

Design and Analysis of Additively Manufactured Components with Integrated Lattice Structures

RISE IVF

Master thesis in Product Development

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Department of Industrial and Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2020

MASTER THESIS 2020

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Abstract

Additive Manufacturing (AM) for metals is a fast growing field which is almost ready for industrialisation. Structural optimisation(SO) tools like Topology optimisation(TO) are now the most beneficial tools to the area of structural design. But, these tools give a design output that is very difficult to be manufactured by conventional manufacturing techniques like casting. This is where AM comes into the picture as it helps to overcome the rigid boundaries of other manufacturing methods due to its ability in helping produce objects of complex shapes and functionality. Lattice structures are very useful elements in structural design but are very difficult to produce by other methods , especially for the purpose as infill for objects. This gives an opportunity to use AM for producing objects with integrated lattice structure.

There are various types of lattice structures like octet, gyroid etc. By properly aligning the lattice structure inside an object instead of completely filling it, structures with low density and weight can be achieved while also being strong. Lattice structures have been used as temporary support material for AM prints, but here they will also be a part of the final component itself serving as functional structures. This master thesis conducted at RISE IVF consists of first studying various types of self-supporting lattices and conducting virtual tests with regard to shear, tension, compression stresses etc. The second part of the thesis concerns topology optimization of a structural component design provided by Volvo Cars. This is done in order to get a design output that is suitable to be integrated with lattice structure to achieve lightweighting with minimal changes to the strength characteristics. A homogenized model is developed to verify the effects of the lattice unit cell in the optimized component.

The final results of the linear analysis of the homogenized model was compared to the linear analysis of the steel sheet metal pivot bracket given by Volvo Cars. The final result comparison and analysis showed that the topology optimized pivot bracket component with integrated lattice structure was slightly lighter than the steel sheet metal pivot bracket designed by Volvo Cars and of comparable stiffness. This methodology allowed the authors to create a component design that is integrated with lattice structure and has a comparative stiffness design parameter of the original component. The design is also potentially manufacturable by AM, but the time limit prevented the actual printing process and hence all results were verified virtually. This methodology can be used for components that are fit for manufacturing via additive manufacturing for the purpose of lightweighting without much loss of structural integrity .

Keywords: Unit Lattice Cell, Topology Optimisation, Lattice Optimisation, Homogenisation, Additive Manufacturing .

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Abbreviations

AM	Additive Manufacturing
CAD	Computer Aided Design
SO	Structural optimisation
SIMP	Solid Isotropic Material with Penalization method
STL	Stereolithography
RVE	Representative Volume Element

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1

Introduction

This chapter gives a brief overview about the background , purpose , limitations of the thesis and finally the methods used to find and validate the results.

1.1 Background

Light weighting of components is an area that has become a major point of focus in many industries in recent times due to various factors like mechanical advantages, cost savings, efficiency increase etc [1]. This especially holds in the case for complex metal components where Additive Manufacturing helps to achieve light weighting by solving many of the constraints present in traditional manufacturing methods[2] . Lattice structures such as gyroid, honeycomb etc. used as infill materials is an especially relevant strategy to reduce weight of the component while keeping the strength and stiffness characteristics almost equal to the base component. Manufacturing of lattices is very difficult using any of the traditional methods and hence AM is the best suited for this purpose.

The effective utilisation of limited resources is critical in the modern engineering and the strategies used to achieve is generally defined as optimisation. Structural Optimisation(SO) is defined as creation of structural design that meets the target objectives against a set of limitations [3]. Topology Optimisation(TO) is the most frequently used type of Structural Optimisation that is based on Finite Element algorithms that uses both size and shape optimisation to optimise the component design with regards to important properties like the optimal stiffness/mass ratio. In addition to weight savings offered by TO while achieving certain performance objectives, the other main advantage is the high speed with which a structure can be optimised. Also, with improvement of codes the optimisation is also now available for stiffness, strength, compliance etc which makes it highly suitable to any light weighting strategy compared to other forms of SO like shape and size optimisation [4]. Thus, the software tools based on this concept are important assets that can be used to lightweight components in mass critical applications such as aerospace, medical industry, racing etc.

The component designs derived from TO can be very complex to print even in AM due to presence of long overhangs that require numerous external supports to keep their shape which creates many new problems such as extra material costs, excess time required to post process etc. This can be minimised or eliminated by combining it with correctly chosen lattice infill at the required areas or members thus eliminating the need for these supports. TO results in formation of pseudo densities which are either interpreted as void

or complete solid, thus deviating away from the optimal stress and stiffness distribution. This can be solved by using lattice structure as infill so that the final TO design is completely translated to the print thus also acting as a bridge to solve practical AM problems [5].

After the integration of the lattice structure into the TO design, the analysis process becomes very computationally expensive[6] after discretization of the component with the lattice structure. Hence, there is a need to use a method to simplify the analysis and get an accurate model idealization of the geometry. This is where material homogenisation helps in easing the analysis by averaging the material properties across the lattice structure instead of resolving the entire lattice chain made of numerous unit cells thus changing the analysis view from a microscopic level to a macroscopic level[7].

1.2 Purpose

The purpose of the thesis is to establish a methodology for:

- Structural verification of various unit lattices under various loading conditions.
- Utilisation of the selected lattice structure as infill in a topologically optimised AM component for purpose of light weighting, increase robustness of the component and solving certain AM print prerequisites/ condition (overhangs, stiffness, build direction, etc.)
- Methods to calculate the various loads in the component and the lattice structure were studied and documented in the report.

1.3 Limitations

The following limitations are applicable to the thesis:

- No physical testing was carried out on the printed lattice test structures due to time limits and scope restrictions..
- There are numerous types of lattice structures available, but the choice was limited to those available in the Ansys Mechanical.
- Out of the lattice structures available in Ansys Mechanical all were not studied as the main requirement for their selection was that they should be self-supporting during the print.
- The choice of the component to carry the TO work and lattice integration for this thesis is given by Volvo cars. The design space was also fixed for the same.
- The final optimised component design could not be printed due to time limitations and hence all the stress tests were conducted virtually in Ansys Mechanical.
- The choice of printing material and the material properties studies are not conducted in this thesis as this is primarily a product development thesis. Less focus is put on

the choice of metal alloy material used for printing.

- Certain decisions on printing of test geometries, the size and orientation of the test geometries are based on reports and tests conducted internally at RISE IVF and details of those reports are confidential and a property of RISE IVF Mölndal.

1.4 Method

The first phase of the thesis started with an initial planning report that briefly stated the respective expected timeline of the different parts that constitute the thesis. The thesis was split into three major parts, i.e. 1) Lattice Structure study 2) Topology optimization 3) Homogenized material model. The next step was to conduct a thorough literature study to get idea about the State of the art, gaps in the current research etc. regarding the three parts with concentration towards their applications to Additive Manufacturing.

The entire thesis was handled using tools and suites present in ANSYS 2020 R1 from ANSYS Inc mainly consisting of ANSYS Mechanical , ANSYS Spaceclaim and ANSYS Discovery Live. In this thesis products from ANSYS are chosen due to familiarity and due to commercial license available at RISE IVF. The lattice structure used for the analysis was generated by using the ANSYS Spaceclaim suite. The main program used for performing finite element analysis is the Ansys Mechanical where all the steps involved in FEA from importing CAD (Computer Aided Design) geometry, discretising the structure (mesh), setting up loads, material data etc. and the final compilation of results. The application component i.e. the Pivot Bracket(component provided by Volvo Cars which has been explained in section 5.2) is then topologically optimised to remove the mass after setting up boundary conditions in the ANSYS Discovery live suite. The heavily faceted model or the STL output file from the suite is then converted to a smoothed solid for analysis by using various design tools in ANSYS Spaceclaim. All the remaining stress and strain calculations are conducted in ANSYS Mechanical itself.

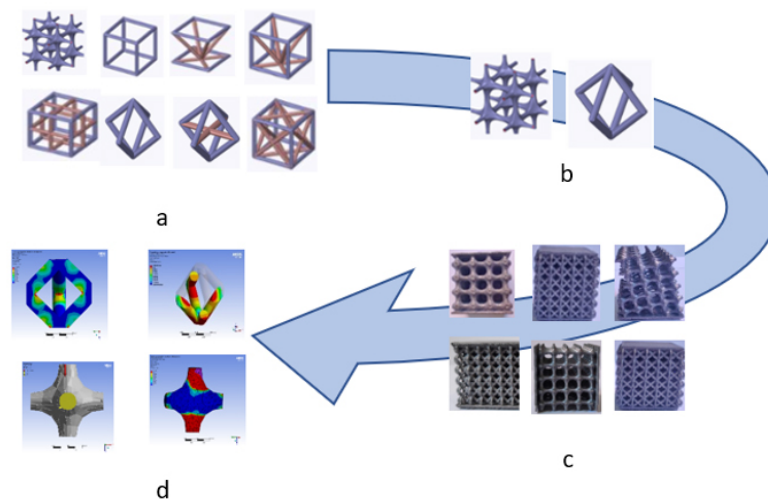


Figure 1.1: Lattice Structure Study , a - Lattice structures present, b - selection of the lattice structure , c - test print , d - analysis

The first portion of the Lattice structure study was conducted in order to find the best suited lattice structure among all the options present in Ansys Spaceclaim that satisfy the condition that the lattice unit cell and lattice chain should be self-supporting. Test prints of the lattice structure also helped in selecting the best orientation of the selected structures (further conditions are mentioned in chapter 4). A linear analysis was conducted in Ansys Mechanical for various unit cell sizes and orientation of different lattices. This gives the stiffness for the different lattices which enabled the shortlisting of lattice structure that is going to be researched further. A plasticity analysis was conducted to estimate the collapse load for the unit cells of the finalised lattices. Figure 1.1 gives a brief overview of the entire process.

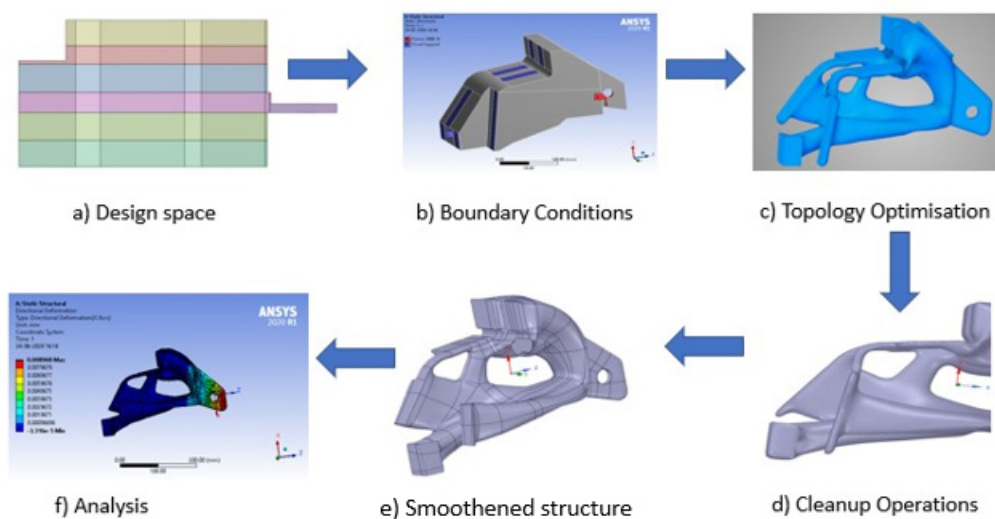


Figure 1.2: Topology Optimisation

The next part of thesis was at the component level which included TO combined with geometry cleanup to provide a usable structure. A component provided by Volvo Cars called as Pivot Bracket was topologically optimized to provide a structure that is suitable for being integrated with an internal lattice structure that was studied in the previous section. The TO took place in several steps where the boundary conditions and optimization setup (mesh sizing, optimization algorithm etc.) were varied until a satisfactory structure was obtained. The finally selected structure was further improved using tools in ANSYS Spaceclaim to get a usable component design on which further analysis and complete lattice integration could be achieved. Figure 1.2 gives a brief overview of the entire TO process applied to the Pivot Bracket.

The addition of numerous structural elements which comprise the lattice structure makes it very difficult to define boundary conditions (including material conditions) and makes it difficult to compute the finite element solution due to the vast number of elements involved [8]. The solution to this problem is homogenisation of the lattice structures which is further explained in the theory section 3.3. Instead of studying the entire lattice structure plus component at micro scale like in a normal finite element calculation, the material of the entire structure is represented by a small element called Representative Volume Element (RVE). An Ansys tool known as material modeller is used to find out the details of the RVE.

2

Additive Manufacturing

In this chapter, the theoretical background for AM is explained with benefits and areas of application. A brief information of metal AM with a focus on Selective Laser Melting is also provided.

2.1 Introduction

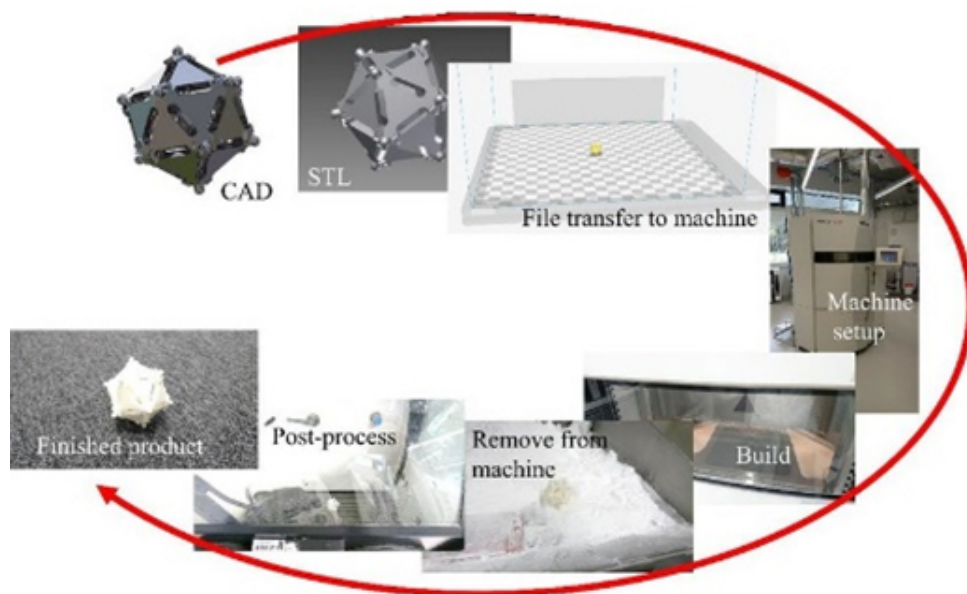


Figure 2.1: Steps in AM [9]

AM, also called Rapid Prototyping is a collection of manufacturing methods in which components are created by addition of material layer by layer by receiving input from three-dimensional (3D) CAD data [10] . The general steps in producing or manufacturing components in AM are as shown in the figure 2.1.

The first step is to convert the component to be designed from CAD to STL format . STL breaks down the surface of the part to be produced into triangles for easy build-ability. The STL file is then transferred to the machine which interprets it in the form of movement codes i.e how much should the bed move for each layer print and all other details are stored in the file. The machine for different types of AM are to be setup

according to needs related to the particular method. The component is then built layer by layer in the desired material choice and once the print is complete it is removed from the build plate or bed. Post process operations like filing of rough edges or sanding makes the finished product ready for use.

The AM process can be classified into seven process categories [11] :

- Vat photopolymerization - processes that use a light sensitive liquid photopolymer in a container that is selectively exposed to Ultraviolet light to cure it in the desired form to produce the component.
- Powder bed fusion - processes that use the required material in powder form stored in a container that is selectively exposed to source of energy like various beams and lasers.
- Material extrusion - processes that extrudes the required material through a nozzle in the required shape.
- Material jetting – similar to normal ink jetting process where ink is replaced by print material.
- Binder jetting - processes where a binding agent is printed into a powdered material container to produce the required parts.
- Sheet lamination - processes that produce a component by bonding material sheets layer by layer.
- Directed energy deposition - processes that concurrently deposit the material (in powder or wire form) and expose them to energy sources to melt or sinter them into required form.

The main advantages of AM are: - (1) It can be used to produce components with complicated shapes and intricate details when compared to conventional machining processes. (2) A wide range of materials like plastics, ceramics, metals etc. can be used in AM to produce numerous components. (3) Low volume production runs of new components can be finished sooner due to absence of die and specialized tooling requirements [12]. Another area where unique application of AM can be utilized is in production of novel customized art items that can't be manufactured using other techniques especially with respect to metals. The main areas of application are for spare parts production, prototyping of components and custom parts production. Also, AM has progressed into being capable of producing certified parts in highly advanced fields like aerospace and medical. Repair work of components was previously very difficult can now be easily patched using AM processes. It has helped companies in fundamentally changing the ways in which they operate by helping to reduce development times since AM offers an easy way in visualization of the product at each stage of development, thus avoiding expensive redesigns frequently. This has enabled the companies to become Agile with quick product turnovers and be more efficient.

2.1.1 Selective Laser Melting

The industrially relevant AM processes used to produce high value objects for industries like aerospace, medical implants are Selective Laser Melting (SLM) and Electron Beam Melting (EBM). The available technology at RISE Mölndal is Selective Laser Melting (SLM) which is an AM process in which parts are fabricated layer by layer by focusing a high intensity laser beam onto a metal powder bed in an inert atmosphere which results in subsequent melting and solidification in the desired shape [13]. The powder required for the process can be produced using various methods like gas atomization and plasma atomization.

The first step in the process is to spread a thin layer of metal powder up to 100 μm with help of a scraper. The laser is then focused to melt the desired 2D shape which will be one cross section layer of the final product. The cross-section shape is derived from the sliced CAD model. The build plate moves by the distance that is equal to the layer height for each subsequent pass and the above process of powder addition and melting is performed repeatedly to get the final structure. The whole process is conducted in inert atmosphere to prevent formation of defects like oxidization, pitting etc.

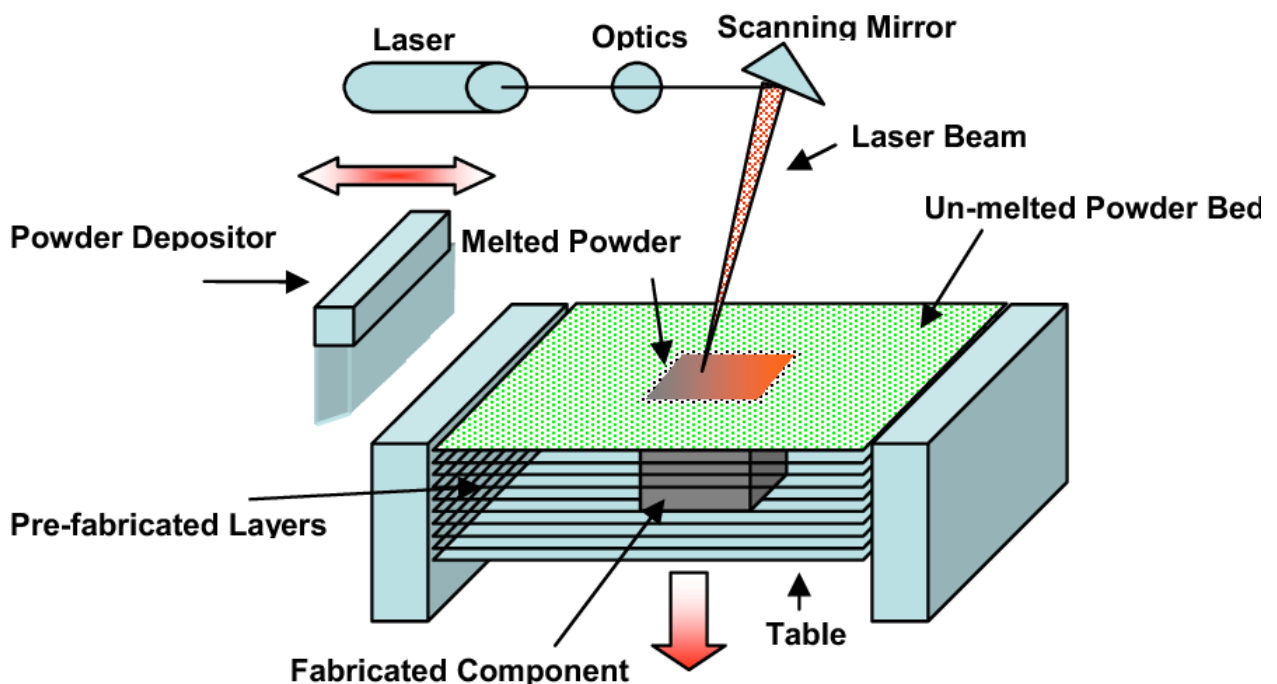


Figure 2.2: SLM setup [14]

3

Theory

In this section, a brief introduction and background about the main components of the thesis i.e Lattice structures , TO and Material homogenisation.

3.1 Lattice Structures

A lattice structure is a type of porous cellular structure that is periodically ordered and composed of repeating unit cells[15]. They are divided into two categories i.e periodic and stochastic for which example is shown in figure 3.1. Periodic lattices are structures that is formed of regularly repeating cells in an ordered manner like honeycombs, gyroids etc. They can also be mathematically defined. Stochastic structures are the random composite structures that exist in nature like wood, bone structure etc. that cannot be mathematically defined and are difficult to recreate.

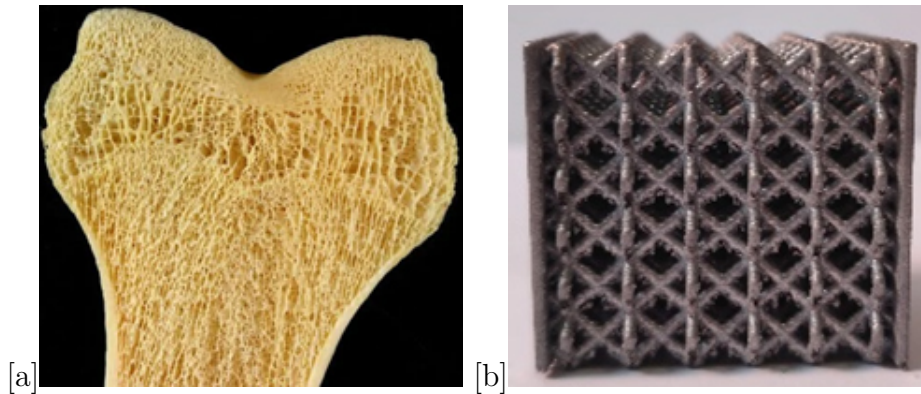


Figure 3.1: Different types of lattices (a) Stochastic lattice e.g. Femur Bone [16] (b) Periodic lattice

Lattice structures are applied to a wide variety of industries ranging from civil to medical sectors[17]. It has helped to revolutionize medical industry because they help structures have large surface areas due to their porous nature which helps in better integration of medical implants with the human body. Many automotive components like pistons are being produced with integrated lattice structure to help improve rigidity and provide channels for cooling. They are also being widely used in sound absorption materials and crash resistant structures. They help in effectively distributing loads across nodes in a structure which makes them good support material and thus help in achieving light weighting. They also help in achieving objectives like[18]:

- They help in reducing the amount of material used due to them being porous in nature.
- They help in printing the complex shapes produced by topology optimization as they are good support structures.
- They can be used to design structures with different stiffness values in different directions thus helping the robustness.

Manufacturing of Lattices is a complicated process when traditional manufacturing processes like cutting is used as there is an additional task of assembling all the cut pieces together. This has led to emergence of AM processes like SLM and EBM to produce lattice structure for industrial applications since lattice can be produced in one piece.

3.1.1 Types of Lattice Structures

* These are the lattice structures present in ANSYS spaceclaim CAD tool available as options for lattice infill.

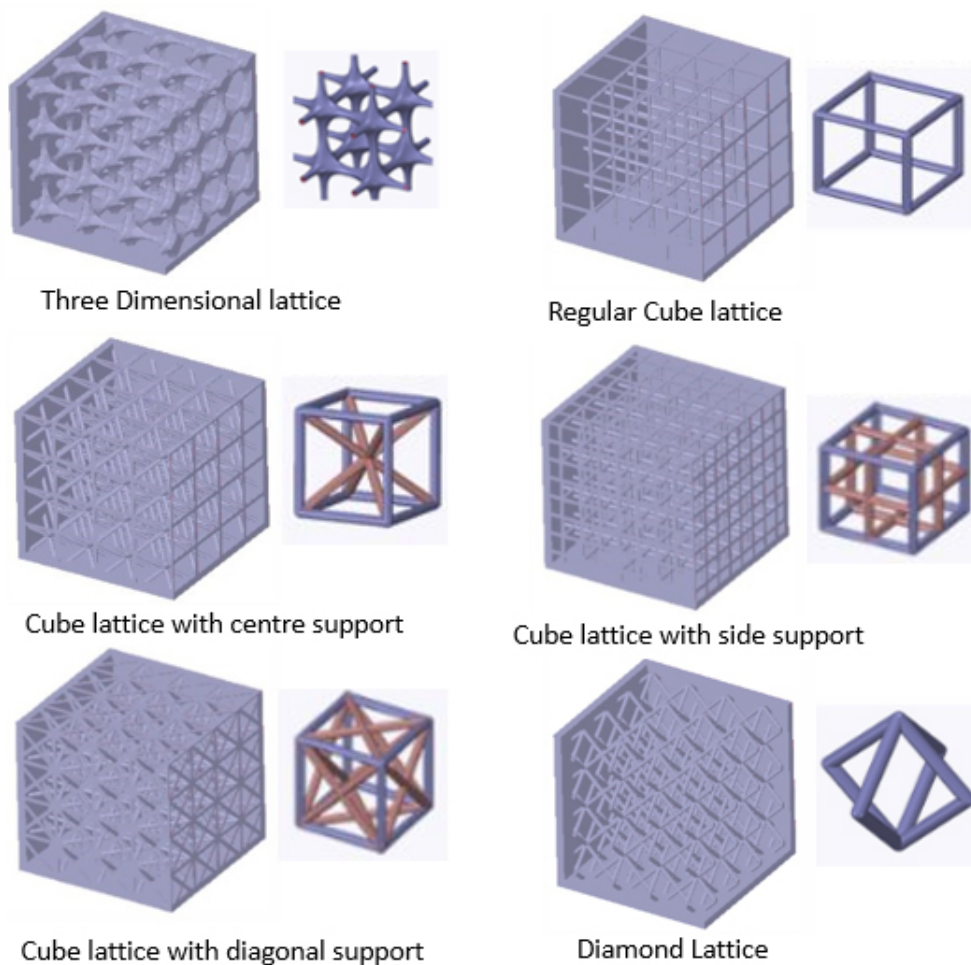


Figure 3.2: Different types of lattices

3.2 Structural Optimisation

Structural optimisation (SO) is a type of optimisation where the aim is to ensure the correct distribution of material for a structure in such a way that it optimises (maximise or minimise) one or multiple structural characteristics while keeping certain structural characteristics as constraints. The common structural characteristics are weight, stiffness, critical load, stress, displacement and geometry[19]. A SO problem is composed of the following:

- Objective function (f): it represents the objective that has to be maximized or minimized.
- Design variable (x): aspects of the design that can be modified.
- Parameters (p): the aspects of design that are fixed for the optimization.
- Constraints: the restrictions present in the optimization

The general formulation for the problem is:

$$\begin{array}{ll} \text{Minimize} & f(x,p) \\ x & \\ \text{subject to} & g(x,p) \leq 0 \\ & h(x,p)=0 \end{array}$$

3.2.1 Sizing Optimisation

Sizing optimization is the most basic form of SO[20] where the dimensions or cross section of structural members are optimized to reach a particular target objective like reducing mass, increasing stiffness etc [21] . The common design variables are usually diameter , thickness , length or width of beams etc. It is beneficial in cases where the positioning and member shapes are already known and only the dimensions of members are to be optimised[22] . Refer figure 3.4 a for example.

3.2.2 Shape Optimisation

Shape optimization is similar to sizing optimization as the layout of the structural elements (no of holes, beams, positions) is already known. In addition to varying the dimensions or cross sections of the structures the shapes of the members can be varied e.g. Non-symmetrical features can also be part of final design. The common design variables can be dimensional variation of beams, chamfers, fillets, radius etc. Refer figure 3.4 b for example.

3.2.3 Topology Optimisation

The most widely used form of SO[19] . It is a mathematical tool used to find the optimum distribution of material like size and shape optimization. The layout of the optimization like placement of holes, member thickness etc. is not fixed before and only boundary conditions are fixed. Refer figure 3.4 c for example. TO process results in formation of areas with blank spaces and solid areas. The FEM approach is used to solve this problem

by discretising or meshing the structure which gives rise to a binary problem consisting of voids where material is not present at all and regions where material is present. A. Olason and D. Tidman in their thesis[20] that:

The total number of solutions for this problem is 2^N where N is the no of elements which includes both voids and solids which gives rise to very complex solution due to huge number of elements . The solutions to these problems are the different topological methods like density based and homogenization based. Density based TO is a process where densities of the numerous elements that make up a structure are varied between 0 and 100 percent in order to overcome the very strict void and solid problem. The design variable for the SO problem is set to be the density and a gradient based minimisation problem is set up to find a solution. This gives a very complicated structure easy usually elements with pseudo densities i.e. those between 0 and 100 percent are constrained in such a way that they have higher penalty. The density method including this penalty is called as SIMP or Solid Isotropic Microstructures with Penalization.

Level set methods are defined according to N. P. van Dijk [23] as:

Approaches that use an implicit description of boundaries to parametrize the geometry in order to get the results.

Ansys Mechanical uses this method and level set methods to achieve TO while the Ansys Discovery Live uses level set method .

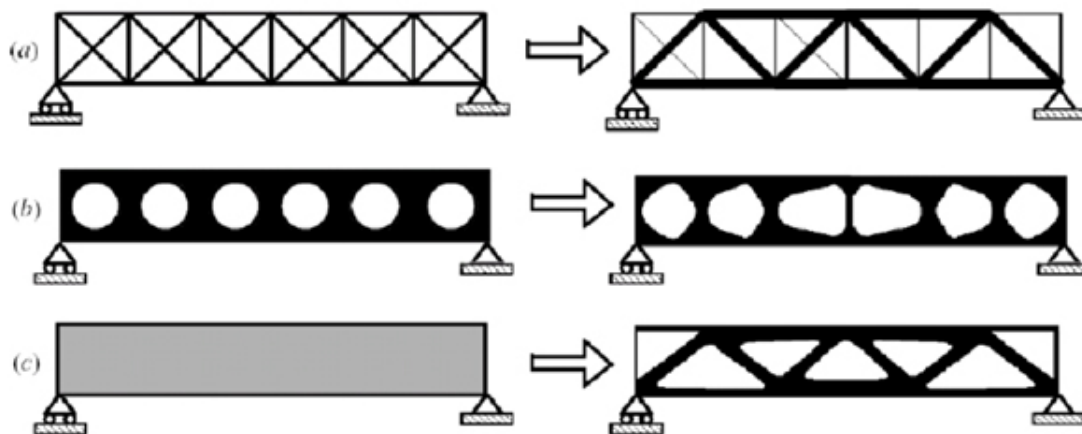


Figure 3.3: Different SO approaches[24]

3.3 Homogenisation of lattice structures

The integration of lattice structures into a structure provides many benefits as mentioned previously. But, the addition of numerous structural elements which comprise the lattice structure makes it very difficult to define boundary conditions (including material conditions)[25] and makes it difficult to compute the finite element solution due to the vast number of elements involved [8] . Material homogenisation is structural framework

that helps in looking at structures from a macroscopic scale by averaging material properties across all individual elements instead of completely defining them at the individual level. The scale at which homogenisation takes place is defined by the application. The figure 3.5 gives a very basic idea of the above.

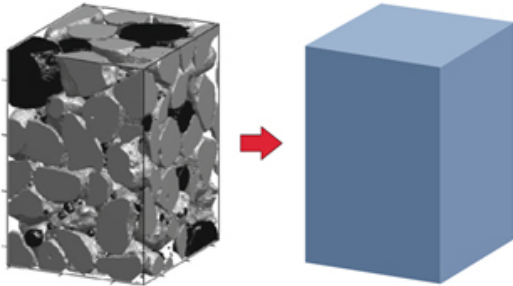


Figure 3.4: Homogenisation [26]

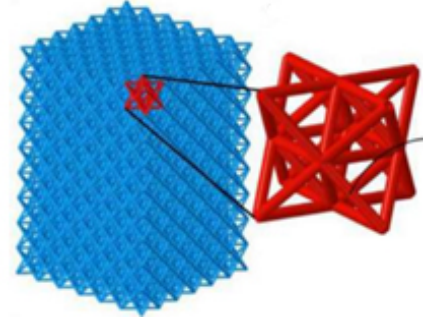


Figure 3.5: RVE example[27]

The fundamental building block for the homogenization process is an element called the RVE which is the minimum volume of element that can effectively represent the material properties of the entire lattice structure at the macroscopic level. Another definition for RVE as stated by P.V. Trusov and I.E. Keller[28][29] is:

An RVE is the minimal material volume, which contains statistically enough mechanisms of deformation processes. The increasing of this volume should not lead to changes of evolution equations for field-values, describing these mechanisms.

For periodic lattices one unit cell is sufficient to be considered as an RVE. The RVE method is also applied in the thesis which would further be explained in chapter 7.

4

Lattice structure study

The purpose of this study was to study and evaluate the best suitable lattice structure which meets the purpose of this thesis work. This section is divided into different parts, each having a specific role to play in the selection of the best suitable lattice structure geometry. The selection of the lattice structure geometries was based on them meeting a certain design requirement which would allow it to be additively manufacturable and some FEM analysis to determine the linear stiffness performance and plastic behaviour. Test plan for the same are also drafted which also contributes to future work.

4.1 Selection of Lattice Structures required for study

The lattice structures were selected based on the following conditions:

- Availability of the lattice geometry in Ansys ‘space claim’ CAD tool.
- Self-supporting nature i.e no member of the lattice structure should be horizontal to the build plate in any orientation in xyz plane. (This criterion is selected to avoid the lattice structure printing failure as completely horizontal members are very difficult to print and are subjected to failure).
- Optimal compressive and shear load stiffness.
- Optimal Load bearing capacity

Based on these four conditions, lattice structures were studied and selected. After analysing the lattice geometries, diamond and 3d lattice geometries were selected as they are completely self-supporting in all directions.

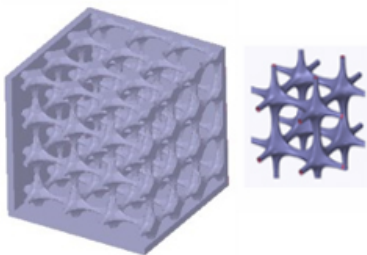


Figure 4.1: 3d lattice

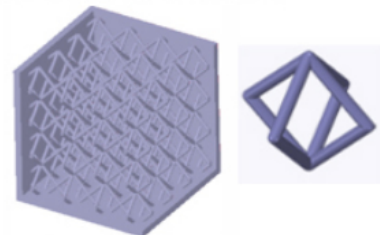


Figure 4.2: Diamond Lattice

4.2 Test Print

Test prints for the selected lattice structures were made to analyse the printability of these lattice structures in different directions and also to analyse the limits on the size of the lattice structures that can be printed. Lattice structures of size 2mm length and cross section size of 0.5mm and 5mm length with 1mm cross section were selected as the smallest and the biggest size of the lattice structure for the purpose of this thesis. This selection was made based on the available internal reports at RISE IVF. These test prints were manufactured in the SLM machines available at RISE IVF and were mainly intended to be test specimen on which mechanical destructive tests were to be conducted (which were postponed as they exceeded the scope of the thesis). The total intended test scope was planned in connection with the analysis made on each unit cell. The scope of these mechanical tests included a total of 31 test specimen, each intended for different tests like compression, tension, shear, 3point bending and the hollow cylinder and the cylinder with infill were intended for buckling test. The test print also included ‘lean sensitivity’ study of 3d lattice structure to find out the if the lattice geometries are printable or would they collapse at different angles to the build plate. See appendix A for print pictures.

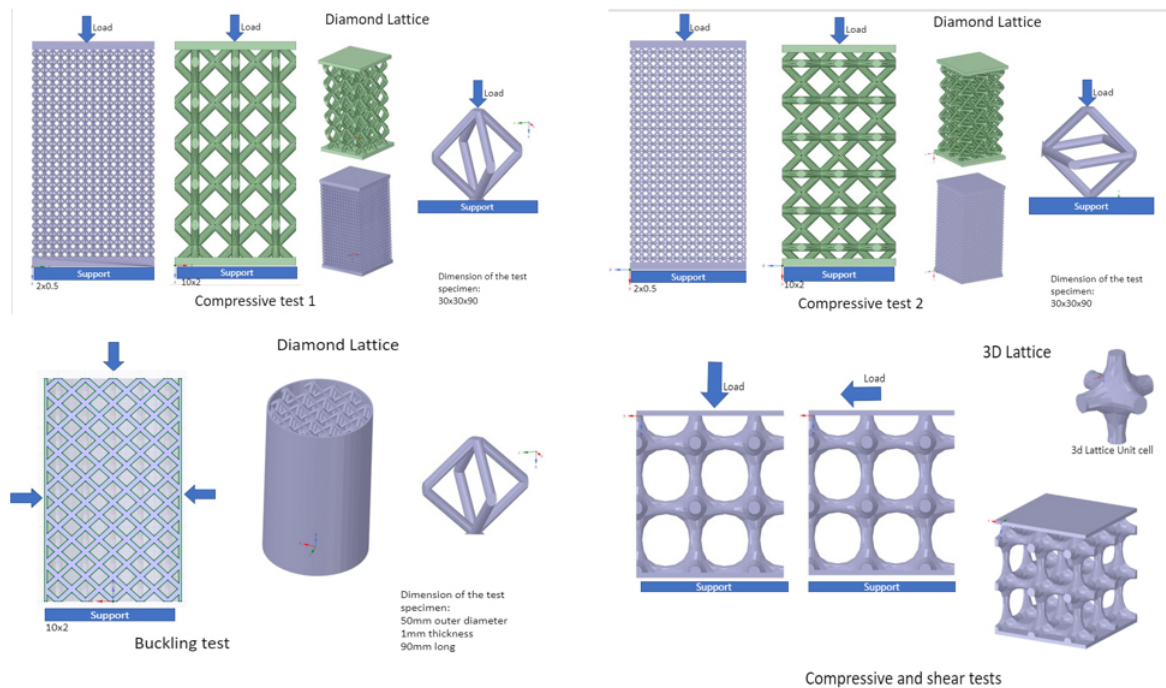


Figure 4.3: Test print plan

The test prints also included diamond lattice oriented in a different direction which makes some members of the diamond lattice to be completely horizontal to the build plate. The results from these prints allowed us to conclude that horizontal members can be printed without any additional supports. This allows us to print the diamond lattice of length 5mm in any orientation without a failure.

4.3 Geometry and mesh structure

Single lattice structure:

The purpose of this study was to investigate the stiffness characteristics of the different lattice geometries under compressive and shear loading. This would give us an idea about the best loading directions for a particular lattice geometry. Based on this data, we can orient the lattice structure in final component in a way which is best suitable for the component's loading conditions. Elastic material properties used for stiffness analysis for both 3d and Diamond lattices are specified below for AlSi10Mg material.

- Young's modulus: 76600MPa
- Poisson's ratio: 0.33

The geometry and mesh configuration used for stiffness analysis for both 3D and Diamond lattices are explained below. This applies to linear stiffness evaluation and for plastic behavior estimation using the plasticity model which is built in the AlSi10Mg material in the ANSYS material library of the lattices for compression load analysis and shear load analysis. Single 3d lattice geometry was created in ANSYS Spaceclaim CAD tool of length 4.1mm, 1mm thickness (mass 6.4331e-005 kg, Volume fraction: 0.193). Single diamond lattice geometry was created of length 5mm, 1mm thickness (mass 4.742e-005 kg, Volume fraction: 0.142). The automatic meshing algorithm targets a uniform mesh size of 0.2mm. Virtual cells were created to allow smooth mesh creation with acceptable aspect ratio between the virtual cells. The orientation of the lattice geometry in space with respect to the global co-ordinate system is shown below. Two different simulations were conducted for the diamond lattice structure and the forces and boundary conditions are defined with respect to the global co-ordinate system.

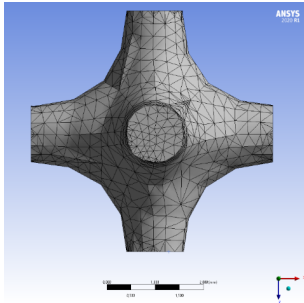


Figure 4.4: 3d Lattice geometry with mesh

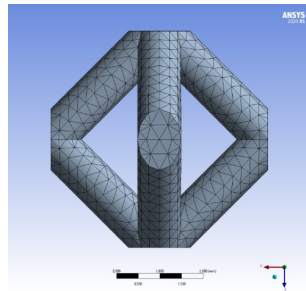


Figure 4.5: Diamond lattice geometry with mesh

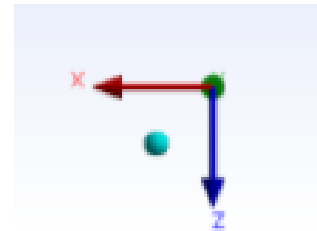


Figure 4.6: Co-ordinate system

4.4 Boundary conditions

In-plane displacement boundary condition was specified on the faces of the lattice geometry as shown in the figure 4.6 (highlighted by yellow color). The in-plane displacement boundary conditions specify in-plane motion of the specified faces to capture the proper linear behavior of each lattice unit cell. A force was specified on the top of unit cell face (indicated by the red arrow), the other boundary conditions specify displacement

boundary conditions where each of them is restricted to their respective planes. These boundary conditions completely constrain the lattice geometry in all the directions. Similar boundary conditions are applied for shear load testing as well.

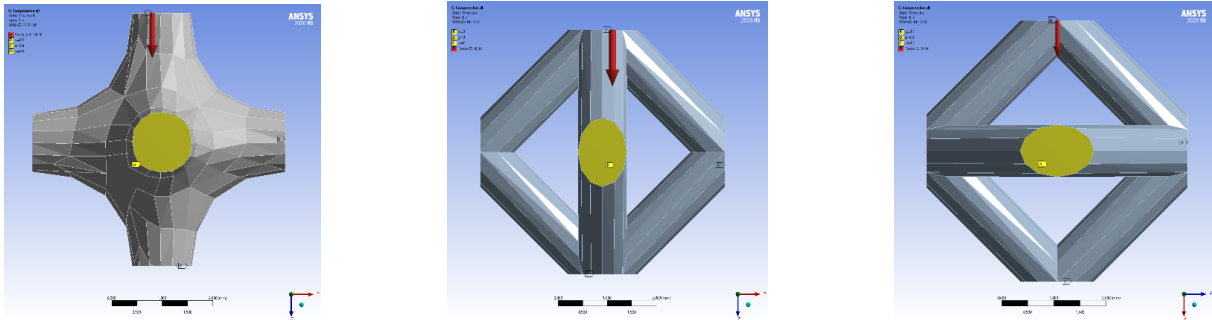


Figure 4.7: Lattice geometries with boundary conditions

4.5 Summary of stiffness evaluation

The stiffness evaluation simulations were conducted for two load cases:

- Compressive load
- Shear load

Below figures show the summarized results from stiffness evaluation simulation. These include the direction of loading and the type of load. Two different loading conditions were evaluated for diamond lattice to find the stiffness and the behaviour. This was done to find how the diamond lattice behaves for loads in x and z directions with respect to the global co-ordinate system.

3d lattice geometry:



Figure 4.8: Linear stiffness of 3d lattice

Diamond Lattice geometry:



Figure 4.9: Compressive stiffness of diamond lattice geometry for x direction load and z direction load respectively

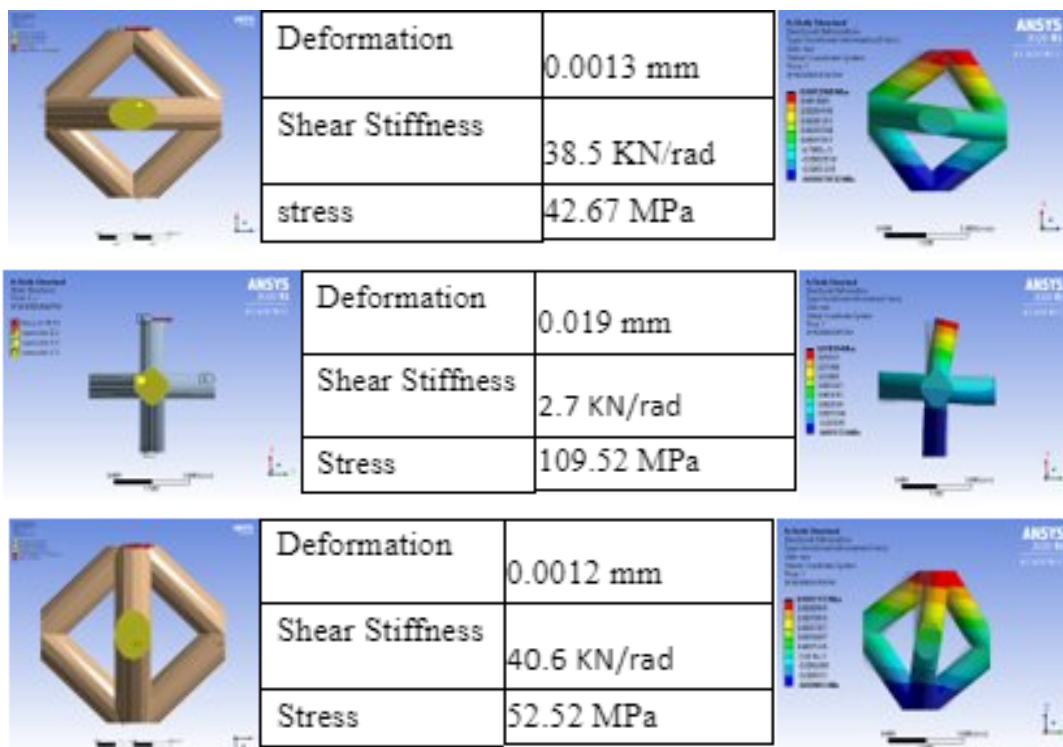


Figure 4.10: Shear stiffness of diamond lattice geometry for x, y and z direction load respectively.

- Stiffness evaluation study was conducted to evaluate stiffness values of the different lattice structures for different loads and different loading positions. The 3D lattice structure is symmetric in all directions. The diamond lattice is unsymmetrical about one particular plane (Depends on the plane in which the geometry is created) and

hence there was a need to evaluate the stiffness performance of the diamond lattice in the two different directions.

- The compressive stiffness of diamond lattice geometry varies for the two different loading directions considered. The compressive stiffness of the diamond lattice geometry oriented in z direction is higher compared to the compressive stiffness of diamond lattice geometry oriented in x direction. This shows that the diamond lattice can absorb more energy along z direction (Ref Figure 4.8).
- The horizontal members of the diamond lattice geometry as seen in pictures for compressive loading x direction do not contribute to carry any load. Hence, the deformation is higher and stiffness is low compared to compressive loading in z direction.
- The max stress seems to be concentrated around one particular element in the mesh which indicates that the actual stress values may differ slightly. The highest stress values should be disregarded since they occur due to discontinues and the local mesh resolution. Instead of making a detailed stress evaluation with categorization of stresses, the strength assessment is made by plastic collapse load estimation, see next section.
- The compressive stiffness of 3D lattice in relation to its mass is 477.355521×10^6 N/mm/Kg and that of Diamond is 422.90025×10^6 N/mm/Kg. This shows that the 3D lattice is stiffer than the Diamond lattice but at the same time it is a tiny fraction heavier than the Diamond lattice.
- The Elastic modulus and the shear modulus values of the diamond lattice was later computed manually to be co-related with the material modeler data in chapter 7. The Elastic modulus E was calculated using the formula $E, G = (F/A)/(\Delta L/L)$ where F = force(N), A = Area(mm^2), ΔL =Directional deformation(mm), L= length of the unit-cell(mm).

Parameters	Calculated Elastic Modulus			Calculated Shear Modulus		
	E1	E2	E3	G12	G23	G31
F(N)	10	10	10	10	10	10
L_0 (mm)	5	5	5	5	5	5
A (mm^2)	25	25	25	25	25	25
ΔL (mm)	0.000977	0.000977	0.000493	0.0188	0.0013	0.00121
Calculated modulus (MPa)	2047.08	2047.08	4060.17	106.406	1542.14	1651.12

Table 4.1: Elastic and shear modulus calculation

4.6 Plastic behaviour analysis of Lattice structures

The purpose of this analysis is to find out the behaviour of the lattice structures in the plastic region. This would give us an idea about the individual lattice structure's load

bearing capacity and failure modes. The raw data gathered from this analysis can be used to run analysis of the complete component geometry with integrated lattice structures.

The geometry and mesh settings for analysis of plastic behaviour analysis and collapse behaviour of single unit cell for both 3D and diamond is same as explained for the linear stiffness analysis. The names assigned to the boundary conditions may differ from the linear analysis case as these two analyses were conducted separately. The boundary conditions for the plastic collapse load analysis is the same for all the cases considered in this section. The cases considered in this section are:

- Compression load analysis
- Shear load analysis
- Tension load analysis

*Tension load analysis used same boundary and support conditions for the respective unit cells with the only difference in the direction of the load.

Plastic Material properties used for stiffness analysis for both 3d and Diamond lattices are specified below. The plasticity model is by default built in to the material selected from “Additive manufacturing materials” in the Ansys Material library. AlSi10Mg material has the following properties:

- Young’s modulus (E): 76600MPa
- Tangent modulus: $E/10=7600$ MPa
- Yield Stress: 250 MPa
- Plasticity model: Bi-linear isotropic Hardening.

All the above-mentioned analyses were conducted with bilinear material properties and nonlinear geometry properties by switching on “Large Deflections” in the analysis settings menu. The tangent modulus value for compression, shear and tension load analysis was set to $E/100$ value. Further, the load is specified in two-time steps in order to capture a proper bilinear curve and till the last converged time step.

4.7 3d Lattice

4.7.1 Summary of plastic behaviour analysis on 3d lattice

1) Compressive load:

- Last converged time step load: 699N.
- Failure occurs due to rupture as strain exceeds the rupture strain of the material.

The force deflection curve in figure 4.11 shows the plastic behaviour of 3d Lattice geometry under compressive load. It can be noted that ‘o’ represents the point on the force vs

deflection curve where the curve starts moving towards the plastic behaviour region. The eq. plastic strain at last converged time step can be seen in the above picture. We can observe a region of high plastic strain exceeding 0.3mm/mm which means that the plastic strain is higher than 30 percent. Here it is quite clear that the local plastic strain is exceeding more than 30 percent which means that the structure will rupture. The load at this time step can be considered as the failure load/rupture load as the 3D lattice geometry ruptures at this load. The plasticity in the lattice keeps increasing and before the plasticity is reaching all the way to the center of the lattice so, the structure ruptures. Failure of 3d lattice happens due to rupture and not because of the formation of plastic hinge.

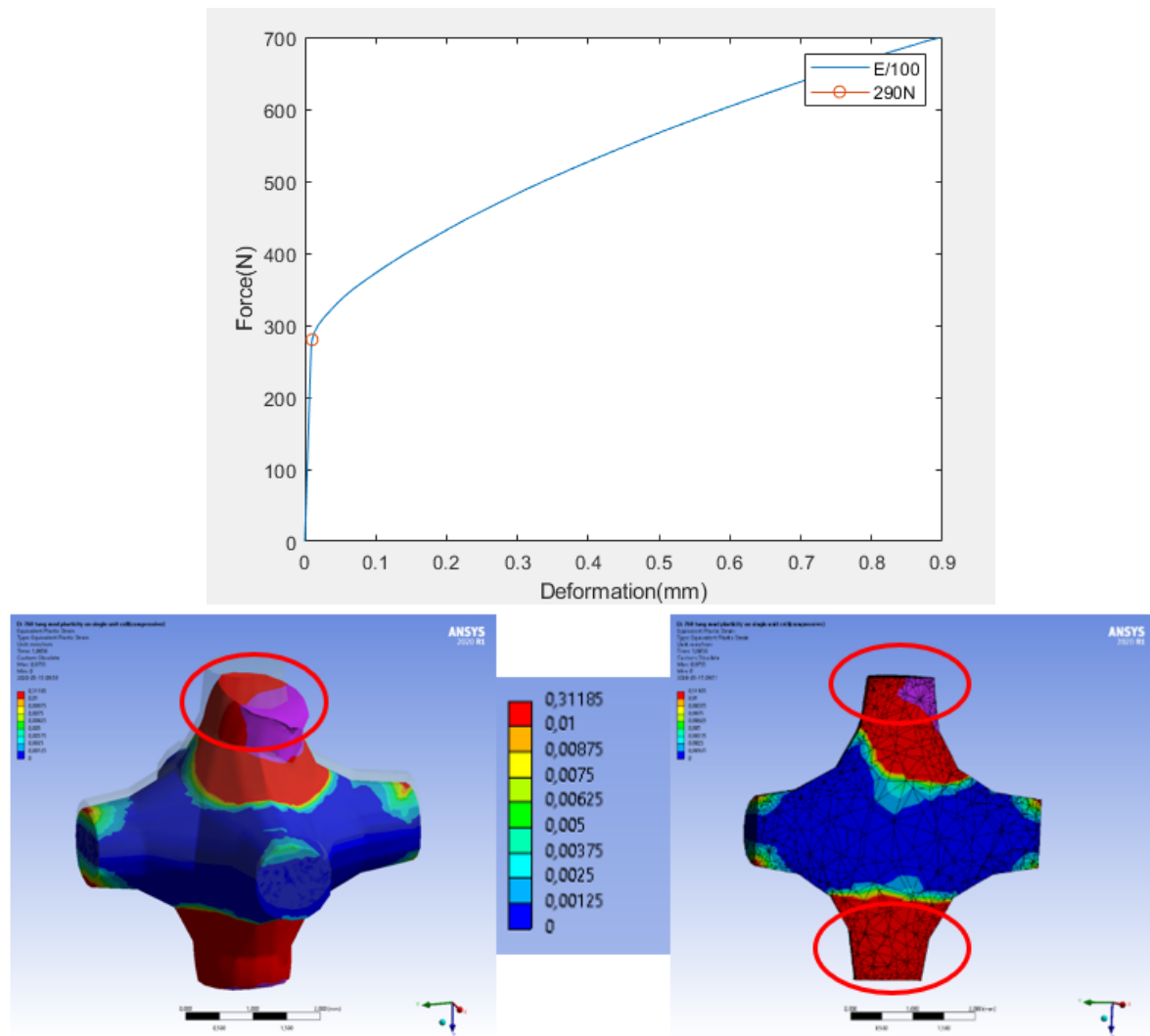


Figure 4.11: Force vs deflection curve for 3D lattice geometry and eq. plastic strain at last converged time step.

2) Shear load:

- Failure happens between 36N – 44N because of the formation of plastic hinge.

The force deflection curve in figure 4.12 shows the plastic behaviour of 3d Lattice ge-

ometry under shear load. It can be noted that * represents the point on the force vs deflection curve where the curve starts moving towards the plastic behaviour region. The force- deflection curve moving upwards indicates hardening. The lattice structure seems to undergo hardening in the plastic region before eventual collapse.

By analyzing the above two pictures, it can be concluded that the failure happens due to the formation of plastic hinge eventually leading to rupture at the top and bottom portion of the 3d lattice structure. The failure happens between time step 1.2405s and 1.2901s which is between 36N – 44N.

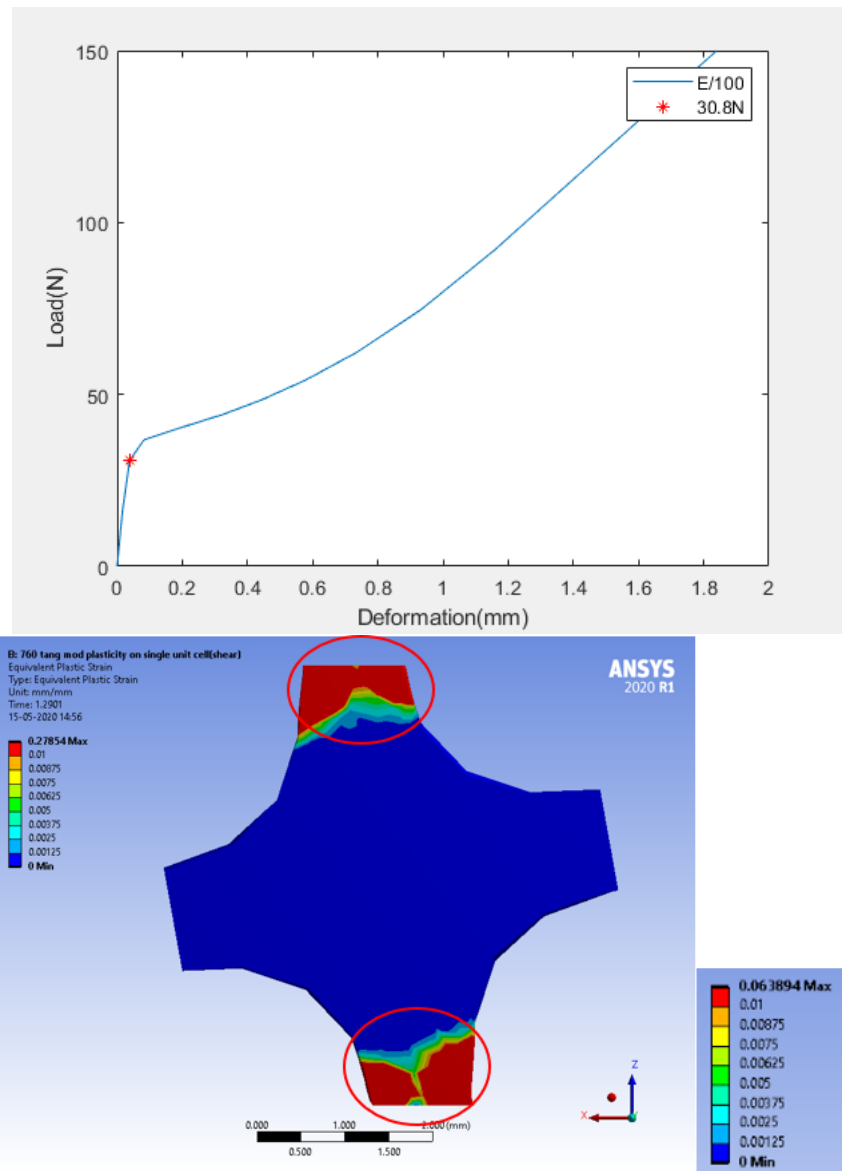


Figure 4.12: Force vs deflection curve for 3D lattice geometry and eq. plastic strain at time step 1.2901s.

3) Tensile load:

- Plasticity starts at 320N.

- Failure occurs between 748-800N because of the formation of plastic hinge.

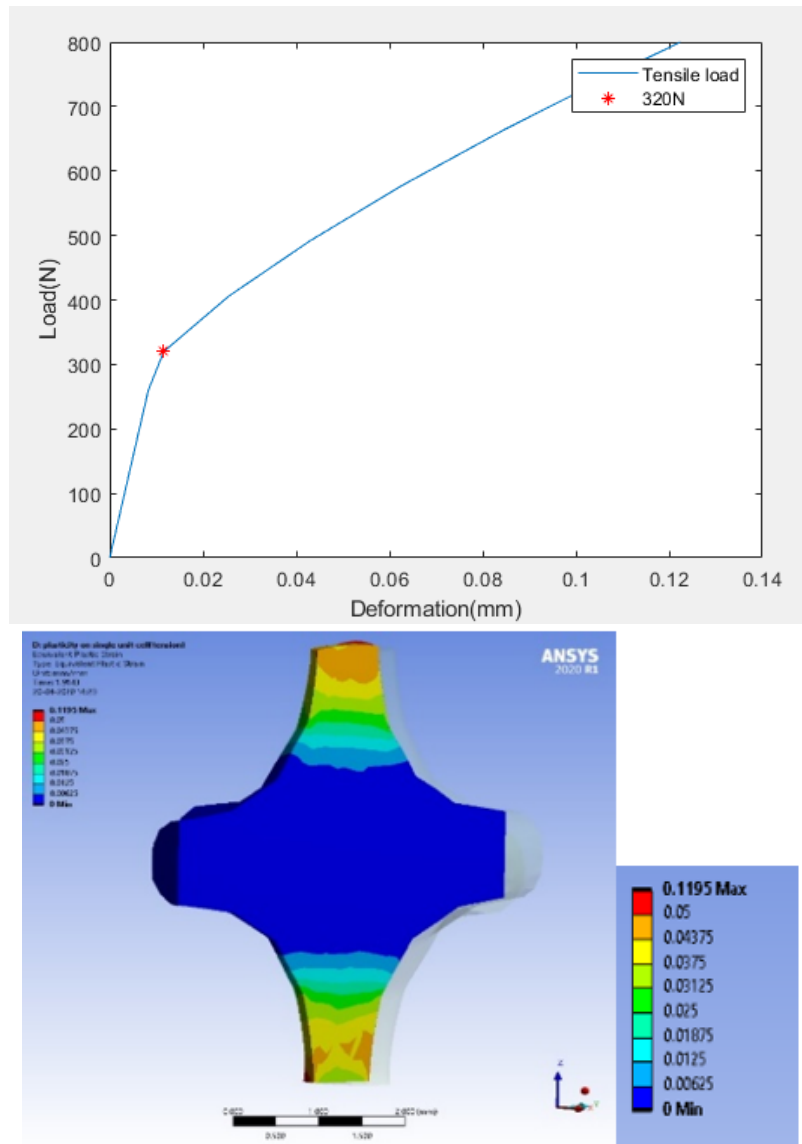


Figure 4.13: Force vs deflection curve for 3D lattice geometry and eq. plastic strain at time step 1.9143s.

4.8 Summary of plastic behavior analysis on diamond lattice

1. Compressive load:

The diamond lattice has better load bearing capacity in z direction compared to x direction load. The load bearing capacity in z direction is almost 2 times better.

- Load in X direction:

1. Failure occurs between 273-280N.
2. Failure happens due to the development of plastic hinge.

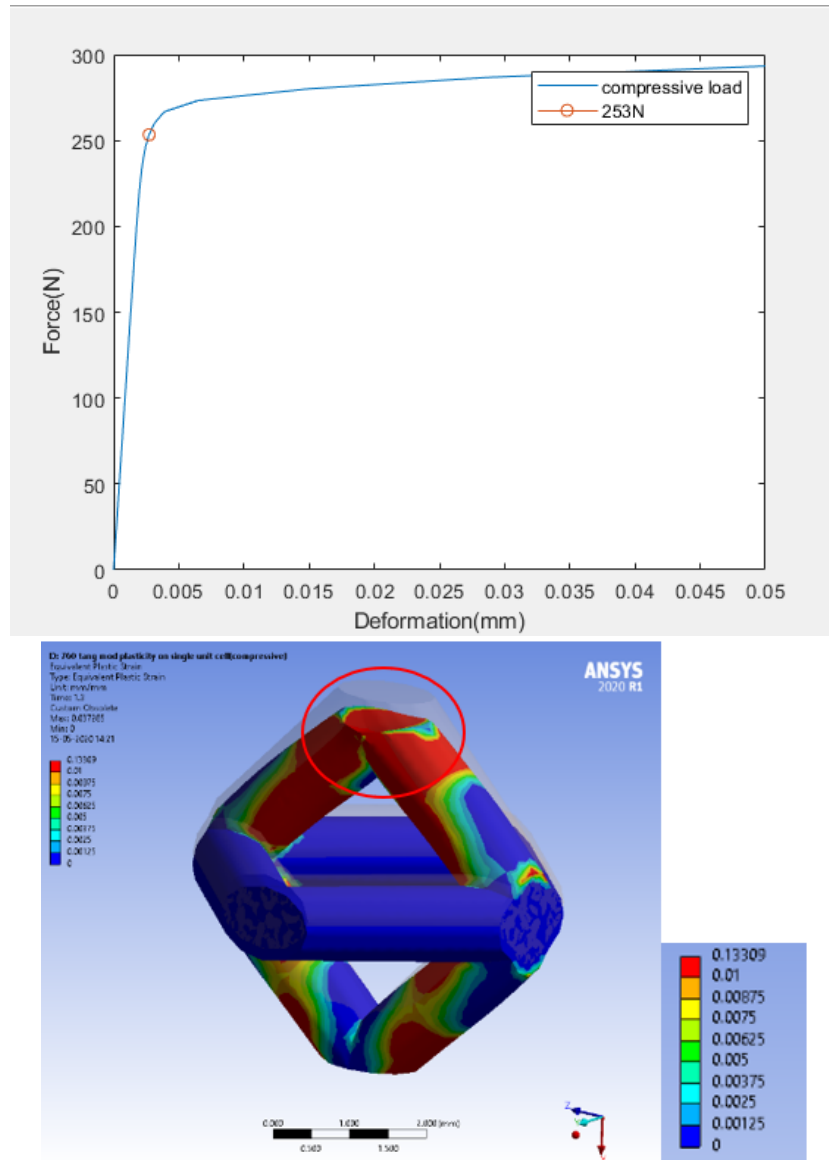


Figure 4.14: Force vs deflection curve for diamond lattice geometry and eq. plastic strain at last converged time step

As seen in the below pictures, the plasticity in the model creeps into the center of the truss member between time step 1.2889 and 1.3s. The load applied at this time step are 273.33N and 280N respectively. This shows that there is a plastic hinge being formed in those truss members causing it to collapse after the last converged time step.

Directional deformation:

From the directional deformation graph, we can conclude that the failure due to the development of plastic hinge happens shortly after time step 1.2889s as the deformation increases rapidly after this time step. From this, it can be concluded that the lattice does not have any more load bearing capacity and collapses shortly after. This abrupt increase in deformation makes the force-deflection curve to continue increasing. For this reason, the last two points on the force-deflection curve is disregarded as they do not represent the true behavior of the lattice structure.

4. Lattice structure study

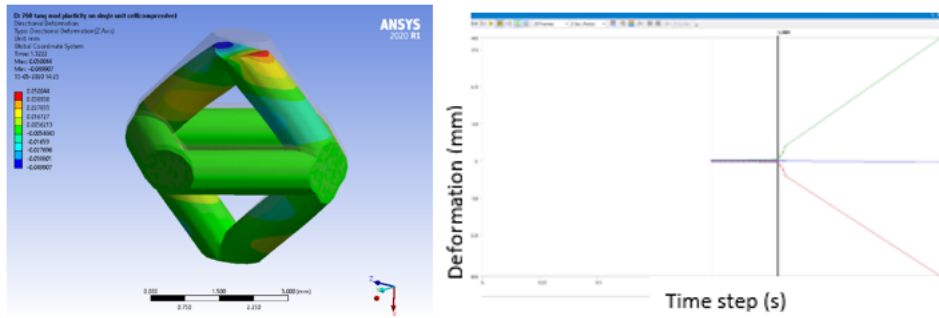


Figure 4.15: Directional deformation of diamond lattice for load in X direction.

- Load in Z direction:
 1. Failure happens due to buckling at the joint.
 2. Failure occurs at 545N.

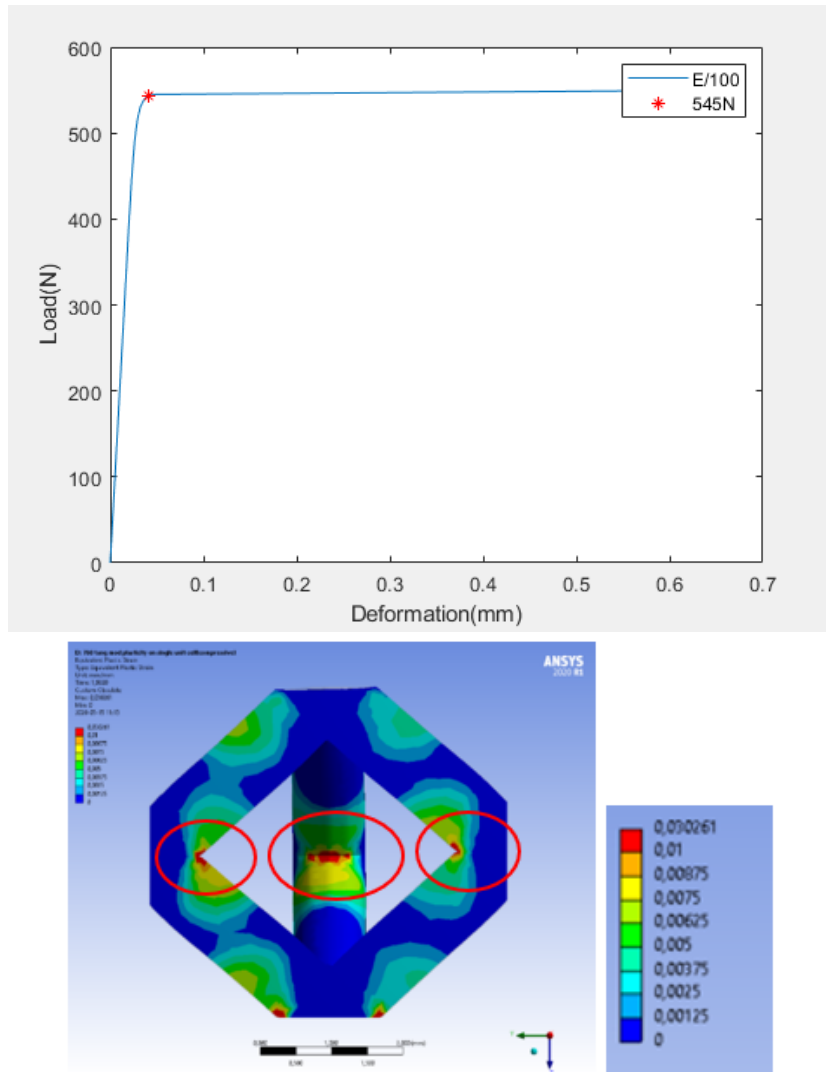


Figure 4.16: Force vs deflection curve for diamond lattice geometry and eq. plastic strain at last converged time step

Plasticity around the edge at the last converged time step exceeds more than 3 percent. The plasticity does not creep in all the way to the middle of the cross-section, this indicates that the failure does not happen due to formation of plastic hinge. However, the deformation suddenly rapidly at time step= 1.9778s which indicates buckling of the diamond lattice structure. The failure of the diamond lattice structure happens due to buckling and not because of development of plastic hinge or rupture. From the force-deflection curve shown above, the energy absorption characteristics of the diamond lattice is very poor as the failure occurs very early in the plastic deformation region.

2. Shear Load:

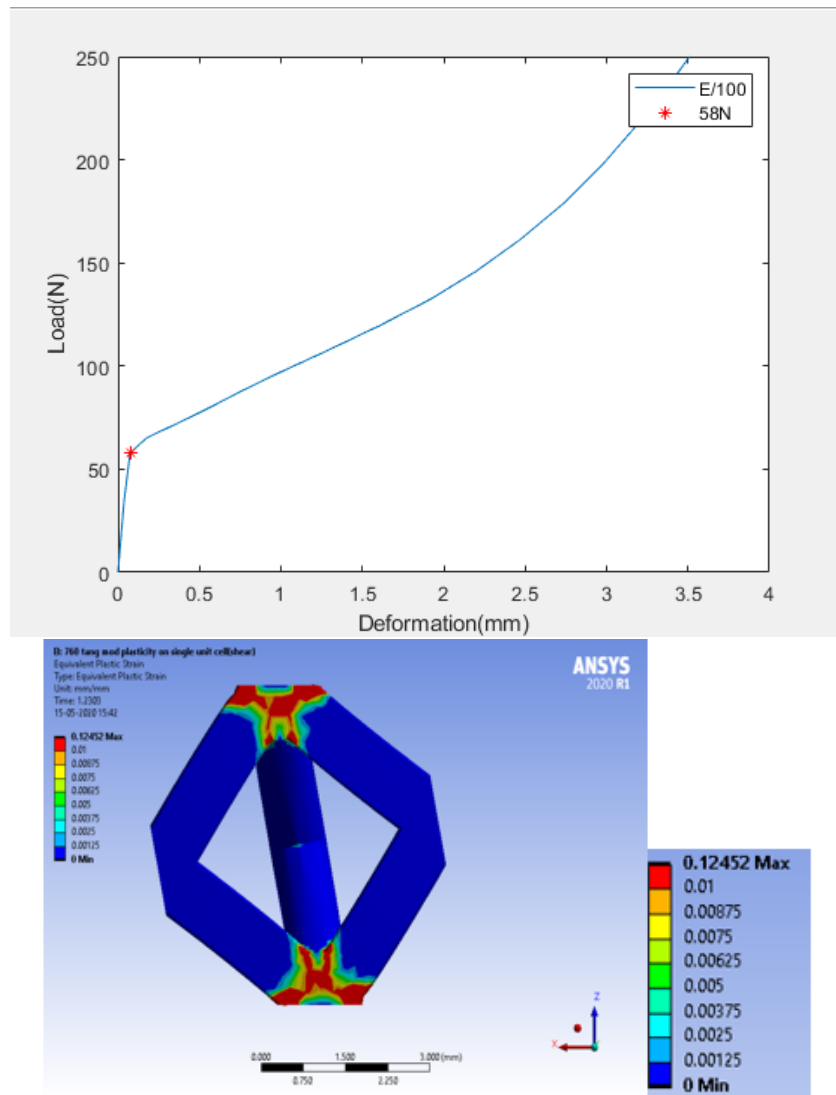


Figure 4.17: Force vs deflection curve for diamond lattice geometry and eq. plastic strain at last converged time step

Shear load analysis was conducted only for one directional load as the linear analysis suggested that the horizontal members do not contribute to carrying the load.

- Failure occurs due to the formation of plastic hinge.

4. Lattice structure study

It can be seen that the extent of plastic strain is all across the lower cross section of the diamond lattice. This results in plastic hinge formation and failure of the lattice structure in the direction of load.

3. Tensile load:

- Failure happens between 1120-1128N.
- Failure happens due to formation of plastic hinge.

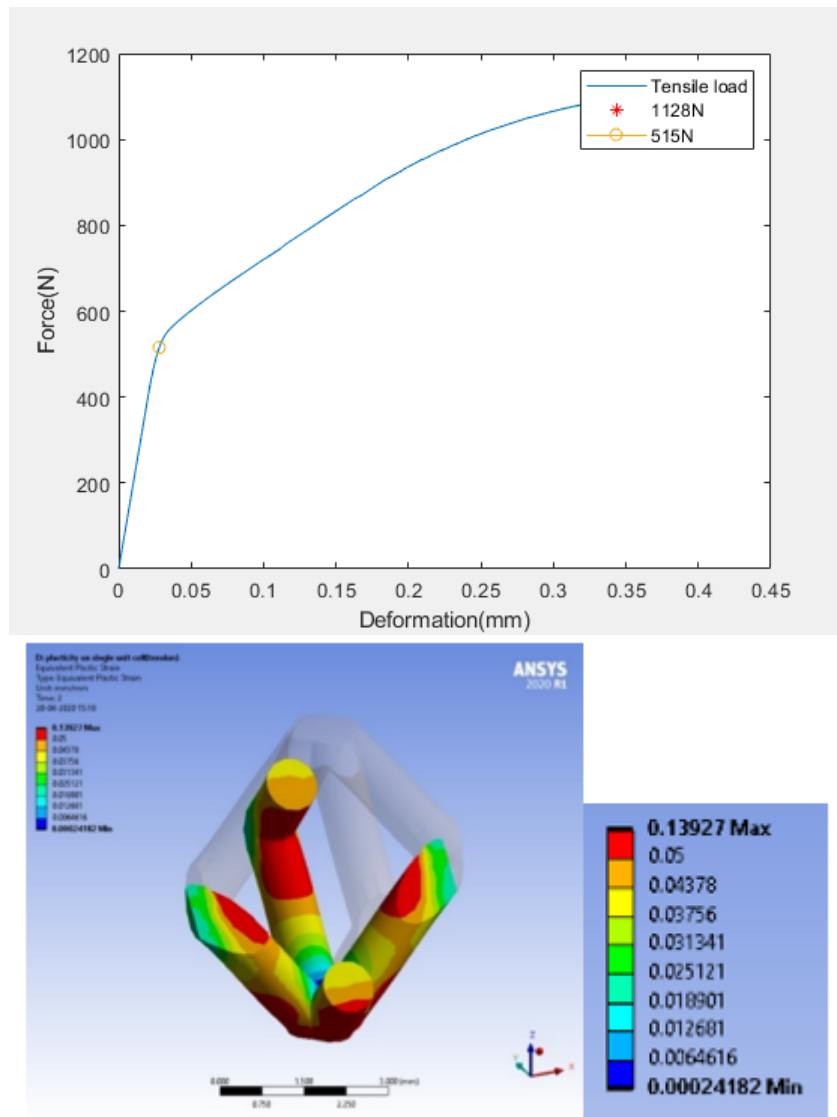


Figure 4.18: Force vs deflection curve for 3D lattice geometry and eq. plastic strain at time step 2s.

5

Topology Optimisation

As stated in the introduction of the thesis and in the theory, TO is an important tool which helps in reducing weight of component keeping parameters like stiffness and stress within acceptable limits. This chapter provides the practical aspect of the TO process along with all the relevant results.

5.1 Background

The design space provided for the finding the TO design to be infilled with a lattice network was not the actual part, but a modification of the actual component(section 5.2) and can be seen in section 5.3. All the boundary conditions for the design space (only the supports was known but the loading conditions was unknown except that a single force of around 1000N is applied to the hinge as explained in section 5.4.1) were not available and hence there was need to implement a reverse engineering approach to properly setup the TO problem in order to get an usable design output. Two simulation strategies were chosen to accomplish the reverse engineering process using Ansys Discovery Live suite for both of them. Ansys Discovery Live which provides a platform to conduct TO in a very quick and iterative way, expecially important in case of reverse engineering approach as various combination of boundary conditions and design space modifications have to be undertaken to get an usable design.

These strategies are documented as trial 1 and 2 in the section 5.4 and 5.5. All the controls like mesh , algorithms etc was automatically selected by the program and only variable in the system was the percentage of material retained and this served as different iterations for both the trial cases. Before starting the trial cases the stiffness of the reference geometry was found in order to act as a benchmark for the TO process helping in deciding the amount of material to be removed from the base design due to lack of boundary conditions. This also ensured the finally selected TO design met the minimum stiffness criterion.

Trial 1 was the simple approach to TO without any modification to the design space and just a single force applied at the hole in the neck .In Trial 2, the design space was modified and a lateral force was added to improve the robustness of the TO setup and the the maximum deformation constraint was replaced by percentage of volume to be retained. The chosen material was Aluminium due to its ability to support long lattice chains during AM prints without sagging.

5.2 Component

The component is pressed sheet metal made of steel called a PIVOT BRACKET and is provided for usage in the thesis to establish the methodology by Volvo Cars. The purpose of the part is to attach the seat to the chassis of the car. It is divided into two parts i.e. left and right which are crimped at several points to attach them together to form the whole component.

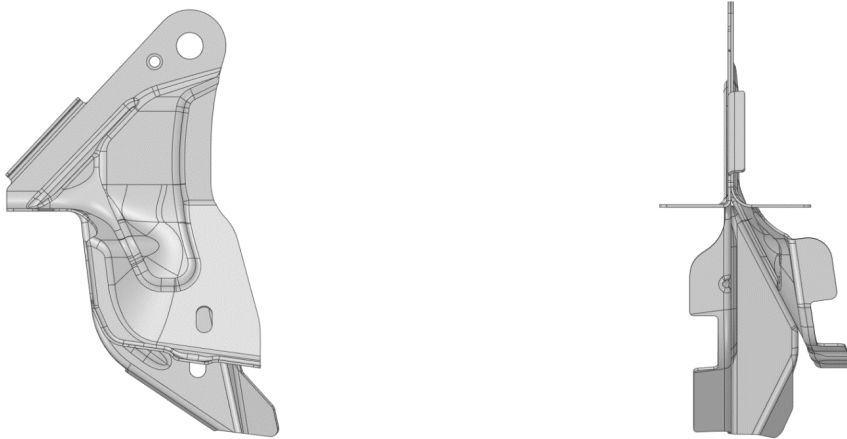


Figure 5.1: Reference geometry (PIVOT BRACKET) in sheet metal

5.2.1 Stiffness Analysis of reference geometry

The stiffness analysis was conducted on the reference geometry by using a force of 1000 N in the -x direction at the centre of the hole and fixed supports were provided at the places where the component is tacked to body of the car. As seen from the figure 5.2 below the deformation value is 0.048 mm for a force of 1000N in -X direction thus giving a stiffness value of 20833 N/mm. This value is the baseline value for the topology optimisation results.

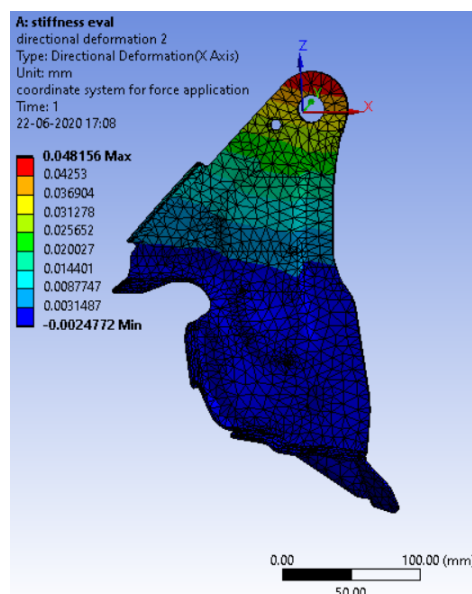


Figure 5.2: Directional deformation of reference geometry in mm.

5.3 Design Space

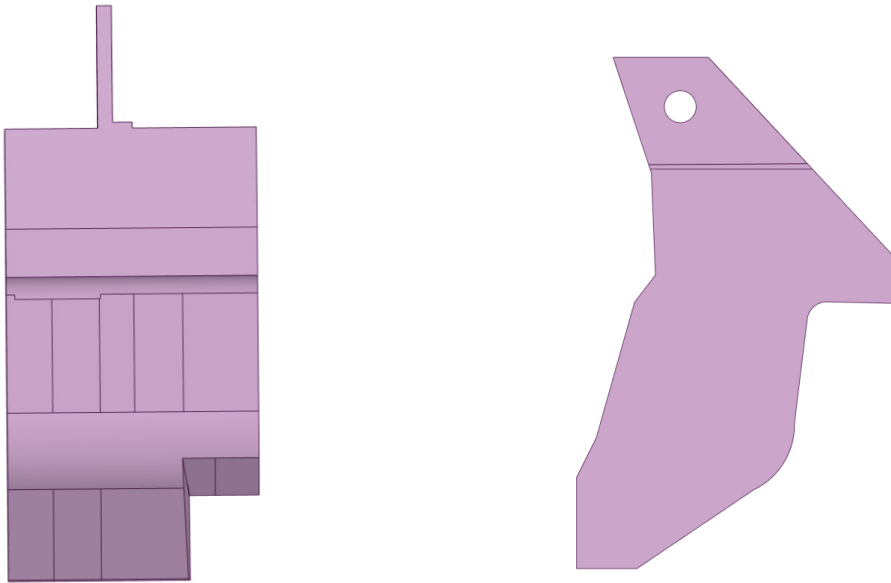


Figure 5.3: Design space

The design space as seen in figure 5.3 is a modified version of the reference geometry for the purpose of demonstrating the process of TO in conjunction with lattice optimisation. It was formed by adding rectangular blocks to the sheet metal design. The fixed support regions were superimposed on the design by tracing them out from the reference design.

5.4 Trial 1

5.4.1 Boundary Conditions

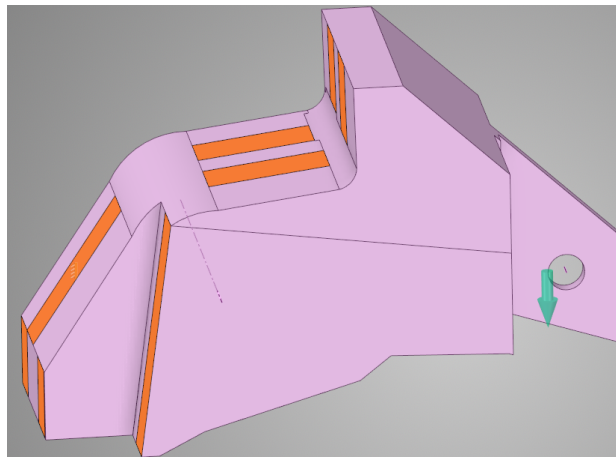


Figure 5.4: Boundary conditions for trial 1, Fixed support(orange areas) , Force(green arrow)

A force of 1000N is applied to the hole in the -x direction. 8 faces are selected as fixed supports in accordance with the reference geometry which act like the welding spots or crimping locations at which the reference geometry is attached to the body(floor) of the vehicle . In the figure 5.4 the orange areas represent the fixed support while the green arrow around the hole represents the force application area.

5.4.2 Design Realisation

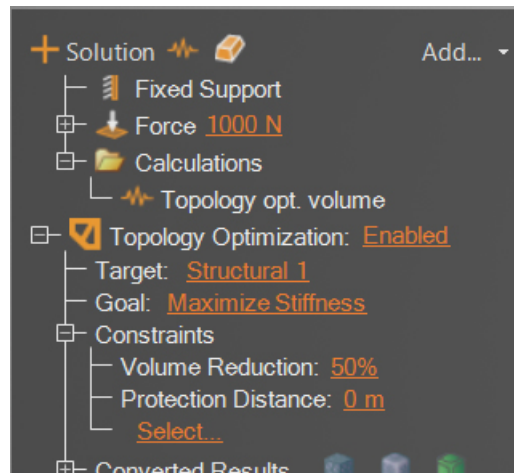


Figure 5.5: Design setup in Ansys Discovery Live for trial 1 showing protection distance, goal and volume reduction.

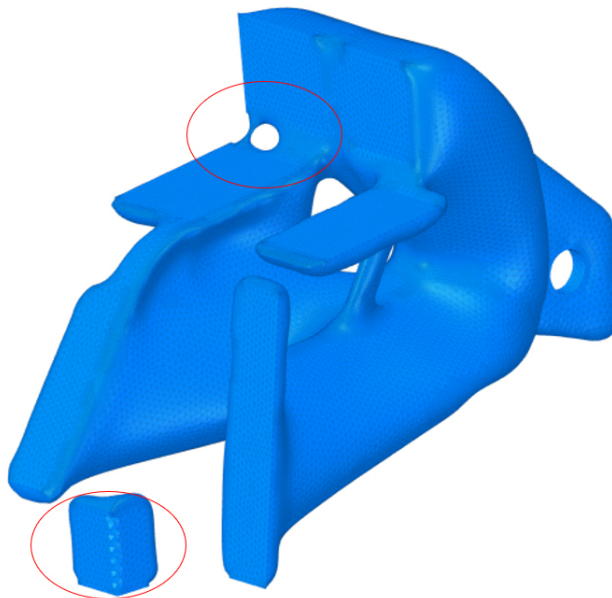


Figure 5.6: TO output for Trial 1 showing gaps in the support areas and hence need to change the TO boundary conditions

The figure 5.5 shows the topology setup that was used to arrive at the design. A volume reduction of upto 70 percent along with a goal of achieving maximum stiffness was tried in an iterative process with a aim of getting an usable TO output. The figure 5.6

gives the final design output from the program. The final design output is a heavily faceted (triangular faces or portion instead of a smooth surface) model called as the STL (Stereolithography) file from which it is clearly visible that there are gaps in the model as marked in red in the figure which shows that even support areas are being removed for the TO program. This was observed even with low volume reduction percentages and hence there was need to safeguard the support structures with the use of protection distance which can be seen in the next trial.’

5.5 Trial 2

5.5.1 Design Space

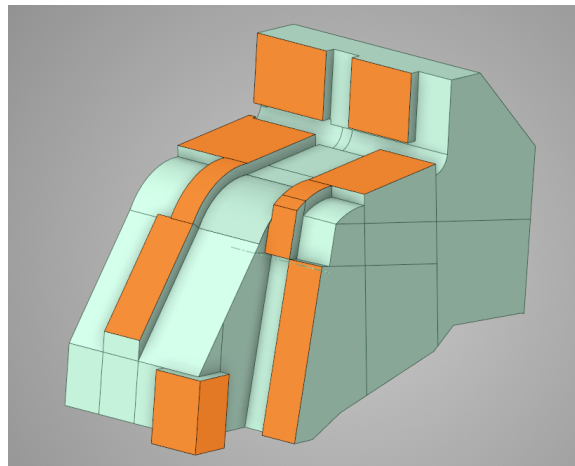


Figure 5.7: Design space for Trial 2 showing the addition of raised fixed support surfaces

In the next trial the design space is slightly modified by addition of raised surfaces (highlighted in the figure above) each of 7mm to the fixed supports. This represents a better solution to the welded or folded joints in the sheet metal design as filler material or crimp volume is also taken into account. The goal of TO is to provide a structure with maximum stiffness for a set amount of material volume to be removed during the TO process.

5.5.2 Boundary Conditions

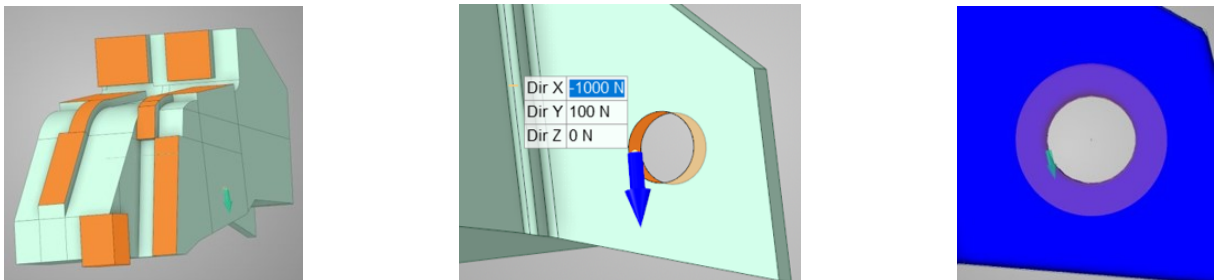


Figure 5.8: Boundary conditions for trial 2 showing fixed supports , applied force and protection distance.

The boundary conditions for this topology setup is as shown in the figure 5.8. The fixed supports are raised 7mm from the original surfaces. The other major change compared to the previous case is the inclusion of lateral force of 100N in the y direction along with a force of 1000N in -x direction to give a resultant force of 1005 N. This is to ensure a more robust design when compared to the previous trial which included force in only one direction. The protection distance for the features(the cross sectional thickness around the supports and the areas where force is applied that should not be part of the TO) is set at 7mm so that an cross section of 7mm from selected surfaces is retained after the topology optimisation. This is to ensure that there is proper connection between the pads and the original structure during the TO process.

5.5.3 Design Realisation

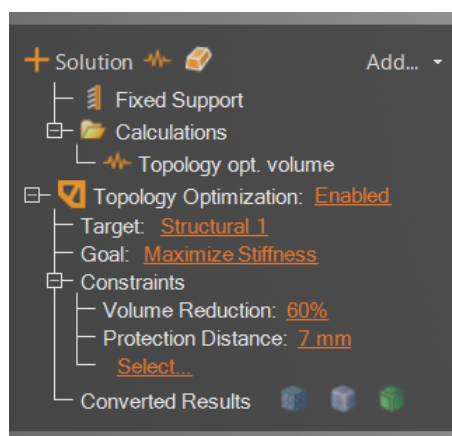


Figure 5.9: Design setup in Ansys Discovery Live for trial 1 showing protection distance, goal and volume reduction.

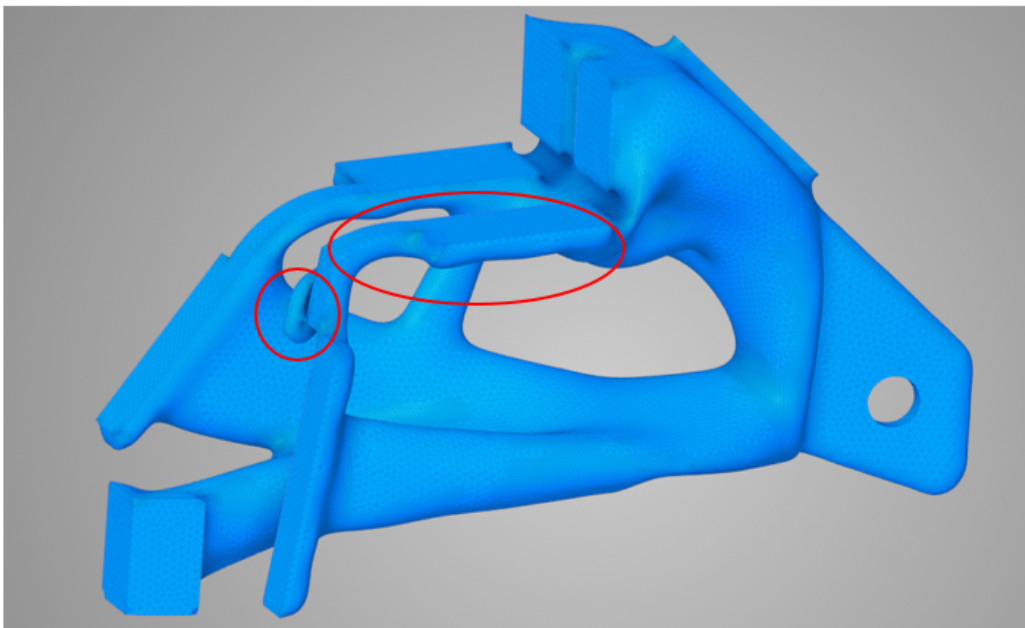


Figure 5.10: Initial TO result in STL format for 2nd trial showing the extra appendices in red.

The figure 5.9 shows the topology setup that was used to arrive at the design. A volume reduction of 60 percent was chosen after an iterative process as this is the maximum volume reduction percentage at which an usable structure (with all the sections attached) could be achieved along with a goal of maximising the stiffness. The figure 5.10 gives the final design that was achieved. As seen from the figure the final design output is a heavily faceted (individual triangulated faces instead of smooth surfaces) model called as the STL (Stereolithography) file which will cause computational problems due to problems in selecting features as they are fragmented. Also, some areas like the appendix marked on the figure needs to be removed as they don't provide any functional support and to further improve lightweighting without appreciable loss to the stiffness. This requires further actions to be performed in order to get a structure that is suitable for FEM calculations and latticing.

5.5.4 Further operations

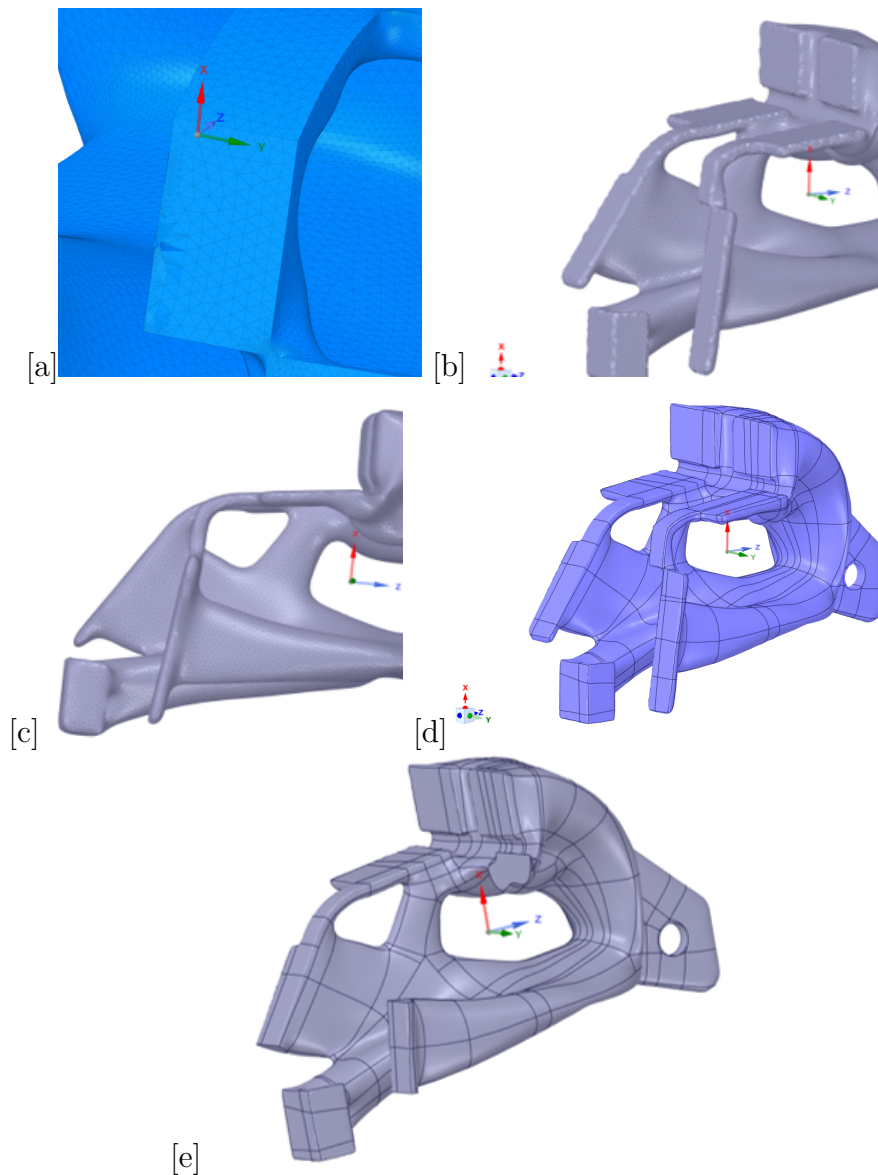


Figure 5.11: (a) Cutting of appendix (b) Shrinkwrapping (c) Smoothing Operations (d) Patch surface generation (e) Final result after excess area removal

The design from topology optimisation is further worked upon in Ansys Spaceclaim to ensure that the STL file(file containing surfaces as triangular facets) is converted in such a way that the structure has smooth surfaces for easy meshing in Ansys Mechanical. The following steps are performed to arrive at the final TO design:

- The original design space is interpolated onto the body and excess areas are cut as shown in Fig 5.11 a.
- The body is then shrink-wrapped which ensures a very tight mesh around the facets and makes the mesh watertight (no elements will be outside the required design area) as shown in Fig 5.11 b.
- The next step as shown in Fig 5.11 c is the smoothing operations where the rough edges and peaks (irregularities in the skin of the body) are made flatter.
- All these operations lead to even more increased number of facets as each resolved peak or valleys adds more facets and hence the final step before converting to a solid is for a reduction in the no of facets. Followed by these steps the faceted STL file is converted to a solid body consisting of many patch surfaces (they are basic surfaces formed by simplifying the facets by using Coons patch method [30])as seen in Fig 5.11 d.
- The final step is to cut out portions that lack support(non-functional) and are free hanging as shown in Fig 5.11 e.

5.5.5 Discussion

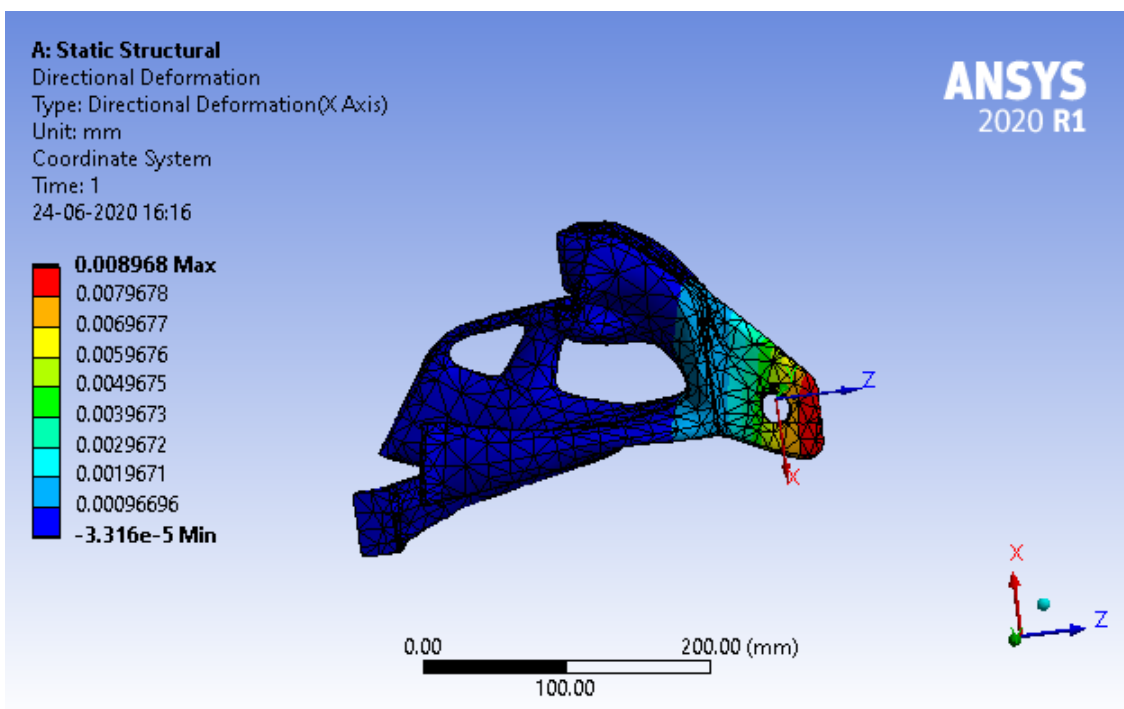


Figure 5.12: Directional deformation for the final TO design in mm.

The final TO design is again subjected to the same boundary conditions in Ansys Mechanical and then a stiffness analysis is carried out. The maximum displacement that the redesigned design file undergoes is 0.008968 mm for the same forces as applied to the design space as shown in figure 5.12. This gives a stiffness value of 112.06 KN/mm.

Original Mass = 10.55 kg

Final Mass = 4.22 kg

Percentage retained = ca 40 percent

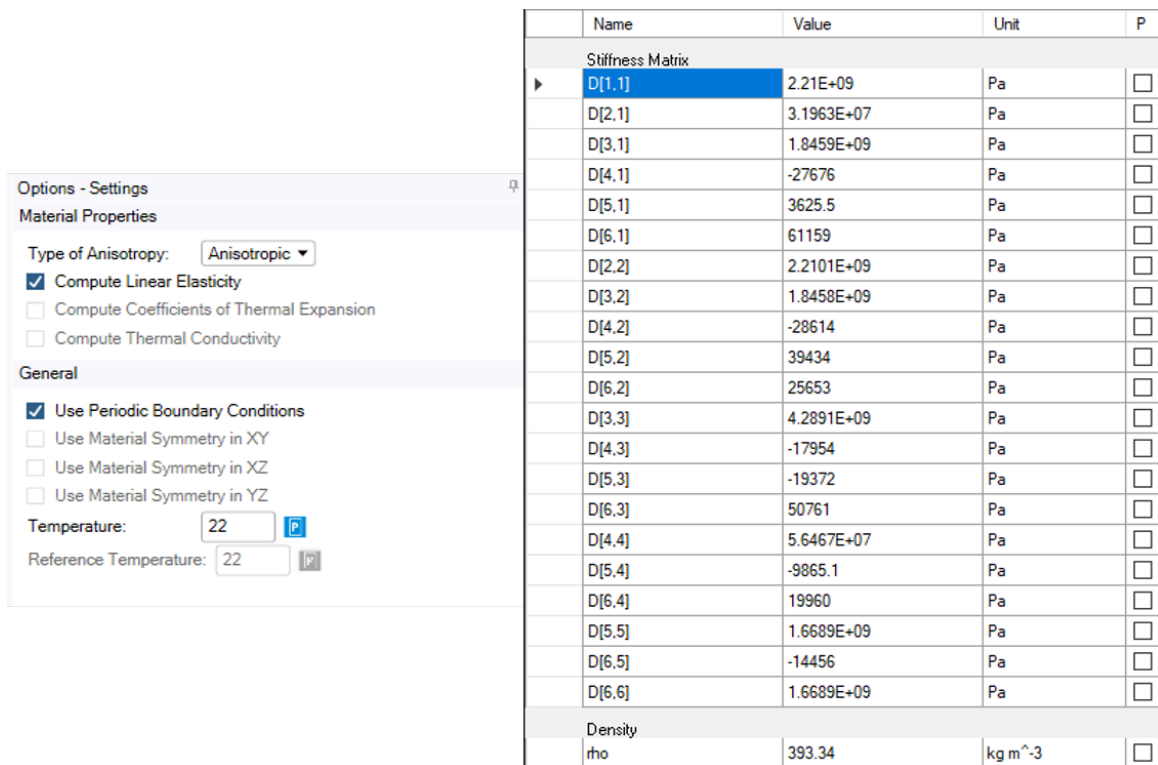
6

Homogenized Model

This chapter explains the practical part of the material homogenisation theory which is present in section 3.3. The procedure to conduct the same in Ansys and results are also tabulated in the chapter.

6.1 Procedure

Homogenised material properties are attained from material designer tool available in Ansys 2020 R1. Using this tool, we can calculate the properties of RVE based in a lattice structure. We start off by linking the engineering data of the analysis system to the take material model data from the material designer tool.



The image shows a software interface for material modeling. On the left, there is a 'Options - Settings' panel with 'Material Properties' and 'General' sections. The 'Material Properties' section includes a dropdown for 'Type of Anisotropy' set to 'Anisotropic', and three checkboxes: 'Compute Linear Elasticity' (checked), 'Compute Coefficients of Thermal Expansion' (unchecked), and 'Compute Thermal Conductivity' (unchecked). The 'General' section includes 'Use Periodic Boundary Conditions' (checked) and three unchecked checkboxes for material symmetry in XY, XZ, and YZ planes. Below these are input fields for 'Temperature' (22) and 'Reference Temperature' (22), each with a unit icon.

On the right, a table displays the 'Stiffness Matrix' and 'Density' properties. The table has four columns: Name, Value, Unit, and P. The 'Stiffness Matrix' section lists 18 entries (D[1,1] to D[6,6]) with their respective values and units (Pa). The 'Density' section lists one entry (rho) with a value of 393.34 and a unit of kg m⁻³.

Name	Value	Unit	P
Stiffness Matrix			
D[1,1]	2.21E+09	Pa	<input type="checkbox"/>
D[2,1]	3.1963E+07	Pa	<input type="checkbox"/>
D[3,1]	1.8459E+09	Pa	<input type="checkbox"/>
D[4,1]	-27676	Pa	<input type="checkbox"/>
D[5,1]	3625.5	Pa	<input type="checkbox"/>
D[6,1]	61159	Pa	<input type="checkbox"/>
D[2,2]	2.2101E+09	Pa	<input type="checkbox"/>
D[3,2]	1.8458E+09	Pa	<input type="checkbox"/>
D[4,2]	-28614	Pa	<input type="checkbox"/>
D[5,2]	39434	Pa	<input type="checkbox"/>
D[6,2]	25653	Pa	<input type="checkbox"/>
D[3,3]	4.2891E+09	Pa	<input type="checkbox"/>
D[4,3]	-17954	Pa	<input type="checkbox"/>
D[5,3]	-19372	Pa	<input type="checkbox"/>
D[6,3]	50761	Pa	<input type="checkbox"/>
D[4,4]	5.6467E+07	Pa	<input type="checkbox"/>
D[5,4]	-9865.1	Pa	<input type="checkbox"/>
D[6,4]	19960	Pa	<input type="checkbox"/>
D[5,5]	1.6689E+09	Pa	<input type="checkbox"/>
D[6,5]	-14456	Pa	<input type="checkbox"/>
D[6,6]	1.6689E+09	Pa	<input type="checkbox"/>
Density			
rho	393.34	kg m ⁻³	<input type="checkbox"/>

Figure 6.1: Material modeller toolbox

In the material modeller toolbox as shown in figure 6.1, we can define the type of lattice structure of which we want the homogenized properties of by setting up the materials,

geometry and mesh inside the material modeller tool. The diamond lattice is created of length 5mm and 0.142 volume fraction. This volume fraction corresponds to the volume fraction of the lattice in the linear stiffness evaluation. The lattice geometry used in this section is diamond lattice and the calculations and material properties discussed in this section is for diamond lattice only. It was not possible to get the isotropic material properties of 3D lattice as it was not readily available as a RVE inside of the material modeller toolbox.

Clicking on analysis tab and adding ‘constant material evaluation’ and selecting ‘Compute Linear Elasticity’, we can generate the required results for the desired lattice structure. In the material modeller toolbox, we can define the type of lattice structure of which we want the homogenized properties of by setting up the materials, geometry and mesh inside the material modeller tool. Clicking on analysis tab and adding ‘constant material evaluation’ and selecting ‘Compute Linear Elasticity’, we can generate the required results for the desired lattice structure. The data shown in the figure 6.1 gives us the consecutive relationship matrix and the diagonal elements D[1,1] to D[6,6] gives us the 3 Elastic modulus values and the 3 shear modulus values. The table 6.1 shows the correlation between the data from linear stiffness evaluation and material modeller data. The difference in the result may be because of the algorithm and the mathematical model used in the calculation of the linear elastic data in Ansys. The differences also arise due to the boundary conditions and meshing resolution.

Values	D[1,1]-Ex (MPa)	D[2,2]-Ey (MPa)	D[3,3]-Ez (MPa)	G12 (MPa)	G23 (MPa)	G31 (MPa)
Calculated	2047.1	2047.1	4060.1	106.4	1542.1	1651.1
Material Modeller	2210	2210	4289	56.50	1669.9	1669.9

Table 6.1: Elastic modulus calculation

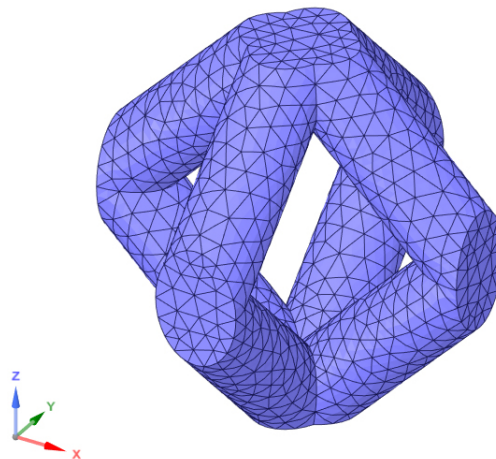


Figure 6.2: Lattice RVE created in material modeller toolbox

The topology optimized design is taken and hollowed out with shell thickness 1mm. This hollow volume inside the topology optimized model represents the lattice structures. The

lattice infill in this case is the diamond lattice infill. This volume is defined by material properties from material modeller data. For FE analysis purpose, we need to specify this hollow volume as a new body inside the topology optimized model and assign the material modeller results to this.

The directional deformation produced by the homogenised model as shown in figure 6.3 with internal diamond lattice geometry yields a stiffness of 20.41 KN/mm. This stiffness is comparable to the stiffness of reference geometry (steel sheet metal pivot bracket designed by Volvo Cars) along with a small reduction in mass.

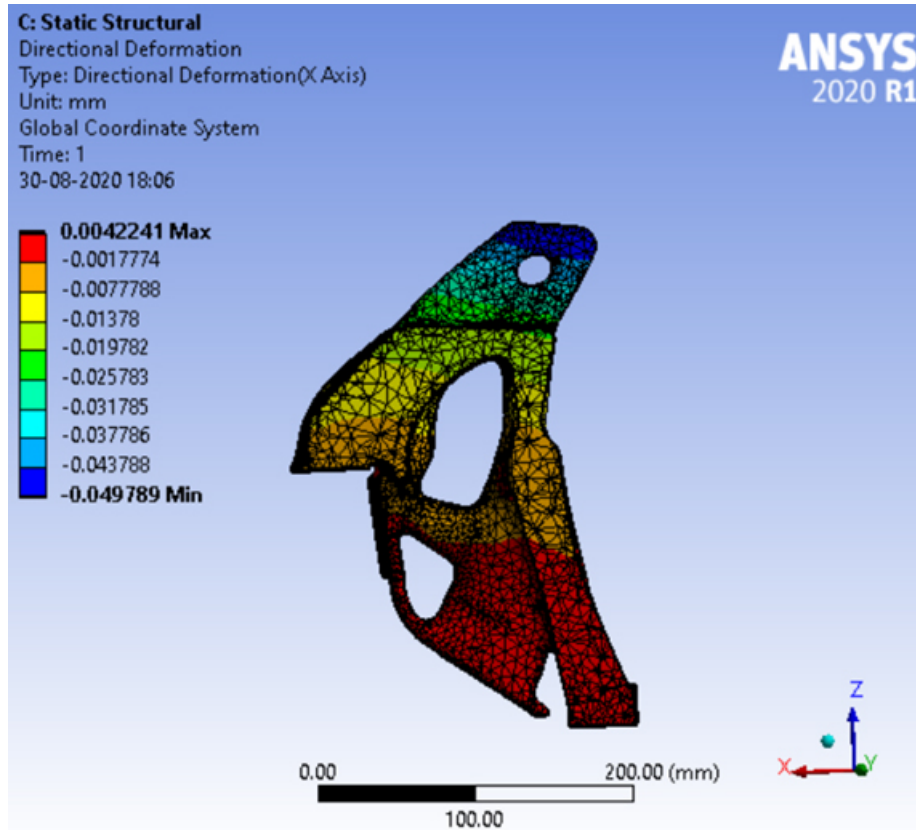


Figure 6.3: Directional deformation of TO model in mm with diamond lattice infill

Original Mass of TO model before hollowing and latticing = 4.22 kg
 Final Mass after hollowing = 0.44 kg
 Final Mass after hollowing and latticing = 1kg

6.2 Overall summary

Structure	Ref Geometry	Solid TO Model	Hollow TO model	Homogenised model
Stiffness (KN/mm)	20.8	112.06	8.33	20.4
Mass (Kg)	1.15	4.22	0.44	1

Table 6.2: Overall summary comparing all the designs

The table 6.1 shows the mass and stiffness values of the reference geometry (steel sheet metal design provided by Volvo Cars), Topology optimized model, hollow topology optimized model and the homogenised model. The results show that the new topology optimized component with integrated diamond lattice structure is of comparable stiffness and weight to that of the reference geometry. This methodology which is derived in this thesis work can be used to a variety of components and their linear behaviour can be analysed and compared to the original design. This methodology allows the component design engineers to design the components considering additive manufacturing constraints.

7

Discussion

This section summarises the results and reflects on the methodology used in the thesis.

The thesis was conducted at RISE IVF, Mölndal. The thesis was conducted on a component provided by Volvo cars called a ‘pivot bracket’. The work was conducted in close collaboration of the authors with the supervisor at RISE IVF, the analysis engineer Mr. Harald Hasselblad, Ph.D at Volvo cars and other personnel at RISE IVF which enabled easy knowledge transfer by conducting weekly meeting which helped the authors gain knowledge along the different stages of the development work.

The work was divided into three main parts which involved TO, Unit cell analysis and homogenized model development and analysis. The main focus of the thesis was to develop a methodology which enables design, development and analysis of components with integrated lattice structures. Latticing alone doesn’t always result in light weighting of the component, but in correct conjunction with TO, latticing can be used in different ways depending on the functionality to reduce weight while maintaining the strength characteristics of the component. A completely solid component can be hollowed out and filled with lattice structure to reduce weight and at the same time maintain the design parameters like stiffness, heat transfer etc. On the other hand, a completely hollow component can be filled with lattice structure which increases the weight but at the same time increases the design parameters like stiffness, heat transfer etc. This thesis provides a methodology to analyze these functionalities and to help designers use latticing based on the function of the component. Additive manufacturing Aluminum and its data available in Ansys material library was used as the material in every step of this thesis. Steel was used as the material for the sheet metal pivot bracket provided by Volvo Cars.

In the TO leg of the thesis, the focus was on creating a topology for the pivot bracket which is completely different from the original sheet metal design. The TO allowed us to create a 3D component which serves the same purpose as the steel sheet metal pivot bracket designed by Volvo cars. The purpose of TO was to create a 3D component which can later be filled with lattice infill and the performance of the component can be analyzed and compared to the original steel sheet metal design. The outcome of TO was hollowed out and it served the purpose for the next step of this thesis work. The second leg of the thesis considered linear stiffness evaluation and plastic behavior analysis of the different lattice structures which were considered for this thesis work. Two different lattice structures were considered in this thesis work. Thesis two lattice structures are completely

different from each other and have different stiffness and plastic behavior. The purpose of linear stiffness evaluation was to find out the stiffness behavior of primarily the diamond lattice because it is un-symmetric along one plane and can be oriented in different directions to the load. The linear stiffness evaluation for compressive load shows that the diamond lattice loaded in Z direction is almost twice as stiffer than it being loaded in X direction. The stiffness behavior of the diamond lattice for shear load is also different for loading in different directions. The difference in the stiffness behavior in different directions of loading is because of the number of truss members of the diamond lattice geometry involved in bearing the load. The diamond lattice with load in Z direction has 4 truss members distributing the load to the bottom which results in lesser deformation of the unit cell where as a load in X direction is transferred through only 2 of the truss members which results in higher deformation and lower stiffness. This is also similar for shear loading and tensile loading of the diamond unit cell. This is the reason why the diamond lattice plasticity tensile analysis was performed for loading in Z direction only. The 3D lattice is stiffer than diamond for compressive load. The shear load stiffness of the 3D lattice is very similar to that of the shear load stiffness of the diamond lattice. The plastic behavior analyses of the two lattice structures gives us an idea about how failure occurs for these different lattices. The 3D lattice fails mainly due to rupture during compressive load whereas the diamond lattice collapses suddenly. The raw data from plastic behavior analysis can be used to evaluate the plastic behavior of the complete component with integrated lattice structures.

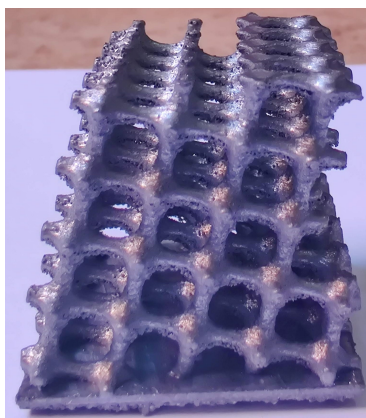


Figure 7.1: 3d lattice buildability

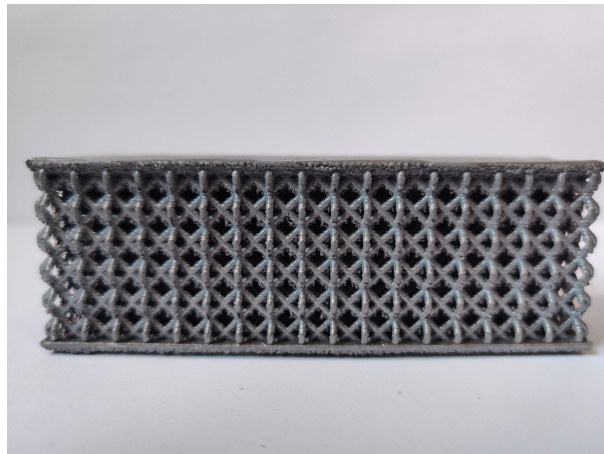


Figure 7.2: Horizontal slab

The following data which will be very important to future lattice structure builds was found out from the test prints:

- The results from the test prints helped us conclude that horizontal members of 5mm can be printed without the need for additional supports. This conclusion means that the other lattice structures available in Ansys Spaceclaim can be used without the need for elimination of the lattices due to one or more members of the lattice geometry being horizontal to the build plate. This means that lattice geometry like ‘Double Pyramid’ of unit cell length 5mm can be printed without the

need for additional supports. The double pyramid lattice is a completely isotropic geometry like the 3D lattice geometry.

- 3d lattice buildability test proves that it can be printed in a few orientations. This allows the designer to have a conformal lattice(body hugging) all through out a AM component.
- Completely horizontal slabs of thickness 1mm can be printed without distortion.

The third leg of the thesis focused on creating a homogenized model and analysis of the same. The homogenized model of the component with integrated lattice structure was created by combining the topology optimization geometry and the linear data from material modeler. The hollow part of the topology optimized component was replaced by a volume of material. This volume had the properties which were derived from material modeler. The data derived from material modeler was only for diamond lattice in linear elastic stage. The 3D lattice data was not available in material modeler as there is no option for creating a 3D lattice and extracting the values for the same. The material modeler data is only the linear elastic data and not plastic behavior data.

The final results of the linear analysis of the homogenized model was compared to the linear analysis of the steel sheet metal pivot bracket given by Volvo Cars. The final result comparison and analysis showed that the topology optimized pivot bracket component with integrated lattice structure was slightly lighter than the steel sheet metal pivot bracket designed by Volvo Cars and of comparable stiffness. This methodology allowed the authors to create a component design design and that is integrated with lattice structure and has a comparative stiffness design parameter of the original component. The design is also potentially manufacturable by AM, but the time limit prevented the actual printing process and hence all results were verified virtually. This methodology can be used for components that are fit for manufacturing via additive manufacturing for the purpose of lightweighting without much loss of structural integrity .

8

Recommendations

The thesis was bound in respect to both time and resources. Hence, these are suggestions to carry out potential future works to build upon the thesis.

- Some more constraints for additive manufacturing like beam thickness, wall thickness, resolution of lattice etc. can be added to the TO process during trial case 2 to get a design that can be printed at a single time without internal supports due to component being supported by internal lattice network.
- Lattice optimisation can be used in conjunction with TO to get an optimised structure already infilled with lattice instead of doing the steps separately.
- Further types of lattice structures to the ones already studied within Ansys can be explored.
- Investigate lattice design in softwares that are specialised on geometrical customization of lattice as a contrast to ANSYS which has a limited customization capabilities and is more focused on structural analysis.
- Further application of lattice structure other than for strength and robustness for heat conductivity , sound absorption , crash structures etc . can also be studied. This will ensure wider application of latticing which would also answer the high cost question raised for AM since lattices are most efficiently or sometimes only produced by AM.
- No physical tests were conducted on the test prints due to scope limitations . Tests like tensile, compressive, shear tests can be conducted on the test specimens to validate the structural simulation results.
- Although the 3D lattice geometry was not readily available as an RVE in material modeller, there is a possibility to create it separately and then get the linear elastic properties of it through material modeller. This needs some looking into as it requires phase definition and other things which make it a little more complicated.
- Creating the diamond lattice geometry in material modeller in a different direction of orientation needs to be looked into and analyses of the same should follow.
- Other potential lattice structures like ‘Double Pyramid’ or ‘Diamond with cross members’ can be potentially used as internal lattices. The Double Pyramid lattice

is of particular interest because of its isotropic geometry and nature. Future work considering double pyramid lattice or 3D lattice geometry up to a length of 5mm has to be further looked into as they could potentially be used as a body conformal lattice allowing the lattice geometries to be oriented in any direction without the risk of printing failure.

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Test Prints

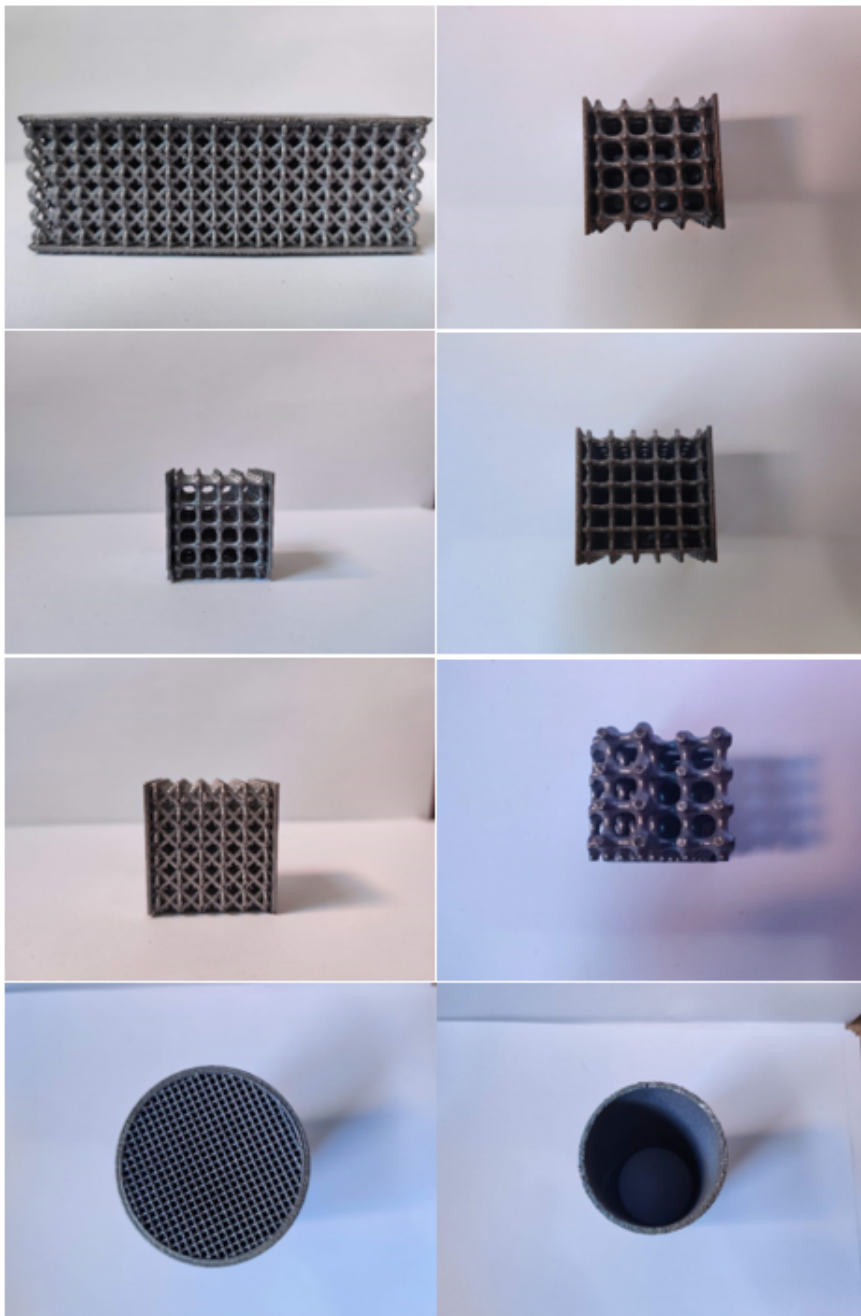


Figure A.1: Test Prints