) dan bahawa format fail CAD dan alat CAD baru diperlukan.

Kata kunci: Struktur kekisi, pembuatan tambahan, reka bentuk berbantu computer, struktur ringan, reka bentuk kejuruteraan mekanikal

1.0 INTRODUCTION

1.1 Lattice Structure History and Background

Lattice structure is a type of architectured material, which is "a combination of a monolithic material and space to generate a new structure which has the equivalent mechanical properties of a new monolithic material" [1]. It can be used to obtain lightweight structures. Most common cellular structures in everyday life are wood, cork and sponges. These structures have existed for ages and human beings have benefited from their various uses. For example, cork has been used for bottles since the Roman age. Engineers are capable of making cellular structures such as honey-comb structures to obtain lightweight high strength structures [2].

The Venn diagram in Figure 1 illustrates the different types of architectured materials. It exists two types of periodic cellular structures. First, periodic structures with unit cells translated in two dimensions are known as prismatic cellular materials. For example, the honeycomb structure. The second type are periodic structures which have three-dimensional periodicity. Its unit cells are translated along the X,Y and Z-axis. These structures are frequently referred to as lattice structures [3]. This research concentrates on the performance of CAD tools and file formats to design lattice structures for additive manufacturing.

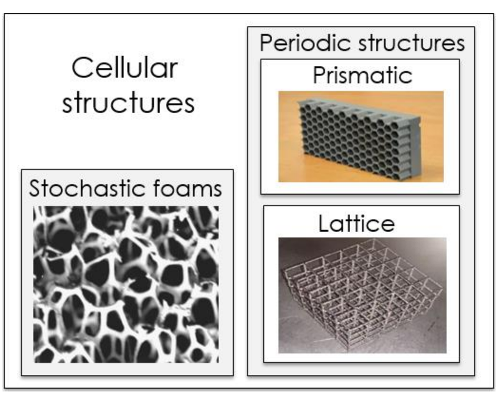


Figure 1 Types of different cellular structures [3]

1.2 The Need for New CAD Tools and File Format for Additive Manufacturing

Lattice structures have many advantages such as lightweight high strength properties, However, despite its benefits, the integration of lattice structures in part designs is not yet common partly due to the inadequacy of CAD tools and file formats to efficiently design lattice structures [4, 5]. The complexity of lattice structures causes the design process in CAD to be computationally inefficient [6]. A new lattice structure generator has been developed to overcome this problem, but it still describes the facets of the struts and uses the STL file format [7]. A recent research has developed and proposed extensions to the STL file format. This extension brings an improvement compared to current file formats, but it is still unsuitable for lattice structure parts. The case study proposed in this paper evaluates whether current CAD and CAE tools and CAD file formats are suitable to design lattice structures and demonstrate their deficiencies. From this case study, it will be possible to determine the causes of the problems and to propose requirements for future developments in CAD tools and file formats.

2.0 METHODOLOGY

2.1 Manufacturability of Lattice Structures

Existing metallic lattice structure manufacturing processes such as investment casting, expanded sheet metal, metallic wire assembly and snap-fit method have limitations in terms of cost and complexity, hence limiting the application of lattice structures. However, for the last ten years, metallic additive manufacturing has become a viable answer to efficiently manufacture lattice structures and is gaining popularity as the primary manufacturing process for lattice structures ahead of conventional methods [8, 9]. Additive manufacturing has received growing interest in recent years [10]. Figure 2 is an additive manufactured lattice structure.

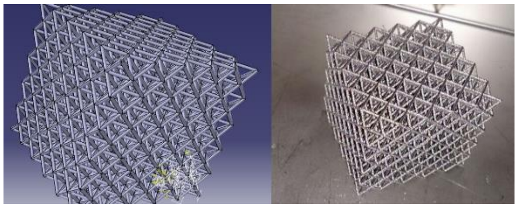


Figure 2 Lattice structure designed in CAD and manufactured with Electron-beam-melting (EBM) machine

2.2 Increased Interest in Lattice Structures and Exploitations in Industry

The breakthrough in metallic additive manufacturing opens many new paradigms and opportunities in manufacturing capabilities such as lattice structures [11]. Its applications can be found in the aerospace, biomedical [8] and automotive industry [11]. As the need for energy conservation and cost reduction increases, the need for lightweight parts increases too. Research field regarding lattice structures has received increased attention due to the breakthrough in additive manufacturing and their advantages over stochastic (foam) structures in producing lightweight high strength parts [13] . This ability to manufacture lightweight structures entices engineers in the aerospace and automotive industry to use lattice structures manufactured with additive manufacturing to reduce fuel consumption and CO2 emissions [14]. The cost factor is important in the automotive industry and low-cost titanium powders are needed to expand its use in this domain [15]. Lattice structures are also important in biomedical engineering, where it is suitable for cell attachment and growth on implants [16].

2.3 Additive Manufacturing Numerical Chain

CAD software must be tailored to meet additive manufacturing needs [17]. Most commercially available CAD software use parametric B-Rep systems, thus making it challenging to produce digital models for additive manufacturing [18]. These CAD software are suited to modeling forms and shapes associated with conventional manufacturing processes such as extrusions, but less suitable for complex geometries associated with additive manufacturing such as lattice structures [17]. Hence, limiting the integration of lattice structures in additive manufactured parts [4, 19].

2.4 Limitations of Current CAD File Formats to Design for Additive Manufacturing

Each file format which exists today was created for other uses and technologies in the past. The stereolithography (STL) file format was originally developed for Stereo lithography machines, but it has become the de facto file format in additive manufacturing for the last two decades [7]. The STL file format is a very simple file format and has only triangular facets [20]. However, it has many disadvantages and consequently, these deficiencies contribute to large STL files which slows down design and manufacturing. These problems are well known, but it is still being used and no real alternative has been able to replace it. There is a new extension to the STL file format aimed at overcoming these problems [21]. These extension proposals show that small work and extensions can improve largely the STL format. However, this study also shows that even with extensions and improvements, it is still necessary to replace the CAD file format for AM.

The proposed Additive Manufacturing Format (AMF) looks to be a very good prospect to replace the STL file format as the de facto format for additive manufacturing [7]. However, this has not been the case because it is not open-source and the capabilities of AMF to define material colors and types of materials are not really needed or used by most additive manufacturing machines. AMF is defined by curved triangles of the surface of a part. Acceptance of AMF in the end depends on its endorsement by both the CAD suppliers and additive manufacturing manufacturers [22]. New methods to generate lattice structures have been proposed, but these are still reliant on the STL file format [23, 24]. Recent work have been conducted to create new CAD file formats for additive manufacturing [25], or modify existing ones to correspond to the need of additive manufacturing [26], but these are yet to replace STL as the de facto CAD file format in additive manufacturing.

3.0 METHODOLOGY

3.1 Evaluation Criteria

The performance of CAD and CAE software can be evaluated in two aspects, the usability and utility of current CAD and CAE tools and CAD file formats to design lattice structures. The performance evaluation was achieved through observation of the CAD human machine interface, data exchange, RAM consumption and duration of operations (see Figure 3. The criteria chosen for the evaluation in this case study are:

- Number of steps and duration to create elementary lattice structures.
- Repetition duration of the elementary structure.
- CAD file sizes of the lattice structure 3D models.
- RAM consumption of CAE and CAM software to import lattice structure parts.
- Duration to execute FEA on lattice structures.
- FEA computation file sizes

Human Machine Interface	**Duration of operations**
• Number of operations to design elementary lattice structure	• Time to generate repetition function • FEA duration
Resource consumption	**Data exchange**
• RAM consumption during file importation	• CAD file sizes • FEA computation file sizes

Figure 3 Criteria for the performance evaluation

3.2 Case Study

The difficulties encountered to design the lattice structures were examined to evaluate the human machine interface. Parts with each different variable were created and each operation and difficulty were observed. The evaluation of a CAD software's utility was investigated by measuring the duration of the repetition operations of the elementary structure to obtain the final lattice structure (see Figure 4).

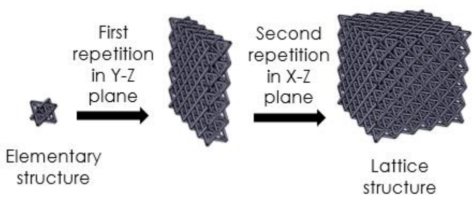


Figure 4 First and second repetition of the elementary structure

Each 3D model was exported to CAD, CAE, and CAM software file formats (STL, STEP and IGES) and the file sizes were measured for each lattice structure pattern and dimension. Then, the RAM consumed by the computer was measured when importing the files in CAE and CAM software. The performance of CAE software was studied by conducting FEA analysis on octet-truss lattice structures. A simple compression test with a 500N force was applied. The dimensions range from 2 × 2 × 2 cm to 7 × 7 × 7 cm with each elementary structure measuring 1 x 1 x 1cm. The FEA duration and computation file sizes were measured. Figure 4 is a summary of the criteria for the performance evaluation in this case study.

Three variables have been chosen for the case study, which are the lattice structure patterns, dimensions of the parts and sections of the lattice structure struts (see Table 1).

Table 1 Variables for the performance evaluation

Dimension (mm)	Lattice structure pattern	Strut section
10 x 10 x 10 50 x 50 x 50 100 x 100 x 100 150 x 150 x 150 200 x 200 x 200	Cubic Octet-truss	Square Circle

The impact of simple and complicated lattice structure designs were investigated with the choice of the two lattice structure patterns, as shown in Figure 5.

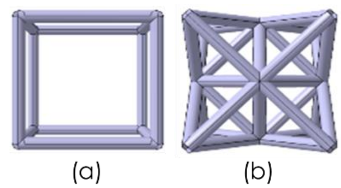


Figure 5 Cubic (a) and octet-truss (b) elementary structure

Different sizes (see Figure 6) are used to study the performance impact due to various lattice dimensions.

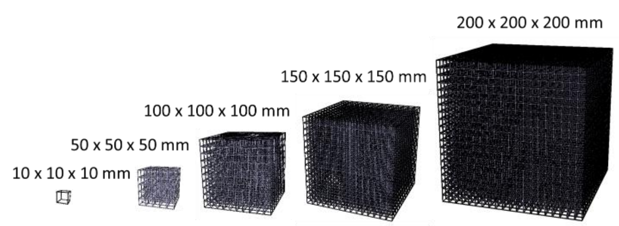


Figure 6 Lattice structure sizes

Circle and square lattice structure sections were chosen to study whether section forms impacted the performance of the software. Figure 7 presents the creation of a circular section strut. First, a plane is defined and then a circle form is created. The circle is then extruded to form a cylindrical strut of the lattice structure.

Figure 7 Creation of a circular section strut

3.3 Evaluation Tools

In this case study, first the elementary lattice structure is designed in a CAD software. After that, a repetition of the elementary structure is applied along the Y-Z plane, then along the X-Z plane to obtain the lattice structure. The 3D model file is then saved and exported to CAE and CAM software. A FEA analysis, simulating a compression test, is conducted on lattice structures. The specifications of the computer and software used to carry out this case study are:

- Processor: Intel Core i7-3540MCPU @3.00 GHz
- RAM: 8 GB
- Hard disc: 500 GB
- CAD and CAE tools: CATIA V5-6R2012, ANSYS R15
- CAM tool: Magics 18.03

CATIA V5 uses the same B-rep models to describe the geometry as other commercially available CAD software. Therefore the results with CATIA will be comparable and representative of other CAD software such as Solidworks and Creo.

4.0 RESULTS AND DISCUSSION

4.1 Steps and Duration to Create Elementary Lattice Structures

The usability of the CAD software to design an elementary structure was observed. The creation of the elementary structure of an octet-truss requires more than 90 operations, consisting of the following operations:

- 35 sketch creations
- 21 extrudes
- 3 rectangular repetitions
- 25 plane creations
- 7 point creations

The whole process took 1 hour and 35 minutes for an experimented CAD operator. A graphic model was required to represent the lattice structure. Some of the operations are illustrated in Figure 8. The process is long because it had to be created manually from zero. Currently there is yet a function for the automatic creation of these structures in CAD tools. Current CAD software are based on B-rep systems, therefore it requires parts to be created and represented with surfaces and volumes.

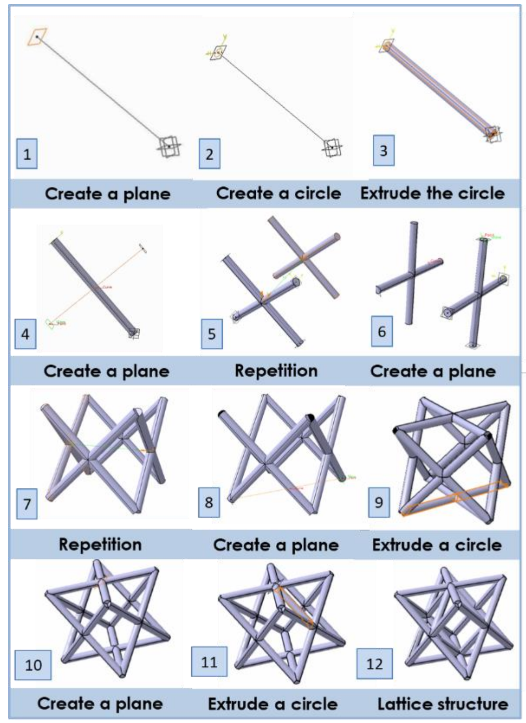


Figure 8 Steps to create an elementary octet-truss structure

4.2 Repetition Duration of the Elementary Structure

The duration to execute the repetition operations of the elementary structure was measured to evaluate the utility of the CAD. The tasks were repeated three times to obtain a more reliable average time. Figure 9 presents the results for the repetition operation durations. A quadratic growth of the duration value in function of the dimension of the part is observed. It becomes time-consuming for large dimensions. The duration of the repetition operations for a lattice structure of an octet-truss pattern is two to ten times more to than that of a cubic pattern. This is a consequence of the high number of surfaces involved. For example, the CAD tool was not capable of executing a repetition function for octet-truss lattice structures of 150 x 150 x 150 mm dimensions or larger and the software stopped working.

4.3 CAD File Sizes of Lattice Structure 3D Models

Figure 10 present the file size of each lattice structure 3D model in STL, IGES and STEP file formats. These file formats store the lattice structure data. Each file format has a specific structure to store data. Once the lattice structure models have been saved in each file format, the file size is taken from the file property. One observation that can be made is that even though a lattice structure is of the same pattern and dimension, its file sizes are not the same. The method and structure of the file format to store information influences the size of the file. The files produced were very large. For example, the size of a 20 x 20 x 20 cm octet-truss lattice structure reached nearly 290 MB.

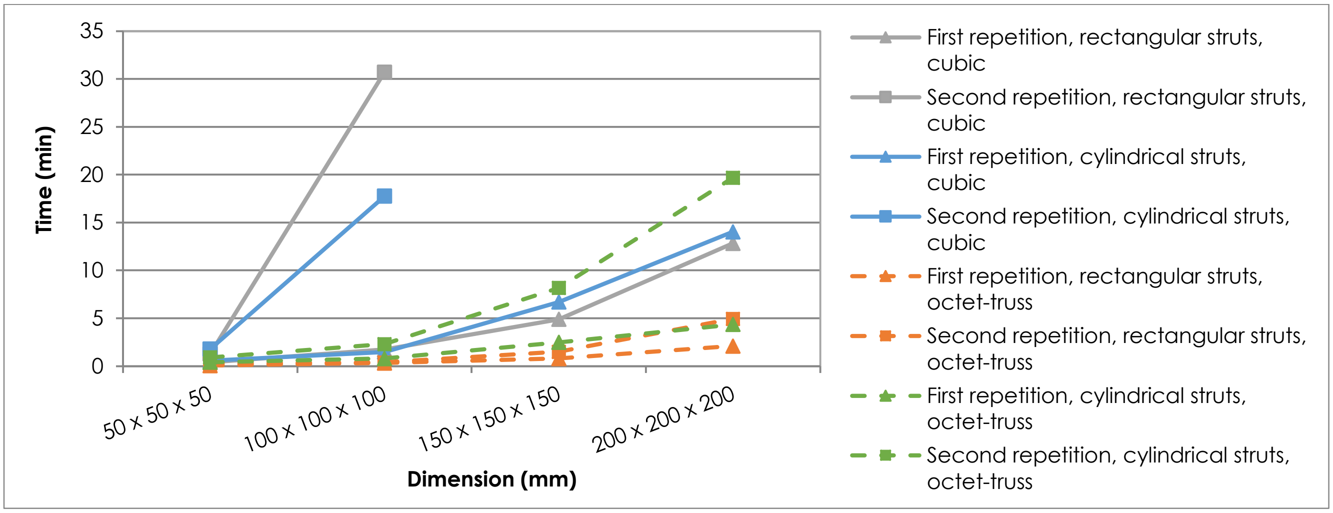


Figure 9 Octet-truss lattice structure 1st and 2nd repetition time duration

The time to conduct the first and second repetition operations was measured using a stopwatch. The result from this case study regarding CAD file formats reveal that they are unsuitable for lattice structure parts. Large files are generated with the STL format due to the triangulation approach used. Thus, making it only suitable for parts with a small number of surfaces. However, lattice structures contain large number of surfaces, thus resulting in the large file sizes. New CAD file formats are needed to overcome this problem, one which does not use triangulations and instead uses an approach suitable for lattice structures, which are generated from a basic elementary structure pattern and repetitions in the Y-Z and X-Z planes.

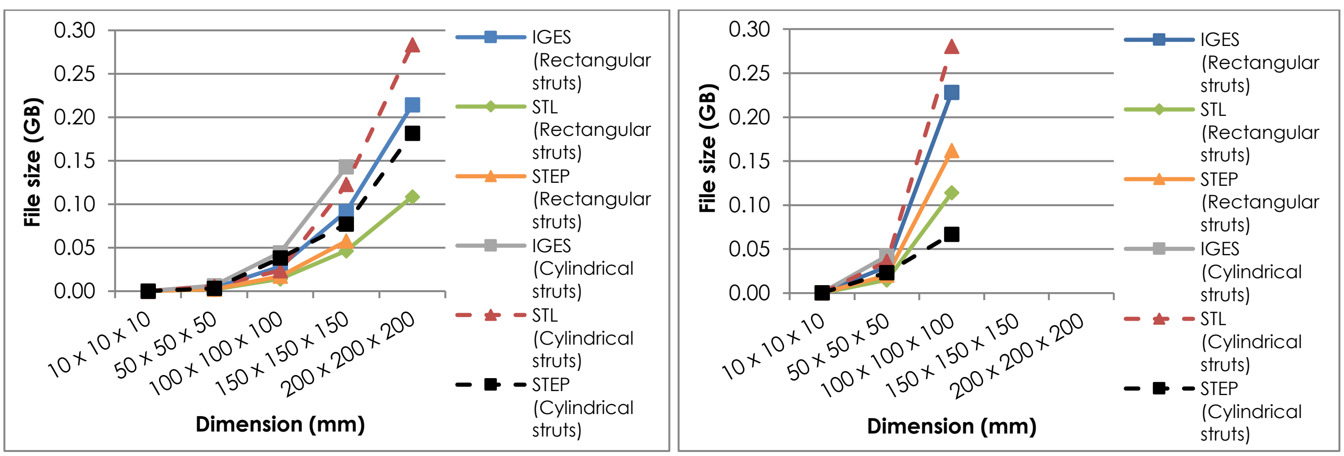


Figure 10 Lattice structure CAD file size: Octet-truss (left) and cubic (right)

4.3 RAM Consumption in CAE and CAM Software to Import Lattice Structure Parts

ANSYS and MAGICS were chosen as the CAE and CAM software respectively. The results are shown in Figure 11. The parameter during the importation of the lattice structure parts in ANSYS and MAGICS was the 8 GB of RAM in the computer. All other software in the computer was closed to ensure the same memory was available for each importation of the lattice parts. The RAM consumed during the importation was observed and measured in the Memory Usage under the Performance Tab in Windows' Task Manager. In five cases during the importation of the lattice structure models, it was not even possible to load the files and it consumed nearly 4 GB of RAM. The method used by current CAE and CAM tools based on the B-rep system is unsuitable for the manipulation of lattice structures, they are not even capable of importing and processing large lattice structure files into the software.

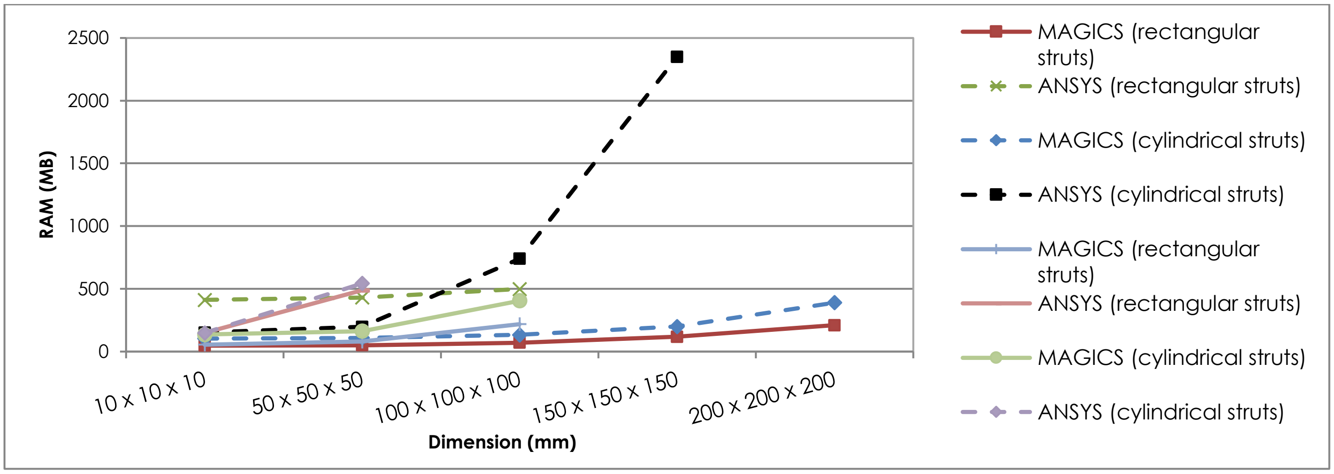


Figure 11 Cubic lattice structure importation RAM consumption

4.5 Duration to execute FEA on lattice structures

The parameters for the FEA on lattice structures were the mesh size and the compressive force applied. The mesh size chosen for each simulation was 0.65mm and the force applied was 500N. Figure 12 shows a significant increase in FEA duration compared to the increase in part dimension. The thickness of the lattice structure strut is 2 mm and the mesh size are 0.65 mm. The FEA simulation was time consuming. If lattice structures are to be the norm in lightweight high strength additive manufactured parts, this is a problem that must be solved. Engineers require tools that are powerful enough to conduct FEA on lattice structures easily and quickly. Current CAE software conducts FEA based on B-rep models. Thus, for parts such as lattice structures which have a large number of surfaces, this causes a problem for the software to execute the FEA analysis. New methods and tools must be constructed to find a solution to this problem.

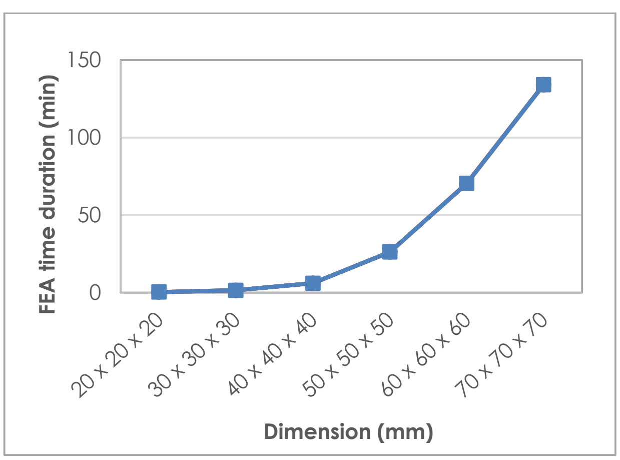


Figure 12 Octet-truss FEA time duration

4.6 FEA Computation File Sizes of FEA on Lattice Structures

A compression simulation was conducted as shown in Figure 13. A 500N force is applied on the top surface, while a clamp is fixed on the lower surface. The computation file size was observed. Figure 14 shows the FEA computations file size in function of the lattice structure dimensions. The graph shows that the FEA computations file size increases tremendously when the dimension of the structure increases. For the 7 × 7 × 7 cm octet-truss lattice structure, the FEA computation file size reached 36.6 GB. This made the computer slow and consumed a lot of hard disc space.

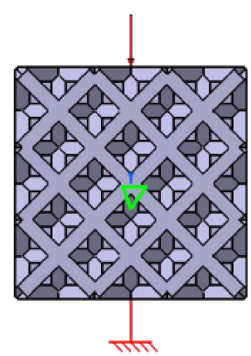


Figure 13 Octet-truss FEA computation file size

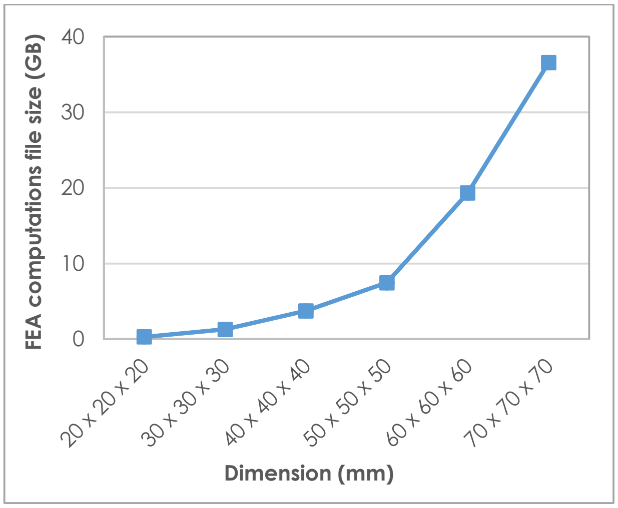


Figure 14 Octet-truss FEA computation file size

5.0 CONCLUSION

The case study in this paper regarding the creation, manipulation and exportation of lattice structure 3D models using CAE and CAD software demonstrate that today's CAE and CAD software and file format do not support the needs required by additive manufacturing to produce lightweight lattice structures. Advances in manufacturing contribute to new requirements in CAD tools, however the performances of current tools are insufficient due to the B-rep system that they are based on, hence unsuitable for lattice structures which consist of many struts and therefore large number of surfaces. The solution to this problem would be to develop new CAD tools and file format specifically for lattice structure designs. From the findings in this paper, since CAD tools use B-rep system to represent parts, the requirements for new CAD tools and file formats would be to replace the lattice structure models in CAD with an equivalent solid model, hence avoiding the need to design each strut of the lattice structures and eradicating the large number of surfaces involved. The equivalent solid model uses the homogenization approach to represent the lattice structures and has the same equivalent mechanical properties as lattice structures.

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