Performance of additively manufactured kagome unit cells and its sandwich structures

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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

SINGAPORE

**PERFORMANCE OF ADDITIVELY MANUFACTURED
KAGOME UNIT CELLS AND ITS SANDWICH STRUCTURES**

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SCHOOL OF MECHANICAL & AEROSPACE ENGINEERING

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ITS SANDWICH STRUCTURES**

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SCHOOL OF MECHANICAL & AEROSPACE ENGINEERING

A thesis submitted to the Nanyang Technological University in
partial fulfilment of the requirement for the degree of Doctor of
Philosophy

2019

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

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I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

24 May 2019

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Assoc/Prof Sridhar Idapalapati

Authorship Attribution Statement

This thesis contains material from 3 paper(s) published in the following peer-reviewed journal(s) / from papers accepted at conferences in which I am listed as an author.

Chapter 3 is published as R. Gautam, S. Idapalapati, & S. Feih. Printing and characterisation of Kagome lattice structures by fused deposition modelling. *Materials & Design*. **137**, 266-275 (2018).DOI: doi.org/10.1016/j.matdes.2017.10.022

The contributions of the co-authors are as follows:

- Assoc/Prof Idapalapati and Dr. Feih provided the initial project direction and edited the manuscript draft.
- I prepared the original draft and Assoc/Prof Idapalapati and Dr. Feih revised the manuscript.
- I co-designed the study with both co-authors. All the experiments were conducted by me at materials lab 1 in School of Mechanical and Aerospace Engineering. I also analyzed the data.
- The roughness measurements and confocal microscopy were conducted by me in metrology lab.
- Assoc/Prof Idapalapati and Dr Feih provided guidance in the interpretation of the results.

Chapter 4 is accepted as R. Gautam, S. Idapalapati. Compressive properties of additively manufactured functionally graded Kagome lattice structure. *Metals*

The contributions of the co-authors are as follows:

- Assoc/Prof and I co-designed the study of functionally graded Kagome lattice structures.
- All the experimental works are carried out by me.
- I drafted the manuscript and Prof Idapalapati revised the manuscript.
- Assoc/Prof Idapalapati provided guidance during the data analysis as well as the interpretation of the results.

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- Assoc/Prof Sridhar and I co-designed the study.
- All the mechanical testings were conducted by me in materials lab 1 at School of Mechanical and Aerospace Engineering.
- I prepared the original draft and Assoc/Prof Idapalapati revised the manuscript.
- The material characterization using optical microscope and scanning electron microscope were conducted by me in materials lab 1.
- The data was analysed by me and Assoc/Prof Idapalapati supervised me during the experiments, analysis and interpretation of results.

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Abstract

Lightweight, high strength and high energy absorption material are of interest in aerospace, automobile and defence industries. Sandwich structures with lattice core exhibit high specific strength and stiffness when compared to monolithic structures. The development of different additive manufacturing technologies has enabled the fabrication of complex cellular structures of low relative density, to enable energy management in impact and crash scenarios. It is necessary to investigate and enhance the mechanical properties of the lattice structure fabricated by additive manufacturing. In this thesis, quasi-static compression and flexural behaviour of Kagome sandwich structure fabricated by additive manufacturing is investigated.

Fused deposition modelling (FDM) is useful to fabricate various parts of unmanned aerial vehicles (UAV). The structural efficiency of the UAV can be improved by using the cellular lattice structures which provides better specific strength and stiff structures. Thus, it is important to investigate the mechanical properties of the cellular structures fabricated by FDM. Initially, the compressive performance of Kagome unit cell structure of acrylonitrile butadiene styrene (ABS) fabricated by FDM is investigated. The influence of part build orientation, strut diameter and surface roughness on the strength and effective moduli is critically explored. The change in the build orientation improved the average peak strength and effective moduli by 23% and 19% respectively due to the change in strut dimensions with different build orientation as well as the anisotropic compressive behaviour of FDM printed parts. The finite element based numerical simulation results of effective

stiffness differed from experimental measurements by 10-17% due to imperfections like voids and surface staircases which are imminent in the parts fabricated by FDM. The surface roughness of the printed parts was reduced by chemical surface treatment with 90% by vol. acetone. Five minutes treatment time on the Kagome specimens proved to be optimal based on the measured surface roughness, compressive strength and effective moduli of Kagome structures.

Then, the compressive performance of unit Kagome structure was compared with the multi-units Kagome structures. The effect of the increase in the number of layers in the compressive performance in terms of average strength and effective moduli was also investigated. Also, the performance of uniform density and gradient density Kagome structure and their deformation behaviour were explored. It was found that the performance of the unit structure and multi-unit structure were comparable. The initial failure in both cases was similar and was around the joint of struts with the face sheets. The increase in the number of layers increased the effective moduli of the structure whereas the strength was almost the same within the relative density range of samples tested. The graded density Kagome lattice structure was found to have better energy absorption over the uniform density structures by 35%.

Another major contribution of the thesis work is in the design modification of the existing Kagome structure to enhance the compressive performance. A vertical strut was introduced in the existing design and called as strut-reinforced Kagome (SRK) structure. The unit SRK and Kagome structure were successfully fabricated through selective laser melting without any additional support structure. The compression properties of SLM printed Ti-6Al-4V SRK

was explored with the variation in the aspect ratio. An analytical prediction for effective modulus and peak strength of SRK structure was proposed and compared with numerical simulation and experimental results. The performance of unit SRK was also compared with unit Kagome structure with the same relative density. The analytical solution well predicted the compressive strength within 12% accuracy with the experimental results whereas the effective moduli differed by 12-24%. For the specific case studied, it was observed that the SRK unit structure had better effective modulus (12.87%) and peak strength (13.42%) than Kagome unit structure. The sub- β -transus heat treatment was carried out on SRK and Kagome samples, and they were subjected to compression tests. The peak strength of the structure reduced by 11-15% while the effective moduli of the structures increased by 40-48% after the heat treatment. The failure strain and energy absorption increased by 37-70% and 19-35% respectively with the heat treatment.

Finally, the flexural performance of the sandwich beam with Kagome structure as a core was studied through finite element based numerical simulations. The analytical solutions for different failure modes under three-point bending were derived. A failure mode design map was constructed with non-dimensional failure loads expressed in terms of non-dimensional geometrical parameters of face sheet thickness and core height. Four different cases of various geometrical parameters were studied under three-point bending simulations in ABAQUS®, and the peak load, stiffness and failure mode were observed. The failure mode of the samples matched with the one predicted by failure map for core shear mode A and B and local indentation. The peak loads were found to be within 10% of the solution obtained by the analytical solution.

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List of Symbols

A	Area of the strut
A_{eff}	Effective area of the Kagome structure
b	Width of sandwich beam
c	Half-length of strut in Kagome structure
d	Diameter of strut
D	Overhang length
d_s	Diameter of slanted struts
d_v	Diameter of vertical strut
E_o	Young's modulus of parent material
E_{cell}	Effective modulus of lattice structure
G_c	Shear modulus of core structures
h	Height of core of unit Kagome
H	Total height of Kagome core in sandwich beam
h_l	Half the height of unit Kagome
l	Total length of strut
L	Length between two support structures in three point bending
P_{CSA}^E	Failure load due to core shear mode A with elastic buckling
P_{CSA}^P	Failure load due to core shear mode A with plastic buckling
P_{CSB}^E	Failure load due to core shear mode B with elastic buckling
P_{CSB}^P	Failure load due to core shear mode B with plastic buckling

P_{FW}	Failure load due to facesheet wrinkling
P_{FY}	Failure load due to facesheet yielding
P_I^E	Failure load due to local indentation with elastic buckling
P_I^P	Failure load due to local indentation with plastic buckling
t_f	Thickness of facesheet
U	Strain energy
δ	Displacement in vertical direction
ε_{cell}	Macroscopic strain of lattice structure
θ	Inclination angle
$\bar{\rho}$	Relative density
σ_{cell}	Stress of the lattice structure
σ_o	Yield strength of the material
τ_{cell}	Shear strength of Kagome structures

List of Abbreviations

3D	Three-dimensional
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
ASTM	American Society for Testing And Materials
BCC	Body Centred Cubic
BCC-Z	Body Centred Cubic with Vertical Column
CAD	Computer Aided Design
CNC	Computer Numerical Control
EBM	Electron Beam Melting
F ₂ BCC	Two BBC Unit Cells
FBCCXYZ	Face and Body Centred Cubic with Vertical and Horizontal Struts
FBCCZ	Face and Body Centred Cubic with Vertical Struts
FCCZ	Face Centred Cubic with Vertical Struts
FDM	Fused Deposition Modelling
LENS	Laser Engineered Net Shaping
LOM	Laminated Object Manufacturing
LVDT	Linear Variable Displacement Transducer
PC	Polycarbonate
SEM	Scanning Electron Microscope
SLA	Stereolithography Apparatus
SLM	Selective Laser Melting

SLS	Selective Laser Sintering
SRK	Strut Reinforced Kagome
SRT	Strut Reinforced Tetrahedral
STL	Standard Tessellation Language
UAV	Unmanned Aerial Vehicles
UTM	Universal Testing Machine

Chapter 1 Introduction

1.1 Background

Light weight structures are important factors in minimising the fuel consumption in the automobile, aerospace and defence industries. The reduction in the weight of the system reduces the overall fuel cost, increases the manoeuvrability without the compromise in the desired performance in terms of strength, stiffness or toughness.

Weight reduction in the aerospace and automobile structures has been achieved in several ways: (i) lighter and stronger metal alloys, (ii) composite materials, (iii) combination of metal and composites and (iv) different geometric configuration. A sandwich structure has two strong and stiff face sheets with low density core as shown in Figure 1.1. Face sheets carry the in-plane loads whereas the core carries the shear loads. Generally, sandwich structures with different core structures: honeycomb, foam filled sandwich, corrugated sandwich, grid and uni-axial stiffened panel and cellular lattice structures (Figure 1.2) have been proposed to fulfil the objective of high flexural stiffness and strength with low increment in weight.

Figure 1.1: Configuration of a sandwich structure [1]

Figure 1.2: Types of sandwich cores [2]

Cellular solids are just a hybrid of solid and gas. In nature, different materials adapt dynamically to various environmental conditions due to their combined qualities of microstructure and mechanical properties. Wood, cancellous bone, sea shells etc. are the naturally available cellularic solids which adopt and grow according to the loading environment. The efficiency in material use is one of the essential reasons for them to be ubiquitous in nature. Furthermore, together with their high-specific properties and multi-functionality, these systems inspired many other new artificial cellular solids created with mechanical properties which are tailored for specific application.

The increasing applications of sandwich structures in aerospace, marine, automotive and defence industries have led to numerous different studies on the improvement of existing materials and core designs of the structures. The most commonly used core structure is a honeycomb structure which provides high specific stiffness and strength, but it is anisotropic. Other cellular materials like foam structures provide good energy absorption property. Another type of core structure with more interest of researchers is cellular open lattice structures which not only provide structural support but also used in functional applications like heat exchangers and biomedical implants.

The cellular structures can be classified as ‘stretching dominated’ and ‘bending dominated’ structure according to their mechanical behaviour under compressive loading. Stretch dominated structures are highly stiff and strong compared to the bending dominated structures with the same relative density and are more weight-efficient for structural applications [3]. Bending dominated behaviour is found in foam structure and whereas stretch dominated behaviour is seen in a closed cell like honeycomb structure and some open cellular structures like octet-truss and 3D Kagome structure. Honeycomb structures are closed cellular structures which have high manufacturing and processing cost. They also suffer from the trapped moisture when used as a core in a sandwich construction.

Conventional manufacturing techniques like investment casting, deformation forming, woven and nonwoven textile method are used in the fabrication of cellular structures. These conventional techniques are relatively slow manufacturing process and produce a lot of wastage of the material during the fabrication of the cellular structures. Moreover, it is highly unlikely to fabricate

the cellular structure with very low relative density through these conventional techniques. To study the performance of newly designed cellular structures, modification on the whole fabrication process is needed.

1.2 Motivation

As discussed, the literature reviewed in Chapter 2 on conventional manufacturing techniques shows the limitations of these methods of fabricating cellular lattice structures. New designs can be easily realised, and the performance of the newly developed structures can be studied with the help of additive manufacturing (3D Printing). Additive manufacturing (AM) is a disruptive technology which helps to realise the manufacturing of complex designs (topology control is possible) directly. It is a process of fabricating a real object by joining the materials together layer-by-layer. These technologies not only reduce the number of parts and the assembly procedures but also help the designers and engineers to focus more on the design and optimisation. The evolution of AM has already established its impact on design and applications in the field of automotive, aerospace, biomedical and electronics. The versatility and accuracy of this manufacturing technology produce precise and complex parts with a reduction in product development time and cost.

Most of the studies are carried out on the lattice structures fabricated by powder bed fusion processes. SLM and EBM have been widely used to fabricate the lattice structure due to their capability to print low dimension complex structure (micron level) through the CAD models. Various metal alloys, aluminium, titanium, steel, etc., powders have been used to fabricate the metal lattice structures. The various designs of lattice structures: cubic structures, octet structures, Kagome, diamond structures, gyroid, primitive etc. have been

successively printed and their mechanical performances have been studied. AM has opened the door for the new and modified designs of lattice structures to be fabricated without any change in the specialized tooling.

For the same relative density, Kagome outperformed tetrahedral and pyramidal cores with its isotropic properties and suppression of premature softening [4, 5]. Similarly, Kagome structures fabricated by SLM were found to perform better than conventional honeycomb structures regarding strength and have similar core stiffness [6]. Kagome structures are competitive to honeycomb structures in terms of energy absorption [7]. Thus, 3D Kagome structure is an excellent choice as a cellular lattice structure to be used in a sandwich construction. They are one of the high performing cellular core structures. As the mechanical properties of the cellular lattice structures depend on the core design, it is necessary to design or modify the existing structures in the search of better performing lattice structures. With additive manufacturing, there is greater freedom in the designing and fabricating the cellular structures with the controlled relative density with better precision.

In sandwich construction, the face sheets are attached to the core with the help of epoxies and other glueing agents. The properties of the sandwich structures also depend on this adhesive interface between the core and the skin of the structures. With additive manufacturing, the cellular structure along with the face sheets can be printed in a single step without the need of the interface joining procedures.

The end applications of these cellular structures are in aircraft and automobile which need high specific strength, stiffness and toughness. Hence, many studies in the performance of the cellular structures have been carried out on titanium

and its alloys, stainless steel and other metals. Unmanned aerial vehicles (UAVs) have been very popular for a wide range of applications in different fields. The use of additive manufacturing has helped to fabricate topologically optimised designs with complex architectures of UAV body parts. FDM has been explored and successfully used in the fabrication of different parts of UAV [8, 9]. The structural efficiency of UAV can be improved with the use of cellular lattice structures which provides better specific strength and stiff structures. The fabrication process affects the quality and performance of manufactured parts. For the use of cellular structures in UAV's, it is necessary to study the mechanical performance of the plastic lattice structures fabricated with FDM.

1.3 Objectives

The main aim of the research is to investigate and enhance the mechanical performance of Kagome lattice structure fabricated by additive manufacturing under static loading. The specific objectives are:

- To investigate and enhance the various compressive properties (strength, modulus, energy absorption) of Kagome cellular structure fabricated by fused deposition modelling.

The properties of cellular lattice structures depend on the relative density, architecture and the material properties of the parent material.

The build orientation of the structure also affects the properties of the parts fabricated by FDM. Thus, the effect of build orientation and relative density of the core structure on the compressive properties of the Kagome unit cell fabricated by FDM was investigated. The use of

chemicals to reduce the surface roughness of the structure and its effect on the compressive properties was explored. The graded density design of Kagome structure was proposed and investigated to enhance the overall energy absorption of multilayer Kagome structure. Overall, the compressive properties of the Kagome structure fabricated by FDM were investigated and the properties were enhanced with the use of chemical treatment and graded density design.

- To design a novel cellular structure with better mechanical properties (compressive strength and modulus) than existing Kagome lattice structure under compression.

A modified design of Kagome structure with an inclusion of a vertical strut is proposed and its compressive properties are investigated with an analytical solution and numerical modelling. Experimental measurements on Ti-6Al-4V SRK structures fabricated through SLM was carried out to validate the analytical solution for compressive strength and modulus. The properties of the SRK were compared with Kagome structure with the same relative density. Further, the effect of heat treatment on the compressive properties was investigated.

- To investigate the flexural performance and failure mechanisms of sandwich beams with Kagome lattice structures.

The flexural performance of the sandwich beams with Kagome structure as a core structure was investigated through the numerical simulation and analytical solution. The analytical solution for the various failure modes was derived and the failure mode map was constructed using these equations. The failure mechanism of Kagome sandwich structures

with different geometrical parameters was investigated through numerical simulations and compared with the failure mode map.

1.4 Scopes

Due to the availability of the printing machines, most of the work is limited to polymers. Only limited work is on metals. The scopes of the research are as follows:

- ABS (polymer) and Ti-6Al-4V (metal alloy) were the two different categories of materials used for the fabrication of the Kagome structure using FDM and SLM, respectively.
- Only one relative density was considered for the comparison of the compression and deformation properties of the graded and uniform density Kagome structure due to logistic reason.
- A single built orientation (facesheets face perpendicular to the substrate) was considered in the fabrication of Ti-6Al-4V SRK and Kagome unit samples. The unit cell with the facesheet parallel to the substrate would require the additional support material during the printing and are difficult to remove.
- The properties of SLM fabricated structure have low ductility. Thus heat-treatment is one way to enhance the ductility of the SLM printed structures. In our study, only sub- β -transus heat treatment effect on the mechanical properties of the SRK and Kagome unit cell was investigated.
- Only analytical solution and numerical modelling of the flexural properties of Kagome sandwich beam was carried out due to the limited availability of metal printing machine.

1.5 Organisation of Report

This thesis consists of seven chapters.

The thesis begins with the introduction, describing the background of the research and stating the objectives and the scopes of the research work in Chapter one.

Chapter two of the thesis covers the literature review on the cellular structures with various designs. It provides a comprehensive review of different cellular structure designs fabricated by conventional methods as well as different additive manufacturing technologies. The mechanical characterisation of different lattice structures is presented. Similarly, details about the mechanical performance of 3D Kagome structures are highlighted. Finally, a few research gaps in the field of cellular structure design, fabrication and analysis are presented.

Chapter three explores the compressive performance of Kagome unit cell structure fabricated by FDM. The effect of build orientation, strut diameter, and the height of the core on the compressive performance and failure behaviour is investigated experimentally. The effect of the acetone chemical treatment on the surface roughness and overall compressive performance is explored.

Chapter four of this thesis discusses the compressive performance of FDM fabricated Kagome lattice structure from a unit cell structure to multi-layer structure. The deformation and compressive properties of the graded and uniform density Kagome structure are explored.

Chapter five covers the compressive performance of modified Kagome structure (strut reinforced Kagome) in relation to relative density. The compression properties are compared with the Kagome structure with the same

relative density. The effect of heat treatment on the compressive properties is investigated in terms of the effective moduli, peak strengths, failure strain and energy absorption.

Chapter six presents the bending performance of the sandwich structure with Kagome as a core structure. The failure mode map for Kagome sandwich beam is constructed using the competing failure mode equations. The results and failure modes of the structure obtained from numerical simulations of the three point bending are compared with the analytical prediction and the failure map.

Chapter seven discusses the overall conclusions and possible scope for future work in this research area.

Chapter 2 Literature Review

This chapter introduces cellular solids, their different morphologies and their conventional manufacturing. The state-of-art technology of different additive manufacturing processes is also presented. The mechanical characterisation of different lattice structures is discussed briefly. Further details about the mechanical performance of 3D Kagome structures are highlighted. Finally, the research gaps in the field of cellular structures are presented.

2.1 Cellular structures

Cellular structures, also known as foam or lattice structures are the hybrid structures formed having two phases of solid and gas. Foams could be either closed cell or open cell. Lattices usually consist of ligaments and nodes. They are made of interconnected networks of solid struts with and without plates. Their physical and structural properties depend on the relative density, cell-wall or edge material properties, and topology as shown in Figure 2.1.

Figure 2.1: Factors influencing the properties of cellular structures [10]

Cellular structures are known for their lightweight with high strength, stiffness and toughness. Natural cellularic structures include coral, bones, honeycomb, etc. These biologically adaptive structures simultaneously optimise their strength, stiffness and weight (mineral density) for the specific application. Artificial cellular structures with low relative densities have permitted the design of strong and stiff lightweight structures which have been used in automobile, aerospace, marine and defence industries [11, 12]. According to their geometric characteristics they can be classified as stochastic structures and periodic structures. Generally, natural structures are more stochastic whereas artificial can be both stochastic and periodic.

2.1.1 Stochastic cellular structures

The stochastic cellular structures have a random arrangement of the material and do not exhibit repeatability. Metal or polymer foams, sponges, cancellous bones and cork fall under this group. Metal foams are manufactured by the injection of gas into liquid metal with the help of a rotating impeller or vibratory nozzles. An alternative method is an addition of a blowing agent in the metal melts which would decompose and release gas when heated [13]. The mixing of liquid resin can also form polymer foam with air by the mechanical agitation or with the mixing of a chemical blowing agent which liberates the gas with high pressure and temperature. Though these have random morphologies, they are predominantly used for load bearing, acoustic insulation or in the thermal management application. The main disadvantage is the lack of control and freedom for the manufacturer to control the cellular architecture and distribution of relative density [14].

There are arguments on the superiority of the strength in the ordered lattice and randomised cellular structure. Luxner et al. [15] using finite element modelling analysed both periodic and stochastic open cell cubic structures and discovered that the highly ordered lattice structures are stronger than the disordered structure. However, the problem with the ordered one is that they are significantly sensitive to strain localisation. They also have mentioned that disordered structures are more robust against a change in orientation and they do not exhibit the deformation localisation. Rehme [16] has stated that better mechanical properties are obtained from the periodic cell structure than the random formation. The increase in the performance is due to the less connection of the joints with a smaller number of cell wall or struts linked to edges or vertices. The stochastic systems have inferior structural performance than periodic structures which also have the advantage of multi-functionality [17]. These advantages have grown large interest in the periodic lattice structure.

2.1.2 Periodic cellular structures

We should consider four conditions while selecting the appropriate cellular metallic material for any specific application [18]. They are morphology, metallurgy, processing and economy. Morphology includes type, size, amount and scale of porosity and internal surface area. The open cell is mostly used for functional applications such as heat exchanger whereas closed cell is more useful in the structural application. Metallurgy includes the selection of suitable metal or alloy for the fabrication of cellular structure. Alloys like titanium, aluminium which have light weight are used for the structural application. The selected structure and the material should be easily processed, and the cost

associated with the used technology should be reasonable as it impacts the final product cost.

2.1.2.1 Closed cellular structures

Honeycomb is the most common closed cellular structures with regular arrays of polygonal cells. They are composed of plates or shells forming the edge of the cell as shown in Figure 2.2. These sheets are arranged such that regular polygonal structures like triangular, square, hexagonal shapes are formed [19].

Hexagonal honeycomb cells are used heavily in construction applications due to its resistance to bending and its high strength to weight ratio [12]. With the presence of continuous cell wall, the stretch failure mechanism is predominant in closed cellular structures hence are stronger than open cellular structures. These structures have been used in the aerospace industry for structural applications.

Figure 2.2: Honeycomb structure with a) hexagonal, b) square and c) triangular unit cells [19]

2.1.2.2 Open cellular lattice structures

Lattice structures are periodic structures which are made up of trusses. They are arranged in various configurations (Figure 2.3) depending on the intended applications. Different mechanical performance has been investigated in different lattice structures like tetrahedral pyramidal, Kagome and Octet.

Figure 2.3: Examples of various lattice structures a) tetrahedral, b) pyramidal, c) three dimensional Kagome, d) diamond textile, e) diamond collinear and f) square collinear [19]

Deshpande and Fleck [20] investigated the effective properties of tetrahedral core structures experimentally and also developed analytical predictions of the same using upper bound collapse mechanism methods. In most cases, the deformation of the structures was found out to be stretch dominated. The shear failure was also observed due to the plastic shearing of the pins which attach the trusses with the faceplate.

Chiras et al. [21] used a gap design for the nodes where the intersection of struts was in the mid-plane of facesheet for the fabrication of the tetragonal core. They used the ductile beryllium-copper alloy to fabricate the core with different radii. The three-point panel bending test revealed that trusses with smaller radius failed by the core shear and softening was gradual whereas the larger radius specimens failed by face yielding and with rapid softening. The compression test showed that the truss exhibits plastic buckling at the maximum load. The node design was successful in attaining the expected stiffness and did not fail in the undesirable failure modes.

Wicks and Hutchinson [22] investigated the optimisation of tetragonal truss core sandwich structure subjected to crushing stress, bending and transverse shear and compared the performance with the hexagonal honeycomb structure. It was found that the tetragonal truss core was as efficient as honeycomb core to withstand the prescribed combination of moment and transverse load with the minimum crushing strength. In contrast, when there is no constraint, honeycombs have more weight advantage. However, at low core densities, truss cores have a better advantage in terms of crushing strength.

Zhou et al. [23] studied the deformation behaviour of a truss of pyramidal core structure made of aluminium under compression. The deformation exhibited progressive plastic buckling of the struts during the compression. The plastic buckling was found to be homogeneous across all the struts. Finally, the fracture of struts occurred with further loading.

Tice et al. [24] investigated the compressive behaviour of the periodic pyramidal core structure manufactured from cold-rolled titanium. Analytical models for peak strength and effective stiffness were formulated. The peak

strength model was accurate for determining the core performance whereas the effective stiffness was (by 33%) less than depicted by the model.

Hyun et al. [5] simulated the compressive and shear behaviour of 3D Kagome structure and compared with the tetragonal one. Kagome structure can support the higher load and shows the higher load carrying capacity before softening. During the shear simulation, the Kagome structure exhibited the isotropic behaviour in three orientations whereas tetragonal showed anisotropic and asymmetric behaviour. The experimental results verified these simulation results conducted by Wang et al. [4].

Figure 2.4: The comparison of compressive properties of 3D Kagome and tetrahedral structure [4]

Queheillalt and Wadley [25] investigated the compressive response of the square and diamond collinear lattice. They constructed the collinear arrays of either solid or hollow trusses and were connected by the brazing process. The square structure showed higher through thickness stiffness than diamond structure. The plastic buckling governed the peak compressive strength. The

hollow trusses increased resistance to buckling which reduced the sudden drop in the strength when the relative density was decreased. Rathbun et al. [26] investigated the shear compression, tensile as well as the bending on the diamond and square orientated structures. The diamond structure had higher shear strength but had lower stretch strength than the square structure.

The combinations of tetrahedrons with interior octahedral form octet truss structure. Deshpande et al. [27] investigated the effective mechanical properties of the octet-truss structure through the analytical, finite element calculation which was validated by experiments.

2.2 Manufacturing methods

Many manufacturing techniques and methods have been developed to fabricate periodic as well as foam structures which ranges from the conventional casting method to new additive manufacturing technologies.

2.2.1 Conventional methods

Investment casting is a conventional method of manufacturing cellular lattice structures. In this method, the sacrificial truss patterns are produced by injection moulding or rapid prototyping with volatile wax material or polymer. Thus, manufactured patterns are coated with ceramics slurry and are dried. Then, wax or the polymer is vapoured or melted out, and the molten metal is poured in to create required topologies as shown in Figure 2.5. This approach has allowed producing different complex, non-planar structures. However, the structures requiring optimal geometry and low-density cores are difficult to manufacture because of the narrow metal pathways creating casting defects on the produced

part [28]. Many cellular structures such as pyramidal, tetrahedral [21] and 3D Kagome [4] have been fabricated by this method.

Figure 2.5: Molten metal being poured into the ceramic cell as a part of investment casting [21]

The perforated sheet method is another processing route for the fabrication of open lattice structures. A plane sheet is perforated with different shapes like hexagonal or diamond structures. They are deformed at the nodes to produce tetrahedral or pyramidal structures [29]. The formed structures require immediate annealing to increase the ductility of the struts [30].

Figure 2.6: A pyramidal core structures being prepared from the perforated sheet by folding at the nodes [29]

Wire weaving technique can be used to fabricate the cellular lattice structures. The wires of the metal are twisted together until they deform plastically. The frame is used to fix the wires and the twisted wires are woven together to form the required periodic cellular structures. Wire woven method was used to fabricate multilayer 3D Kagome structures [31, 32] with twisted helical wires. The non-woven metal textile method produces the cellular structures by wire lay-up process which is followed by transient liquid phase bonding or brazing. An illustration of the use of a brazing technique for the fabrication of lattice structures is depicted in Figure 2.7.

Figure 2.7: Lattice structures from nonwoven metal textile approach a) square orientation and b) diamond orientation [25]

The conventional manufacturing methods has several drawbacks. Investment casting cannot produce the low relative density structures due to narrow metal pathways. It requires different mould design and set up if you want to change the dimensions of the cellular structures. Similarly, in perforated sheet method,

the metal sheet is perforated in different shapes wasting a lot of raw material. Weaving and braiding techniques can be used only in the materials which can be drawn to the wires. With these drawbacks of the conventional techniques, the AM provides the freedom for designing various cellular structures. It only requires the dimensional details, AM process and the material to be used.

2.2.2 Additive Manufacturing

Additive manufacturing, also popularly known as 3D printing, is based on the principle of developing the object with layer by layer addition of cross-section of a provided 3D model of the object. Other manufacturing technologies require minute details about the part geometry of the object in order to determine the different machines involved, the alignment of the processes, different tools and fixture required [33]. However, AM only requires dimensional details, understanding of the AM process and material used. The general procedures of AM are described in Figure 2.8. It involves the design of the structure in CAD software and to convert the finalised design into STL file format. The STL file is then uploaded into the AM machine with the desired setting before the build process. The building part is usually automated hence minimal supervision is required. Upon completion of the building, the parts are removed from the AM machine. If the parts are built with supporting feature, the support material must be removed and proceed to post-processing such as cleaning up or chemical surface treatment to provide acceptable surface texture and finishing. AM reduces the number of stages, machines involved, and resources required to produce a structure with an accurate prediction of the manufacturing time.

The AM is classified based on the state of the raw material used. i.e. liquid based, solid based or powder based [34]. According to ASTM F42, AM, based

on process technology, is classified into binder jetting, power bed fusion, direct energy deposition, material jetting, material extrusion, sheet lamination and vat photo-polymerisation. The several additive manufacturing technologies are Stereolithography (SLA), Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM), Fused Deposition Modelling (FDM), Polyjet and Laminated Object Manufacturing (LOM) [35].

Figure 2.8: General process involved in additive manufacturing [33]

2.2.2.1 VAT photo-polymerisation (SLA)

It is a liquid based additive manufacturing technology in which the liquid photopolymer is cured using the UV light source to form the solid part. Photopolymer with the suitable photo-initiator are exposed to the UV light, and the exposed area is converted to solid. The leftover remains as a liquid. The generally used photopolymers are either acrylate or epoxy based. Acrylate-based photopolymers work on free radical photo-polymerisation and have high photospeed (quick reaction with UV light). The main drawback of the acrylate-based polymer is its high shrinkage with the tendency to curl or warp. Epoxies

work on cationic photo-polymerisation and have less shrinkage resulting in the less curl and warp [36]. The proper amount of photo-initiator is required to start the photopolymerization. With the development of micro-stereolithography, the layer thickness of around 10 μm can be achieved [37].

2.2.2.2 Material Jetting (Polyjet)

The main working principle is based on the inkjet printing technology. The liquid polymer is passed through the piezoelectric print-head to spray the model as well as the support material at the required cross-section. The laser immediately cures the liquid polymer to solid. After the build, the support materials are removed with the help of water jet spray as they are water soluble. Polyjet has layer thickness resolution of 16 μm and the process is very precise and quick. Different thermoplastic materials are used to produce the object with different properties. The materials that are used can vary from the modelling propose to some engineering plastic materials like ABS with capability of printing multiple materials. Some polyjet machines can also print coloured parts. The main disadvantage is that material choices are limited [38].

2.2.2.3 Fused Deposition Modelling (FDM)

The working principle of FDM is the extrusion of melted plastic through the nozzle. The filament of the material is fed to the nozzle where it is through an in-built heating coils, melted and is extruded out. The head can move on the x-y axis to release the material in the required area, and the build platform moves in the z-axis for printing another layer once the current layer is completed. Acrylonitrile butadiene styrene (ABS) and polycarbonate (PC) are used as a model material, and support material is used to build overhanging parts. The

major advantage of FDM is the range of materials it can be worked on. The built parts do not require extensive post-processing. The major disadvantage of the process is its poor precision level giving poor surface finish due to the staircase effect [39].

2.2.2.4 Directed energy deposition (LENS)

It is an additive manufacturing process in which the materials are fused together by melting with the use of focused thermal energy. In this technique, the deposition head supplies the metal powder to a high-powered laser beam. The laser focuses on a particular spot and traces the cross-section of the part. It produces a molten puddle on the substrate where the head supplies the powder into the molten pool and solidifies as laser beam moves away. Once the cross-section is printed, the head moves up for the next layer. The major advantage is that fully dense parts with excellent material properties are fabricated. The major disadvantages are high power consumption, the large size of the unit, poor resolution and surface finish [40].

Figure 2.9: Schematic illustration of different AM processes (a) SLA process [41], (b) polyjet process [42], (c) FDM process [43] and (d) Laser engineered net shaping (LENS) process [44].

2.2.2.5 Powder Bed Fusion processes (SLS, SLM, EBM)

2.2.2.5.1 Selective laser sintering (SLS)

SLS is the process in which loose powder particles are sintered together using laser source to form the 3D object [45]. Any material in powder form which can be fused or sintered together with the application of heat can be used. Polymers like polycarbonate, polyamide, polystyrene, and engineering alloys are used. Some commercial materials with some reinforcing particle are also available. SLS fuses a thin layer of powder spread across the build area. The chamber is filled with the inert gas for the minimisation of oxidation. It is also maintained at an elevated temperature below the melting point to minimise the laser power

requirement and to reduce warping and curling. Mostly, CO₂ laser is used as a heat source to sinter the powder at the required cross-section, and the remaining powder remains loose to act as support material [46]. One main advantage of SLS is the suitability of many materials that can be worked on. The main disadvantage is its poor surface finish and the requirement of a controlled environment.

Figure 2.10: Schematic diagram of selective laser sintering [47].

2.2.2.5.2 Selective laser melting (SLM)

SLM is also based on powder processing technology in which the metal powder is completely melted and are fused together to form the solid object. As the powder is fully melted, the density of the build material is almost equal to the parent material. So, SLM is capable of producing the parts with the same mechanical properties equivalent to conventional one like casting [48]. The process of SLM is like SLS, but the major difference is that in SLM, the powders are fully melted whereas in SLS the powders are only sintered, and surfaces coalesce. For the melting, SLM uses Nd-YSG laser instead of the CO₂ laser in SLS resulting better absorptivity of metal powders [46]. SLM has

different laser scan pattern compared to SLS. The parts produced are rigidly attached to the base plate to keep it being built free of distortion due to the built-in residual stresses. Hence, the parts produced should be removed by metal wire cutting technique. Currently, the powders used in SLM are stainless steel, titanium alloy, aluminium, nickel alloy and cobalt chromium alloys.

2.2.2.5.3 Electron Beam Melting

EBM working principle is similar to SLM, the major difference being it uses high energy electron beam as the heat source for melting the metal instead of laser. Electron beam when passed through the gas, it interacts with the atoms and gets deflected. So, to focus the electron beam on the metal powder, the consolidation is carried out under vacuum. The conductivity of the powder bed should be very high in order to reduce powder cloud formation which results in no diffusion of the beam [46]. EBM has been used in producing porous titanium parts for the orthopaedic implants such as hip joints, knee joint components [49]. This is because the process happens in a vacuum thus has less contamination. However, the use of inert gas in SLM might have some impurities which may contaminate the fabricated part.

Figure 2.11: Schematic representation of EBM [50].

Conventional methods like investment casting, deformation forming and wire brazing fabricate the lattice structures with relatively simple geometry and have limited design freedoms. They also lack functionality to meet requirements of many applications. Investment casting process is unable to produce low relative density, and deformation forming causes lot of material wastage. These methods also cannot take advantage of topology optimisation [51].

New advanced additive manufacturing techniques like SLM, SLA, polyjet, etc. are drawing the interest of design engineers due to their versatility of producing very complex designs. AM has the great advantage of fabricating complex customised designs with its layer by layer fabricating technique. These advantages have attracted many design engineers to use AM for fabricating periodic cellular structures.

2.3 Additive Manufacturing of Periodic Cellular Structures

2.3.1 Additive manufacturing processes for lattice structures

FDM requires the support structure to fabricate the lattice structures and are generally removed by using the warm detergent water solution. The parts produced by FDM sometimes deviate from the given dimensions especially when the part is circular. The surface defects and imperfection do affect the mechanical properties of the lattice structures. Ravari et al. [52] accounted for the variation in diameter of struts along the length to numerically predict the elastic modulus and compressive strength of the basic centred cubic with vertical column (BCC-Z) lattice structure. The diameters were measured at different places, and these were represented while modelling. It was concluded that variation of diameters (and hence their relative density) has a considerable effect on the mechanical behaviour of the lattice structure. In another study, Rezaei et al. [53] explored the manufacturability and repeatability of polylactic acid (PLA) BCC-Z structure produced by FDM machine. The variation in diameter and the porosity of the printed parts affected the overall performance of the cellular structure. The use of bulk compressive properties in the numerical simulation well predicted the effective modulus whereas there is a pronounced difference in the collapse strength. They suggested that the presence of microstructural defects on the parts which were not considered in the simulation has led to the discrepancies in the results.

Polyjet technology provides an excellent surface finish and has many material choices for the fabrication of the lattice structures. The support structure holding the overhanging parts for low dimension delicate parts can be dissolved easily using caustic soda (NaOH) and sodium metasilicate (Na_2SiO_3) solution.

This makes the fabrication of the complex low relative density lattice structure (smallest diameter of 1 mm) possible.

Electron beam melting (EBM) has been used to fabricate different porous biomaterials (especially Ti-6Al-4V) with tailored porosity. The fabrication of implants for patient specific data with the tailored mechanical properties is possible with EBM [54]. The inherent issue of EBM printed structures is the surface irregularity induced by the surface. This surface irregularity has an adverse effect on the stiffness and strength of the structure [55]. The chemical etching post processing has reduced the surface roughness substantially and had a desirable increase in the stiffness to density ratio.

Selective laser melting (SLM) is a popular AM technology for the fabrication of the lattice structures due to its capability to fabricate the structures with low diameters. The lattice structures are fabricated without any external support structure. But the horizontal parts should be avoided while manufacturing as the fabricated horizontal parts without any external supports are of inferior quality. Recent advances in AM have allowed the fabrication of complex periodic cellular structures in which the relative density of the structures can be controlled. Different AM technologies have their own advantages and disadvantages as shown in Table 2.1. As mentioned earlier in different AM technologies descriptions, the material used by various technologies are different, and the mechanical behaviour of the product also varies.

Table 2.1: Comparison of various additive manufacturing processes

AM processes	Material	Advantages	Disadvantages
FDM	ABS, PC, Ultem	Many materials option, relatively cheap, high strength material	Sacrificial support material, cannot print thin struts in angles, high surface roughness
Polyjet	Digital ABS Simulated polypropylene Rigid (Vero™) Rubber (Tango™) Medical and dental materials	Many material options from engineering plastics and rubber to dental material, high resolution, excellent surface finish	Sacrificial support material, expensive
SLS	Polyamide (PA) Glass filled PA Alumide	Self-support, faster printing	Poor surface finish, high porosity
SLM	Stainless steel Titanium and alloys Aluminium	Faster process, self-support, can print very thin struts (around 0.3 mm diameter), flexibility to new material development	Expensive, low quality printing of horizontal struts without support, requirement of controlled environment, internal residual stress in printed parts
EBM	Ti-6Al-4V Titanium Cobalt chrome	Faster, useful in orthopaedic implant, low residual stress (high build temperature)	Expensive, need of vacuum environment, low quality printing of horizontal struts without support, few developed materials

2.3.2 Lattice designs and the effect on the mechanical properties

Markulla et al. [56] investigated the compressive behaviour of tetrahedral, strut reinforced tetrahedral (SRT) and pyramidal unit cell of ABS fabricated by FDM. SRT exhibited the superior performance in terms of specific strength

(8.84 times) and stiffness (3.44 times) in comparison with the pyramidal structure as shown in Figure 2.12. Tetrahedral structures also showed better compressive performance than pyramidal structures.

Figure 2.12: Specific stiffness and strength of pyramidal, tetrahedral and SRT unit structures fabricated by FDM [56]

Vesenjak et al. [57] studied the mechanical characteristics of open-cell cellular structure made of photopolymer fabricated by polyjet. The brittle fracture of the structure was observed which resulted in the erratic behaviour under quasi-static loading. With the use of silicone as the pore filler material, the mechanical behaviour was more reliable. The silicone also improved the energy absorption capabilities of the structures.

Maskery et al. [58] investigated the crushing behaviour, mechanical properties and energy absorption of SLS printed polyamide PA 2200 BCC and BCC-Z structures. They used both graded and non-graded lattice structure for the investigation. The study concluded that BCC-Z has superior modulus and strength in their reinforced direction compared to BCC. The graded structures have significantly higher total energy absorption capacity before densification of the last layer than the non-graded structures.

Heinl et al. [50] successfully prepared 3D hatched structure from Ti-6Al-4V by electron beam melting which can be used in bone implants. Cansizoglu et al. [59] have investigated the compressive and bending behaviour of a hexagonal lattice made of Ti-6Al-4V by EBM. The lattices with different relative density and with varying angles were produced. The lattice with struts built angle less than 20° has no structural integrity. Most specimens showed brittle failure, and there was no densification and many failed at a maximum shear angle and fractured at the node. Similarly, Zhao et al. [60] studied the influence of cell shape on compressive fatigue behaviour of Ti-6Al-4V lattice manufactured by EBM. Three different lattices namely cubic, G7 and rhombic dodecahedrons were successfully manufactured, and cyclic ratcheting fatigue crack growth was studied.

Santorinaios et al. [61] investigated the compressive and shear behaviour of BCC-Z lattice structure made of stainless steel. They concluded that there should be the optimisation of the manufacturing parameters before the fabrication of the cellular cells. The improper parameters of the fabrication can lead to local imperfections resulting in lower performance of the structures. Tsopanos et al. [62] studied the influence of two processing parameters, laser power and exposor time on the mechanical properties of stainless steel 316L lattice structures. Low laser power ($P < 80 \text{ W}$) with constant exposor time exhibited the porosity resulting high drop in material strength under uniaxial loading. The increase in exposure time and use of high laser power increased the mechanical properties in terms of modulus and yield strength.

Mckown et al. [63] explored the compressive behaviour of SLM manufactured stainless steel BCC and BCC-Z structure with the variation in relative densities.

Buckling failure was observed in the BCC-Z structures whereas stable progressive failure mode was discovered on BCC structures. BCC-Z structures resulted in 3.5 times higher yield strength than the BCC structures. The blast test also exhibited the similar collapse mechanism as observed in the compression test. Shen et al. [64] investigated the compressive as well as the dynamic behaviours of stainless steel BCC, BCCZ BCCZ-H and BCC with woven carbon-fibre reinforced epoxy skins bonded to the upper and lower surfaces. BCCZ structure had better compressive results due to the inclusion of vertical strut in the middle which supported maximum part of the load as shown in Figure 2.13. The quasi-static and low-velocity impact exhibited that the energy was absorbed through plastic buckling of the strands and rotation of plastic hinge in the area close to the point of impact. Gumruk et al. [65] studied the static behaviour of stainless steel lattice structures like BCC, BCCZ, F₂BCC under compression, shear, tension and combined loading experimentally. The structural imperfection has more effects on the shear loading than in compression. Three major factors affecting the performance are relative density, cell topology, and cell size which govern the mechanical properties and the collapse mechanism. They also compared the mechanical properties of micro-lattice structures to those of foam structures. The steel micro-lattices manifested similar properties to those of the metallic foams but have low performance to pyramidal and honeycomb structures (see Figure 2.14).

Figure 2.13: Average yield strength and specific yield strength of four different lattice structures under compression [64].

Figure 2.14: Comparison of mechanical properties of stainless steel micro-lattice structures with other cellular materials in terms of (a) relative collapse stresses and (b) elastic modulus [65].

Maskery et al. [66] investigated the effect of size and number of cells in the mechanical properties of lattices. There was a significant drop in modulus and strength with an increase in cell size. A large number of small cells provided better properties than small number of large cells. They also developed a relation for mechanical properties as a function of cell size. Wauthle et al. [67] explored the effect of built orientation and heat treatment on the mechanical properties of the lattice structure. The diamond-like lattice structures were manufactured by SLM with different build directions. The results showed that the horizontal strut should be avoided while manufacturing as the fabricated

horizontal struts are of bad quality causing premature failure. The heat treatment has effects on the structural properties. Stress relieved samples showed greater stiffness and had higher yield strength. Brenne et al. [68] investigated SLM manufactured Ti6Al4V BCC lattice structure under quasi-static and cyclic compressive loading. Shear failure along the diagonal plane was observed. Mazur et al. investigated [69] the compressive properties of Ti6Al4V basic centred cubic (BCC), face centred cubic with vertical struts (FCCZ), face and body centred cubic with vertical struts (FBCCZ) and face and body centred cubic with vertical and horizontal struts (FBCCXYZ) structures fabricated by SLM. FCCZ exhibited the highest specific moduli with BCC giving the lowest performance. Similarly, FCCXYZ and FCCZ exhibited high specific strength values. BCC developed the diagonal plane bands before the failure whereas other lattice structures with vertical struts showed pronounced deflection of the vertical strut. Yan et al. [70] investigated the fabrication of gyroid cellular lattice structure with the self-support feature through SLM. The gyroid structures were well manufactured by SLM process but had rough strut surfaces. Sun et al. [71] predicted the theoretical fracture load of Ti6Al4V octahedral lattice structures and compared with the experimental results. They illustrated that the fracture load has an exponential relation with porosity. Feng et al. [72] utilised a central difference method to calculate the stress distribution and conducted the quasi-static analysis on Ti-6Al-4V BCC and FCC-BCC structures. Their experimental measurements of effective modulus and ultimate strength were comparable to the analytical solutions.

2.4 Mechanical properties of lattice structures

The mechanical properties of lattice structures depend on the material, size, shape of the cell, periodicity, type of strut, porosity and relative density.

Cellular lattice structures can be classified as bending dominated structure and stretching dominated structure, and they exhibit different mechanical properties. Stretching dominated structures are highly stiff and strong compared to bending dominated structures. Figure 2.15 shows the stress-strain characteristics of different mechanisms of cellular structures. The bending dominated structure mechanism is shown in Figure 2.15 (a) which exhibits the classical plateau stress-strain curve. The stretch-dominated structures show higher peak strength followed by softening region before the plateau region. Deshpande [73] discussed the topological criteria for the foam structure to classify as bending or stretching dominated structure. For the infinite framework, the average number of connectivity was four and six for 2D and 3D cases respectively in satisfying the necessary condition for the rigidity. The connectivity should be six and twelve for 2D and 3D framework respectively to satisfy the necessary and sufficient condition for the rigidity.

Figure 2.15: Stress-strain behaviour of (a) bending dominated and (b) stretch dominated structures [10]

Ashby [10] derived the relation of the compressive properties with the relative density of both bending as well as stretch dominated structures. For stretch dominated structure, the effective modulus of the structure is linearly proportional to relative density.

If the structure fails by plastic yielding, the collapse stress is also linearly proportional to the relative density. If the struts are slender and buckle before yield, the buckling strength is proportional to the square of the relative density.

Fan et al. [74] studied the micro-failure mechanism in different periodic unit cells and reported that there are three failure mechanisms: tensile yielding, compression yielding and compression buckling of the struts. They also predicted the mechanical properties of different cellular structures as listed in Table 2.2. The octet truss structure is isotropic while other manifest anisotropy in terms of the mechanical properties.

Table 2.2: Mechanical properties of different 3D lattice materials [74]

Cell	Specific stiffness			Specific uniaxial strength			Specific shearing strength		
	x	y	z	x	y	z	xy	yz	zx
$0.167\rho^*$			$0.333\rho^*$			$0.167\rho^*$
$0.153\rho^*$	$0.153\rho^*$	$0.296\rho^*$	$0.111\rho^*$	$0.167\rho^*$	$0.444\rho^*$	$0.096\rho^*$	$0.157\rho^*$	$0.181\rho^*$
$0.15\rho^*$	$0.15\rho^*$	$0.2\rho^*$	$0.1\rho^*$	$0.1\rho^*$	$0.2\rho^*$	$0.2\rho^*$	$0.283\rho^*$	$0.283\rho^*$
$0.216\rho^*$	$0.216\rho^*$	$0.135\rho^*$	$0.17\rho^*$	$0.17\rho^*$	$0.27\rho^*$	$0.163\rho^*$	$0.193\rho^*$	$0.193\rho^*$

Deshpande et al. [20] also analysed the compressive properties of stretch dominated structures like pyramidal and tetrahedral. For small slenderness ratio, the contribution of bending of struts on the overall stiffness and strength is negligible compared to the stretching of the struts. Hence, the nodes are considered as pin jointed. The compressive modulus in loading direction is derived by the application of point load and calculates the resulting normal displacement of the facesheet.

$$E_{cell} = \bar{\rho} E \sin^4 \theta \quad (2.1)$$

where E is Young's modulus of parent material, θ is the included angle and $\bar{\rho}$ is the relative density.

The out of plane shear modulus is given by

$$G_{cell} = \frac{1}{8} \bar{\rho} E \sin^2(2\theta) \quad (2.2)$$

Figure 2.16: Relative moduli of different cellular structures against the relative density [10]

Figure 2.16 compares the performance of different cellular structures in terms of relative modulus against the relative density. The broken lines show the locus of bending and stretch dominated structures. Honeycombs, as well as pyramidal and Kagome structures, show stretch dominated properties whereas the foams show bending dominated behaviours.

If the lattice truss is considered to be made of a rigid perfectly plastic material with a tensile strength of σ_y , the yielding is coincident with peak strength. The peak strength is given by

$$\sigma_{cell} = \bar{\rho} \sigma_y \sin^2 \theta \quad (2.3)$$

However, with an increase in slenderness ratio, the peak strength is controlled by elastic buckling. In this case, the yield strength is replaced by the buckling strength of the truss member. The peak strength is given by

$$\sigma_{cell} = \bar{\rho} \sigma_{cr} \sin^2 \theta \quad \text{where, } \sigma_{cr} = \frac{\pi^2 k^2 IE}{Al^2} \quad (2.4)$$

where I is the second moment of inertia and A is the area of cross-section and k is the factor that depends on the boundary condition of truss member: 1 for pin-jointed truss and 2 for the clamped truss.

If the lattice is made from a material with a positive strain hardening rate, it continues to support the increasing stress after the yield. The truss finally fails with plastic buckling at plastic bifurcation stress. This is given by Shanley-Engesser tangent modulus theory which is

$$\sigma_{cr} = \frac{\pi^2 k^2 E_t I}{Al^2} \quad (2.5)$$

where E_t is the tangent modulus which is obtained from the slope of the uniaxial stress-strain diagram after the yield point for bi-linear response.

Figure 2.17: Relative strength of different cellular structure against the relative density [10]

Figure 2.17 shows the collapse strength of different cellular structure at different relative densities. The bending dominated structures have the strengths that scale with the power of 1.5 of relative density whereas stretch dominated scale linearly with relative density. The truss structures have better strength capabilities than honeycomb as the thin wall of honeycomb can buckle easily. The open lattice structures like Kagome and pyramidal have near ideal performance in terms of strength.

2.5 Bending performance of sandwich beams

Sandwich beams are used in applications that require high bending stiffness and strength with low weight. The sandwich beam received great attention since Allen's pioneer work [75] on the mechanics of sandwich panels. The sandwich beams fail with competing failure mechanisms under bending load. Triantafillou and Gibson [76] constructed the failure mode map to predict the dominant failure mechanism of the sandwich beam with the face and core materials that yield plastically. Gibson and Ashby [12] also constructed the failure mode map to show that the failure mechanism depends on the geometric parameters and strength of face sheets and core structure. With the development of regular lattice structures, the bending properties of the sandwich structure with the regular lattice structure and their failure mechanisms have been studied.

The studies on the sandwich beam with different core structure under bending are listed in Table 2.3. In most studies, it is observed that the analytical solutions are derived for competing failure modes, and the failure mode map is

constructed. The analytical solutions are verified either by numerical simulation results or by experimental measurements.

Table 2.3: Bending performance of Sandwich beam with different core structures

Core design and material	Key Findings	Reference
Nomex honeycomb	Theoretical models with honeycomb mechanics, construction of failure map, experimental verification of a theoretical prediction	[77]
Tetrahedral core with triangulated and solid face-sheets, Aluminium –silicon and silicon-brass alloys	The collapse mode of face yield and wrinkling was found for the structure with triangulated facesheet whereas core shear mode was observed for the structure with solid facesheet.	[20]
Aluminium foam	Estimation of initial failure load and peak load, construction of failure mode map, experimental verification	[78]
PVC foam	Failure map construction, experimental verification of analytical and numerical solutions	[79]
Wire woven Kagome, stainless steel SUS 304	Analytical solution for maximum load, optimal design at the confluence of three failure modes, verification by numerical simulation	[80, 81]
Pyramidal core with carbon fibre composite	Optimal geometric parameters were obtained for largest weight efficiency validated by experimental measurements.	[82]

Typical failure modes in sandwich beams are shown in Figure 2.18. From above literature listed in the table, the competing failure modes of sandwich

beams are facesheet yielding, facesheet wrinkling, core shear and local indentation. The operative failure mode of a sandwich structure depends on material properties and its geometric parameters like span length, core height, facesheet thickness. Facesheet yielding determines the limit load when the facesheet attains the yield strength before the yielding of the core structure. The buckling of the facesheet can occur with open core sandwich structure in which the wavelength may scale up to the cell size of the core. The local indentation is predominant with the compressive yield of the core structure lying below the roller. The shear force is carried mainly by the core structure and plastic collapse can occur by the core shear.

Figure 2.18: Failure mechanism of sandwich structures [80]

Limit load estimate for sandwich beams with different failure modes under three point bending are

$$\text{Face yielding: } P_{FY} = \frac{4bt_f(H+t_f)}{L} \sigma_y^f \quad (2.6)$$

$$\text{Face wrinkling: } P_{FW} = \frac{4bt_f(H+t_f)}{L} \sigma_w^f \quad (2.7)$$

$$\text{Indentation: } P_I = bt_f \left(\frac{\pi^2 \sigma_{cr}^2 E_f (H+t_f)}{3L} \right)^{\frac{1}{3}} \quad (2.8)$$

$$\text{Core Shear: } P_{CSA} = \frac{2bt_f^2}{L} \sigma_f^y + 2bH \left(1 + \frac{2D}{L} \right) \tau_{cr} \quad \text{for mode A} \quad (2.9)$$

$$P_{CSB} = \frac{4bt_f^2}{L} \sigma_y^f + 2bH \tau_{cr} \quad \text{for mode B} \quad (2.10)$$

where b , L and H are width, span length and core height of the sandwich structure, respectively, t is the thickness of the facesheet and D is the overhang length of simply supported beam. σ_y^f is the facesheet yield strength, E_f is the elastic modulus of facesheet, σ_{cr} is the uniaxial strenght of the core, and τ_{cr} is the shear strenght of the core.

2.6 Kagome structure

Kagome is a Japanese term which means the basket weave pattern created by the weaving in three different directions. This word is generated by two Japanese words: “kago” meaning basket and “me” meaning eye. So, they are the eyes of the basket as shown in Figure 2.19.

Figure 2.19: Kagome basket weave pattern

Salvatore Torquato at Princeton proposed a three-dimensional Kagome structure which has a pair of tetrahedrons inverted and are rotationally offset by 60° with each other as shown in Figure 2.20. The nodes that are formed on the face sheet have a two-dimensional weave pattern of Kagome.

Figure 2.20: Three-dimensional Kagome Structure [19]

Hyun and Toronto [83] used topological optimisation on two-dimensional isotropic solids for effective elastic modulus. Kagome –like structure provided the best performance over a wide range of densities compared to triangular-like and hexagonal-like structures. It provided not only better elastic properties but also many useful features like heat dissipation characteristics, higher mechanical strength and ease of fabrication.

The pyramidal structure showed significant anisotropy and susceptible to plastic buckling. Hyun et al. [5] studied the mechanical properties of three-dimensional Kagome structure through the numerical simulation and compared with the tetragonal structure and found that the Kagome structure absorbed higher compressive load than the tetragonal structure as shown in Figure 2.21. It not exhibited higher compressive strength but also had low softening rate than the tetragonal structure revealing the less sensitivity to plastic buckling. Though the diameter of the struts may be the same, the truss length of Kagome is smaller than tetragonal one. Hence, the slenderness ratio of Kagome is higher resulting in the higher compressive load carrying capacity. The shear testing results exhibited that Kagome structure has a similar response in all three orientations whereas tetragonal structure has different responses in different directions.

Moon et al. [84] studied the compressive behaviour of Kagome, Hexagonal diamond and Cross pyramidal structure. The structures were fabricated by Polyjet technology, a type of additive manufacturing technology based on inkjet printing. The material used was rubber-like photopolymer named Objet TangoGray FLX950 to build light but strong structures so that it could be applied in UAV wings. The result showed that Kagome structure has high compressive strength compared to other two structures.

Figure 2.21: Non-dimensional compressive force-strain curve of tetragonal and Kagome structure made of Cu alloy and Al alloy [5]

Lee et al. [31] used helical wires to fabricate wire woven periodic bulk Kagome structure. They used force equilibrium and elastic energy conservation principle to predict effective modulus and peak strength of core under compression and compared with the experimental measurements. The failure analysis of WBK core showed that the concentration of the plastic strain on the curved struts led to the plastic bending of the struts. Lee and Kang [32] investigated the effect of geometrical parameters like wire diameter, strut length and number of layers on the compressive properties of wire woven Kagome cores fabricated with stainless wires. With the increase in the number of layers, the strength slowly reduced which might be due to the presence of imperfections present in the specimen, out of plane boundary effect or in-plane boundary layer. It was also

concluded that the diameter alone cannot be the prime factor affecting the properties. Rather it must be the slenderness ratio which has greater influence in the peak strength of WBK structures. They also compared the compressive strength and energy absorption with the other cellular structures like foams, egg box structures and other woven textile metal structures and found that WBK outperformed them.

Figure 2.22: Wire woven Kagome structures with two different configurations: pointed face and the flat faces specimens [32]

Ullah et al. [6] investigated compression and shear loading performances of Ti-6Al-4V Kagome truss core fabricated by selective laser melting. The performances as well as the failure were predicted by the finite element analysis. The optimisation of truss parameters was also conducted. The internal angle of 60° performed better for compression whereas 45° performed better for the shear test. The performance was compared to honeycomb and foam core structure in the design charts as shown in Figure 2.23. The Kagome structures were found to perform better than conventional honeycomb structure regarding compression and shear strength whereas core stiffness was found similar to that of honeycomb structures.

Figure 2.23: Compressive performance of Ti-6Al-4V Kagome and honeycomb in terms of (a) strength and (b) modulus [6]

Ullah et al. [7] also studied the energy absorption characteristics of Kagome structures. Ashby design charts were created for the energy absorption and compared to the other structures from the literature as shown in Figure 2.24. It was found that Kagome structures are competitive with honeycomb structures.

Figure 2.24: Comparison of gravimetric energy absorption for different core structure for compression and shear [7]

2.7 Research Gaps

The literature is reviewed with the objective of understanding the behaviour of the lattice structures under various mechanical loads. Various types of the cellular structures (stochastic cellular structure, periodic cellular structure, closed cellular structure, open lattice structures) with their advantages and

disadvantages are emphasized. Additionally, the conventional manufacturing methods as well as additive manufacturing techniques for lattice structures are reviewed. Various experimental as well as numerical investigations on the behaviour of the various additively manufactured cellular structures under different mechanical loadings are reviewed. The analytical solutions of mechanical properties for different types of cellular structures are presented. Finally, 3D Kagome structure is introduced and various studies on the mechanical response of it are discussed.

From the literature review the following issues have been observed.

1. Most of the studies on the cellular structure are carried out on the metal printed structures for their end application in aerospace industries. A few studies were carried out in the plastic cellular structures for the design and development of unmanned aerial vehicles (UAV). A comprehensive study on the mechanical properties of the plastic cellular structure is needed so that they can be applied in UAV structures to reduce the weight of the parts and increase the structural efficiency.
2. Several studies on the cellular periodic structures have been performed on the multi-unit structures to observe overall behaviour of the periodic structures. A single unit cell study is required to understand in detail how a truss structure behaves in different loading conditions and would be very insightful in improving the performance of the structures.
3. Kagome is a near stretch-dominated structure which has exhibited better mechanical performance than other competing structures. It is the nature of the research that we try to explore or modify the existing designs to achieve the better performance than the existing one. It is necessary to

explore the mechanical properties and deformation behaviour of the modified designs to compare with the existing design.

4. From the literature, it is found that most of the studies are on the performance of the cellular structure under compression loading. The studies of cellular structure on other loading conditions are essential as the structures encounter different loading conditions. Very few studies are carried out on the flexural properties of open cellular structures. It is essential to investigate the flexural performance of the sandwich beams with open cellular structures.

Chapter 3 Printing and characterization of Kagome lattice structures by fused deposition modelling

3.1 Introduction

Unmanned aerial vehicles (UAV) are very popular for a wide range of applications including: military, agriculture and livestock monitoring, films and sports for the aerial views and mapping of landscapes. Conventionally, UAV structural elements were fabricated using Computer Numerical Control (CNC) hot-wire cutting for foam and balsa wood whereas manual wet layup is employed for long fibre reinforced polymer matrix composite. They are labour intensive processes with high processing time. Conventional manufacturing techniques can not fabricate topologically optimized designs which have complex architecture. Although, using regular cellular structure in UAV body (wings) for weight reduction results in the complex design, but provides excellent structural efficiency.

The development of additive manufacturing (AM) technologies has redefined the manufacturing arena by the design simplification and easing the fabrication process. Various manufacturing process like fused deposition modelling (FDM) [8, 85], polyjet [84, 86], stereolithography (SLA) [87], selective laser sintering (SLS) [9, 88], etc. have been used to fabricate whole or certain parts of UAV.

FDM has been explored to fabricate the different parts of UAV with ABS plastic. Michelson and Reece [89] used FDM to fabricate the strong and intricate wing rip structure of entomopter. Easter et al. [8] also used ABS

material for fabricating the UAV wing structure. The common goal of UAV design is to have high endurance which translates to longer flight time with longer breaks for refueling. One method to increase the endurance is to minimize the structural weight [90]. The structural efficiency of an UAV can be improved by the use of lightweight structures. Most of the lift of UAV is generated by the wings. Thus, the wings should be able to resist the pressure generated by the aerodynamic forces acting on it. The solid wings increase the weight of the UAV. Instead, the wing with the lattice structure provides the high specific strength and stiffness and help in significantly reducing the weight of the structure. With AM, the fabrication of wing with complex lattice structure inside is possible as shown in Figure 3.1. As Kagome structure has better mechanical properties compared to other competing cellular structures (tetrahedral, pyramidal, hexagonal) [6, 84], it can be used as the cellular structure in the wings of UAV. Use of cellular lattice provides high specific strength and stiff structures.

Figure 3.1: Airfoil with the cellular structure [84]

The properties of the lattice structure also depend on the fabrication process as it determines the quality of the individual parts and interfaces. FDM is a widely used additive manufacturing technology for producing functional prototypes. Several investigations on the mechanical properties of FDM fabricated parts have been explored and it was found that different parameters such as raster orientation, build direction, air gaps between the rasters and layer thickness

affect the properties of FDM printed parts [91-93]. These factors affect not only the properties but also the dimensional accuracy and surface roughness of FDM printed parts [94-97]. The strength of the structure also depends on the bonding of the filaments. The bonding between the polymer filaments has a significant influence on the properties and failure modes of fabricated parts [98]. The degree of bonding during the filament deposition can be predicted, and the extrusion temperature has a major effect on the bond formation in the FDM process [99].

Surface roughness is another major issue for additively manufactured components. Especially FDM printed parts are known to have increased surface roughness and also suffer from dimensional inaccuracy [100]. The surface roughness reduces with a decrease in layer thickness during printing. Also, when parts are built in certain angles rather than in vertical or horizontal direction, the roughness increases due to the staircase effect of added layers as shown in Figure 3.2

Figure 3.2: The difference in model and the fabricated structure due to the presence of staircase effect.

The surface roughness of the FDM printed parts can be reduced by mechanical polishing or machining [101-103] as well as chemical methods [104-108]. Kulkarni and Dutta [101] used end mill ball cutter to polish the part for the finer surface finish. Williams and Melton [102] made use of abrasive flow machining to enhance the surface finish. Pandey et al. [103] utilized hot cutter machining to remove the staircase for an enhanced surface finish. Semi-empirical model to predict the surface roughness was also developed. Galantucci et al. [108] investigated the effect of process parameters like tip size, raster width and slice height on the surface roughness and used diluted dimethyl ketone to polish the ABS leading to the smooth surface. In their further investigation, the treatment with acetone also improved the surface finish with an increase in ductility and flexural strength but a slight reduction in tensile strength [104]. Garg et al. [105] and Percoco et al. [106] used acetone in vapour and liquid form, respectively, to polish the FDM parts and later found that the chemical treatment improved the compressive strength.

The parts fabricated by FDM process require post-processing to get smooth surfaces. As the struts of Kagome are inclined, the presence of staircases results in high surface roughness. Out of different surface roughness removal techniques, the chemical treatment is simplest and less time consuming but needs a proper investigation of treatment time for the better surface finish without much reduction in the size of the samples.

In this chapter, the compressive performance of Kagome unit cell structures fabricated by FDM as a function of relative density is investigated experimentally and numerically. The effect of built orientation, strut diameter, and height of the core on the compressive response and polymer fracture

behaviour is investigated experimentally. The measured load-displacement responses are simulated using finite element simulations to investigate the deviation of the printed structures from the “as-designed” properties. The constitutive material properties are determined from the uniaxial tensile testing on the dog-bone sample of the cell wall material produced through FDM. The use of chemicals to reduce the surface roughness and its effect on the compressive performance of the 3D Kagome structure is also explored. The time interval of the chemical treatment on the compressive properties for the given samples of Kagome unit structure is investigated experimentally. This study helps to understand the compressive behaviour of FDM printed Kagome structures and explores the use of chemical treatment on the surface to enhance the properties of FDM printed lattice structures.

3.2 Experimental Details

3.2.1 Design and manufacturing

The 3D Kagome structure is formed by a pair of tetrahedral structures lying vertically inverted with each other and offset by 60° as shown in Figure 3.3. To investigate the accurate mechanical behaviour of 3D Kagome structures, a single unit cell is studied minimising the effect of defects and weakest links within the multi-unit structures. It is expected that a unit cell represents the performance of a single layer structure. The unit cell is characterised by the strut diameter (d), the height (of the core) (h) and its inclination angle (θ) to the face-sheet or base plate.

Figure 3.3: Kagome unit cell structure with different geometric parameters

In this study, the effect of build orientation, variation of strut diameter, and core height on the compression response is explored. Two samples were studied for each test case. To investigate the effect of build orientation on compressive effective modulus, strength and failure modes, two different build orientations for a fixed strut diameter of 4 mm were fabricated as shown in Figure 3.4. Parts printed in orientation I have the struts with low angle with the substrate whereas the parts printed in orientation II have the struts with high angle (55° with the substrate). As our samples were printed with facesheets, only two orientation were possible, one with the facesheet face parallel to substrate (Orientation II) and facesheet face perpendicular to the substrate (Orientation I). The height of the core was maintained at 35 mm, whereas the internal angle was set at 55° to the face sheet.

Figure 3.4: Two different part build orientations of 3D Kagome with the compression loading (a) orientation I and (b) orientation II

To establish the effect of diameter variation on the compression response of Kagome cells, struts were designed with 2.0, 2.4, 3.0, and 4.0 mm diameters, respectively and printed in orientation I with the same height of 35 mm. To study the effect of core height, structures with 35 and 25 mm core height with 4 mm truss diameter were printed in orientation II. In some samples fabricated in orientation I, the core was not completely attached to the face-sheet whereas there was no such problem with orientation II. Hence, the Kagome structures for this study were fabricated in orientation II. Lastly, for the study of the effect of surface roughness on the compressive performance of Kagome structures, the core height, strut diameter and inclination angle were set at 25 mm, 4 mm and 55° , respectively, to save material costs, printing time and were printed in orientation II.

A Stratasys® Dimension Elite FDM machine was used to fabricate the Kagome structures using Acrylonitrile Butadiene Styrene (ABSplus™) material. ABSplus™ is a 3D printable version of acrylonitrile butadiene styrene (ABS) and commercially supplied by Stratasys®. P400SR material was used as support material which is soluble in detergent water.

Solid models for printing the parts are created in 3D (Computer Aided Design) CAD software and are saved in ‘stl’ file format. The machine is operated by Catalyst® software which creates the different cross-sectional slices of the part and set the printing path for the FDM print-head. The printing parameters used for the fabrication are listed in Table 3.1.

Table 3.1: Printing parameters of FDM used in the fabrication

Layer Thickness (mm)	0.1778
Model Material printing option	Solid
Support material printing option	Surround
Model Material	ABS <i>plus</i> TM
Support Material	Soluble support technology (SST)

The schematic of fused deposition modelling process is shown in Figure 3.5. The model and support material cartridges are inserted in the machine, which is maintained at 70°C. The ABS*plus*TM is fed continuously through a screw-driven mechanism to the print-head, which is heated to melt the raw material to a semi-molten state. The print-head deposits the ultrafine polymer beads of 0.1778 mm along the extrusion path. We used the achievable lowest layer thickness (0.017 mm) than the upper-limit layer thickness (0.028 mm) for the fabrication because the lower layer thickness provides the higher strength as well as low surface roughness [91, 92]. After printing a cross-section, the build platform is lowered by 0.1778 mm, and the printing of next layer continues until the whole Kagome model with the support structure is printed (Figure 3.6). After the completion of printing, parts are taken off the build plate and are

put in detergent water at 70 °C to dissolve the soluble support structure and get the final parts.

Figure 3.5: Schematic of fused deposition modelling (FDM) process.

The average time taken for the fabrication of unit Kagome cell with two face sheets in orientation I and orientation II are 314 and 281 mins, respectively for the core height of 35 mm and strut diameter 4 mm. Though printing in the orientation I requires higher time, it needs about half the amount of support material required for printing the unit cell in orientation II.

Figure 3.6: 3D Kagome structures and the individual struts aligned as in Kagome printed with the support structures

Tensile specimens according to the ASTM standard D638 (specimen geometry and dimensions are included in Appendix A) were fabricated to measure the parent material properties of the 3D printed parts. The tensile dog-bone samples were printed edgewise with its length along the direction of the struts in Kagome unit structures with both orientations as shown in Figure 3.7. Three specimens in both orientations were tested to obtain Young's modulus, yield strength and peak strength of *ABSplus*TM.

Figure 3.7: Dog-bone tensile specimens with the length printed along the struts of Kagome in orientation I and orientation II

3.2.2 Mechanical testing

Uniaxial tensile testing on the dog-bone *ABSplus*TM sample was conducted using a Shimadzu Universal Testing Machine with 10 kN load cell under displacement control at a rate of 5 mm/min. A TRviewX non-contact video extensometer was used to measure the elongation. The flatwise compression tests of unit Kagome structures were carried on the same test machine with compression plates. The loading was through displacement control at 0.1 mm/min for the whole compression process. Black lines were marked on the side of the top and bottom face sheets (Figure 3.8) of the unit structure to

measure the displacement through TRviewX non-contact video extensometer. The relative displacement of the lines on the face sheets is assumed to be the displacement of the core structure.

Figure 3.8: Compression of 3D Kagome structure with two lines on the face sheets

3.2.3 Fractography of failed structure

To learn about the fracture surface of the failed structure, scanning electron microscope (JEOL JSM-5600LV SEM) was used to extract the images of failed surfaces. As ABS plastic is non-conducting material, the fractured strut surfaces were coated with a thin layer of gold through the (physical vapour) sputtering technique.

3.2.4 Wet chemical surface polishing

For the chemical surface treatment, individual struts and Kagome unit cells were immersed in a mixture of 90% by vol. acetone (99% pure acetone and 10% distilled water by volume) [21] as shown in Figure 3.9. The effect of chemical treatment time (i.e. 3 min, 5 min and 7 min) on the surface roughness and compressive response is explored. For statistical variation, six and five

samples of each strut and Kagome structures, respectively, were treated for each case.

Figure 3.9: Chemical treatment of the specimen.

The diameter of the struts was measured using a digital micrometre having a resolution of 0.001 mm. The Talyscan™ 150 (Figure 3.10) contact and non-contact scanning instrument was used for checking and mapping the topography and surface roughness of the printed specimens. The strut diameter and surface roughness were both measured at ten different random positions along a single sample, and the average was taken. As average surface roughness (R_a) measured was higher than 10 μm , according to ISO 4288:1996, 8 mm cut-off length was chosen.

Figure 3.10: Talyscan™ system for measuring the surface roughness of struts

3.2.5 Finite element modelling

The commercial finite element modelling software ABAQUS/STANDARD® was used for the compressive simulation study of the Kagome structure. Kagome structure was modelled in Solidworks® and imported to ABAQUS® CAE. The Kagome struts were discretised using modified second order tetragonal elements (C3D10M), whereas the solid ABSplus™ face sheets were modelled using solid brick elements (C3D8R) with reduced integration. The Kagome core had approximately 50,000 C3D10M elements depending on strut diameter, whereas face sheets were discretised with up to 4000 C3D8R elements. The bottom face of the lower face sheet was fixed, and the top face of the upper face sheet was restrained to move through the thickness of the core as shown in Figure 3.11. The displacement load was given at the top face in the core height direction. Tie constraints were applied between the surface (interface) of face sheets and core.

Figure 3.11: Boundary conditions applied on Kagome unit structure with two face sheets for numerical simulation

Elastic-plastic constitutive behaviour is assumed for the solid cell wall *ABSplus*TM with material properties obtained from the uniaxial tensile testing. Table 3.2 lists the properties obtained from the samples printed along the orientation of struts in Kagome structure with both orientation, and the uniaxial stress-strain responses of the tensile specimens along with their build directions are shown in Figure 3.12. The tensile samples printed in orientation I exhibited linear elastic region at the beginning followed by the plastic yielding to reach the peak strength. After reaching the peak strength, the structure plastically deformed with slight reduction in the stress with the increase in the strain and finally failed within the gauge length. The samples printed in orientation II exhibited the linear region and failed within the linear region. The samples with the orientation II exhibited the failure in the direction parallel to the layer stack direction which outlined that the failure was due to the failure in the bonding between adjacent layers. The samples in the orientation I failed across the layer

direction meaning that the failure occurred due to breaking of the rasters in the layers. The plastic region in the stress-strain graph of the orientation I was due to the plastic deformation of the rasters. As the samples in the orientation II failed prematurely, finite element analysis was carried out for Kagome samples for unit cells printed in orientation I to allow for additional comparison of maximum unit cell strength. Young's modulus of 1.69 GPa and Poisson's ratio of 0.35 was incorporated in the material model of the simulation. The simulations are carried out with the measured elastic-plastic response with actual true stress versus true strain data for J2 flow-theory with isotropic hardening. The plastic response is incorporated through uniaxial true plastic tensile stress-plastic strain test data as depicted in Figure 3.12.

Table 3.2: Tensile properties of FDM printed ABS_{plus}TM in different orientations as per the orientation of struts in unit Kagome structure

	Young's Modulus (MPa)	2% offset yield strength (MPa)	Failure Strain (%)
Orientation I	1689.17 ± 40.89	23.6 ± 0.69	3.36 ± 0.49
Orientation II	1511.37 ± 108.4	-	1.29 ± 0.23

Figure 3.12: Uniaxial tensile stress-strain response of ABS_{plus}TM specimens built in two different build directions (along with the struts of Kagome in orientation I and orientation II respectively).

The force and displacement are obtained from the UTM machine in-built load cell and the video extensometer, respectively. With the measured force (F) and displacement (Δh) for the compression loading, the macroscopic stress and strain are obtained as follows.

$$\sigma_{cell} = \frac{F}{A_{eff}}, \quad (3.1)$$

$$\epsilon_{cell} = \frac{\Delta h}{h} \quad (3.2)$$

where A_{eff} is the effective area occupied by a stand-alone unit cell and is given in terms of Kagome truss length, ' l ', as

$$A_{eff} = \frac{\sqrt{3}}{2} l^2 \quad (3.3)$$

3.3 Results and discussion

This section is divided into two parts. Firstly, the response of the Kagome unit structure under compression loading is explored. The effect of the build orientation, strut diameter and core height on the compressive properties are investigated. In the second portion, the effect of the chemical treatment on the FDM printed Kagome structures on the surface roughness and compressive properties are explored.

3.3.1 Compression Response of Kagome unit structure

3.3.1.1 Effect of build orientation

Two different build part orientations were printed as shown in Figure 3.4, and the measured compression stress-strain curves of these two orientations are

shown in Figure 3.13. The structures printed in orientation I have a better effective modulus (by 19%) as well as higher compressive strength (by 23%) than the cells printed in orientation II. However, these specimens failed at lower strain than for orientation II due to the delamination of the built strut layers of the core leading to their abrupt failure. Failure in orientation II was gradual in comparison, and there was no complete delamination of the build layers. After reaching the peak strength, the struts start to bend lowering the load carrying capacity.

Figure 3.13: Comparison of stress-strain response for different build orientation

Figure 3.14(a) shows a schematic diagram of compression loading and build orientation of the deposited layers. In orientation I, the loading direction is parallel to the deposition of build layers, and the shear strength exceeds the bonding strength between adjacent layers which results in the early delamination failure as shown in Figure 3.14(b). As the compressive loading direction and the orientation of build layers of the core are perpendicular in orientation II, the failure mode is significantly different. Following strut

bending in the post-buckling regime, a crack appeared on the outer surface of the strut. A gradual decrease in load was observed with simultaneous cracks developing from the tensile side of struts. With the further displacement, the cracks open more leading to the failure of the structures.

(a)

(b)

Figure 3.14: (a) schematic diagram showing the force direction, deposited layer, and failure mechanism and (b) tested samples of both build orientations showing the failure locations and crack development.

Figure 3.15 shows the fracture surface of the failed struts with both orientations. It is observed that the failure of both structures is in a single layer of the

structure. A small portion of the next print layer is also observed, but the majority of the fracture is observed in the same single layer. In orientation I, the print cross-sectional area of the strut is higher than of orientation II. As the fracture occurred on the bonding surface of two layers in both cases, we can see the fracture surface area of orientation I is higher than of orientation II. For further investigation on the fractography of the failed structures, SEM was used, and images were analysed as follows.

Figure 3.15: Optical image of the fracture surface of struts of both orientations.

The differences in the failure modes of both orientations are clearly seen in the fracture surface micrographs shown in Figure 3.16. The presence of surface debris on the fracture surface of parts printed in orientation I indicates high speed fracture as well as crack propagation under shear stresses [109]. It also depicts failure due to the breaking of adhesive bonds between adjacent layers. The relative smooth fracture surfaces in the parts printed in orientation II is due to slow crack growth on the fracture surface [110]. The presence of scarps on the fracture surface indicates the Kagome strut printed in orientation II failed

due to peel stresses with failure occurring from the tensile stress side during strut bending [109]. We also observe gaps between the filled rasters in both orientations making the struts porous in nature.

Figure 3.16: SEM micrographs of the fracture surface of Kagome struts printed in (a) orientation I and (b) orientation II

To measure the diameter of the struts of Kagome structures, individual struts (two each in three angles) orientated in the same angle as in the whole structure were fabricated keeping the same process conditions, but in two different orientations. The average diameter of the individual struts is listed in Table 3.3. It was found that the average diameter of the strut in orientation I was similar to the modelled diameter, whereas the diameter of the strut in orientation II was reduced by 4%. The dimensional accuracy of the parts, therefore, depends on the building direction. Hence, due to the reduction in strut diameter, the effective modulus and strength of the Kagome structure are expected to decrease slightly (about 8%) in orientation II. A similar observation was made by Garg et al. [105] that the part build accuracy at around 45° displays greater variation in dimensions than the parts with horizontal or vertical build direction.

The remaining contribution of the reduction of strength and effective modulus is due to the anisotropic nature of FDM printed parts. The Young's modulus of tensile specimens fabricated in orientation I is about 12% higher than orientation II as shown in Figure 3.12. Thus, the variation in dimension as well as in material properties with change in built orientation results in the observed discrepancies in the compressive properties of Kagome unit cells with different built orientations.

Table 3.3: Average diameter of the struts fabricated in different orientation as per the orientation of struts in unit Kagome structures

	Orientation I	Orientation II
Overall average diameter (mm)	3.99 ± 0.03	3.842 ± 0.02

3.3.1.2 Effect of strut diameter on compression response

To investigate the effect on the variation in diameter on the compressive performance of Kagome unit cells, struts with varying diameters, i.e. 2.0, 2.4, 3.0 and 4 mm were printed in orientation I. Table 3.4 lists the calculated and the measured relative densities of these Kagome unit cells. The calculated value is obtained from the total mass of the unit cell CAD model. Measured relative density is obtained from the measured mass of the core structure. It is found that the measured mass and relative density is generally lower than the respective calculated values. The parts produced are not perfectly solid, and there are variations in diameter due to several stair-like features reducing the mass and the relative density. The difference between measured and designed densities increases with increase in diameter, with a maximum deviation of around 6% for the largest diameter nominally of 4 mm.

Table 3.4: Relative densities from the calculated mass and measured mass for Kagome unit cell fabricated in Orientation I

Truss diameter (mm)	Calculated mass of unit cell (g)	Calculated relative density ($\bar{\rho}$)	Measured mass of unit cell (g)	Measured Relative density ($\bar{\rho}$)	Difference (%)
2.0	0.405	0.007	0.405	0.0070	0
2.4	0.579	0.01006	0.585	0.0101	0.39
3.0	0.895	0.0156	0.85	0.0148	-5.12
4.0	1.564	0.0272	1.476	0.0256	-5.88

Table 3.5: Average Peak strength and elastic moduli of unit Kagome structure with various diameters in orientation I

Strut diameter (mm)	Peak strength (MPa)	Unit Cell modulus (MPa)
2.0	0.0588	4.49
2.4	0.1068	6.59
3.0	0.2311	10.04
4.0	0.5841	19.08

Figure 3.17: Compressive stress-strain curve for the variation in diameter in orientation I

Figure 3.17 shows the measured compressive stress-strain curves. All specimens demonstrate a linear elastic region which is followed by some plastic deformation to reach the peak strength. After reaching the peak strength, all structures demonstrate softening behaviour. The Kagome structure with the largest diameter of 4 mm failed suddenly just after the peak strength due to the complete separation of two neighbouring layers in the strut as discussed previously and shown in Figure 3.14(b). These structures carry the highest shear loading between adjacent build planes. Specimens with smaller diameters displayed gradual failure instead.

Table 3.5 lists the experimental peak strength and effective modulus of the Kagome cell of different diameter with build orientation I. As expected, the results show that with the increase in truss diameter, the peak strength and the elastic modulus increase.

Figure 3.18 shows the stress-strain curve obtained from the experimental measurements and the finite element modelling results for 3.0 and 4.0 mm truss diameter. It is seen that the linear elastic region of the simulated results shows a steeper slope than the experimental results. Hence the simulations over-predict the experimental modulus by 17%. This is because fully solid and cylindrical trusses with uniform diameters were considered while modelling but in reality, there are many stair-like features in the fabricated parts due to the inclined struts. The variation in diameter as per Table 3.3 and the stair-case imperfections affect the modulus and strength of the structures fabricated by fused deposition modelling [52]. The discrepancies in the graph of simulation

and experiments after the peak strength are also due to the exclusion of damage model.

Figure 3.18: Compressive stress-strain curve for simulated and experimental results

The mechanical properties of lattice structure depend on the relative density. Relative density is the ratio of the density of cellular structure to the density in solid form. The analytical prediction of effective modulus and strength of lattice structures has been studied [20, 111] and the effective modulus of the Kagome-like unit cell is given by:

$$E_{cell} = \bar{\rho} E \sin^4 \theta \quad (3.4)$$

where E is Young's modulus of parent material, θ is the included angle and $\bar{\rho}$ is the relative density.

At peak strength, Kagome unit cell encounter either linear elastic buckling or plastic yielding depending on the relative density of the unit cell. The peak strength can be predicted as follows:

Elastic buckling:

$$\sigma_{cell} = \bar{\rho} \sigma_{cr} \sin^2 \theta, \quad \text{where } \sigma_{cr} = \frac{k^2 \pi^2 E}{4} \left(\frac{r}{l_b} \right)^2 \quad (3.5)$$

Plastic yielding:

$$\sigma_{cell} = \bar{\rho} \sigma_y \sin^2 \theta \quad (3.6)$$

where k depends on the boundary conditions of truss member: $k = 1$ for pin-jointed trusses and 2 for clamped conditions at the face plate, r is truss radius and l_b is the free length of the truss between the joints.

Figure 3.19: Comparison of elastic moduli of Kagome structure (a) simulation and analytical results and (b) analytical and experimental results

Figure 3.19 shows the variation of the effective modulus with the relative density. Figure 3.19(a) shows the analytically predicted modulus (using Eq. (3.4)) and the simulated results against the calculated relative density, whereas Figure 3.19(b) shows the predicted modulus and experimental measurements against measured relative density. The analytical calculations agree well with the simulated results. The trends for analytically predicted results and experimental measurements are similar, but experimental values are lower by 10-17% than the calculated results when plotted against the measured relative density. It is expected that the manufacturing defects decrease the modulus in the fabricated structure compared to the predicted modulus. The responsible defects include voids (see optical micrographs in Figure 3.20(a) and (b)), and

irregular cylindrical surface features due to staircase effects as shown in Figure 3.20(c). Structures printed in both orientations contain voids as well as rough surface profile due to staircase effects. The average surface roughness (R_a) values for structures printed in orientations I and II are 30.2 and 16.67 μm , respectively. The structure printed in orientation II has a smoother surface than printed in orientation I which can be seen in Figure 3.20(c).

Figure 3.21 shows the analytical and experimental results for normalized peak strength as a function of $\left(r/l_b\right)^2$. The strength of Kagome unit cells was predicted using Eqs. (3.5) and (3.6). The experimental strength results show that Kagome structures with diameter 2.0, 2.4, and 3.0 mm reach the peak strength before core yielding. The results fall in a range of k values between 1 and 1.2 for critical buckling strength indicating that the face plate support is not representative of clamped boundary conditions. The peak strength for unit cells with 4.0 mm strut diameter is slightly higher than the plastic yielding strength value. This indicates a change in failure mode when the strut diameter increases from 3.0 mm to 4.0 mm for orientation I. These findings are confirmed when investigating the stress-strain curves in Figure 3.17 in detail: The Kagome unit cells with 4.0 mm diameter display significant plastic nonlinearity before reaching peak load. In comparison, the stress-strain response is linear for Kagome unit cell with smaller diameter struts of 2.0 and 2.4 mm. The 3.0 mm strut diameter is in the transition zone, with minimal nonlinearity observed prior to reaching the peak strength.

Figure 3.20: The image of orientation I and orientation II (a) cross-section of the strut at $1.25\times$ and (b) $5\times$ magnification showing the voids, (c) lateral surface of strut showing the stairs like structure through the optical microscope.

Figure 3.21: Failure prediction of ABS Kagome unit structure with the change in the aspect ratio.

3.3.1.3 Effect of core height on compressive response

Figure 3.22(a) shows the compressive response of the Kagome unit structure of 4 mm truss diameter fabricated in orientation II with the change in the height of core from 35 mm to 25 mm. The average effective modulus and strength increase by 1.77 and 2.24 times, respectively, with the change in height. According to Eq. (3.4), an increase in modulus of 190% is expected with the change in the relative density of the unit cell from 0.025 to 0.048. Diameter, angle of the strut, and printing process parameters being the same, the level of porosity and the surface roughness and level of anisotropy remain equal within the experimental scatter. Hence, the decrease in height causes the increase in aspect ratio as well as the effective area of the Kagome. This leads to an increase in relative density, resulting in the increase of peak strength and effective moduli. The experimental results for Kagome structures of 4.0 mm truss diameter in orientation II with height 25 mm, as well as 35 mm, show that

the unit cell fails by elastic-plastic buckling. This agrees with the analytical predictions as shown in Figure 3.21. The analytical yield solution assumes uniform truss loading and ideal elastic-plastic yielding without considering plastic hardening and pressure-dependent yield strength, hence presents initial failure load.

(a)

(b)

Figure 3.22: (a) Compressive response of Kagome unit structure and (b) the tested specimens of the core with the variation in height built in orientation II

Figure 3.22(b) shows the sample with both heights after the compression test. The fracture locations on both the samples are in the similar position as circled in the figure. Within the experimental scatter, the failure mode and the fracture location are similar for both the cases.

3.3.2 Surface Polishing

3.3.2.1 Chemical treatment

With the acetone treatment, the staircases on the printed parts were reduced, and the parts look plain and smooth. Figure 3.23 shows the optical microscope image and confocal image of the struts before and after the treatment. In Figure 3.23(a), the peak and trough are easily seen whereas these features are diminished in Figure 3.23(b). The peak and trough are observed due to the presence of staircases. As the surface area around the peak is high, the etching due to the presence of the chemical pool around it results in the localised removal of peak surface. Finally, a plain and smooth surface is obtained.

(a)

(b)

Figure 3.23: Optical microscope and confocal image of (a) non treated struts and (b) chemically treated struts

The change in surface roughness from the chemical treatment of the ABSplus™ struts of 4.0 mm diameter at three different time periods is shown as a bar chart in Figure 3.24. The average surface roughness (R_a) of all 18 samples is $16.67 \pm 4.5 \mu\text{m}$. It is seen that the average percentage reductions in the roughness of struts after 3, 5 and 7 mins are 39%, 55% and 60%, respectively, due to the decrease in staircase features as shown in confocal images. Two sample t-tests for equal means of surface roughness before and after the acetone treatment was carried out in Microsoft Excel®. T-test rejected the null hypothesis of equal means before and after the chemical treatment for 3 mins with the significance level of 10%. Similarly, t test for before and 5 mins treatment time and before

and 7 mins treatment rejected the null hypothesis of equal means with the significance level of 5%. Two sample t-tests carried out verified that the chemical treatment has significant effect on reduction of surface roughness. Two sample t tests for equal mean are tabulated in Appendix B.

Figure 3.24: The change in average roughness after the chemical polishing as a function of treatment time.

The average change in diameter of the struts after the chemical treatment is shown as bar-chart in Figure 3.25. Recall that the diameter of the modelled struts was 4 mm. But the average diameter of the printed struts is 3.824 ± 0.016 mm, which is lower than the designed one. The dimensional accuracy of the parts, therefore, depends on the building direction. A similar observation was made by Garg et al. [105] that the part build accuracy at around 45° displays greater variation in dimensions than the parts with horizontal or vertical build direction. The average percentage decrease in strut diameter after the acetone treatment of 3 mins, 5 mins and 7 mins was 0.96%, 1.13% and 2.05% respectively. It is seen that while there was not much dimensional change when treatment time increased from 3 mins to 5 mins, the surface roughness

continued to decrease. When the treatment time was increased from 5 mins to 7 mins, the roughness remained similar, but the ABS part starts to dissolve uniformly as shown by the continuous decrease in diameter. Hence, 5 mins of chemical treatment result in the optimum surface finish without unnecessary sacrifice of the strut cross-sectional dimensional accuracy.

Figure 3.25: The change in average diameter of struts after the chemical polishing as a function of treatment time.

3.3.2.2 Compression response

Five Kagome unit cells were treated with the mixture of acetone and water for 3 mins, 5 mins and 7 mins. The treated, as well as non-treated samples, were subjected to uniaxial compression at a strain rate of $6.67 \times 10^{-5} \text{ s}^{-1}$. Figure 3.26 shows the stress-strain response of Kagome structure with and without chemical treatment. One clear distinction of the compressive response between the chemically treated and non-treated specimens is the increase in the failure strain in chemically treated specimens.

Figure 3.26: Stress-strain response of Kagome unit structure (a) without acetone treatment, (b) 3 mins treatment, (c) 5 mins treatment and (d) 7 mins treatment

The average peak strength and effective moduli of non-treated as well as treated specimens for the different treatment times are shown in Figure 3.27. It is observed that the peak load slightly increased with the chemical treatment. The load increased even further with the increase in immersion time from 3 mins to 5 mins but again reduced when the time increased to 7 mins. Interestingly, the chemical surface treatment also resulted in a measurable increase in elastic moduli for all treatment times. The maximum modulus was obtained after 5 mins samples. The causes for this modulus change are not readily understood and needs further investigation.

Figure 3.27: Average peak strength and effective modulus of as fabricated and chemically treated samples

Figure 3.28 shows the average volumetric energy (area under the stress-strain curve) and the average failure strain of treated and non-treated samples: non-treated samples failed at lower strain than the treated samples. The average percentage increase in the failure strain after 3 mins, 5 mins and 7 mins of chemical treatment compared to the non-treated failure strains are 21.15%, 24.28% and 24.96% respectively. Similarly, the average percentage increase in absorption energy after 3 mins, 5 mins and 7 mins of chemical treatment from the non-treated ones are 20.28%, 22.39% and 19.34% respectively. As the non-treated structures have lower strain to failure as well as lower average peak strength, the treated specimen exhibited higher energy absorption per unit volume. The increase in the failure strain contributed more than the peak strength in increasing the energy absorption. Though the average failure strain after 7 mins treatment is highest (Figure 3.28), the average energy absorbed decreased slightly due to lower average peak strength. Single factor ANOVA test was carried out for different mechanical properties: peak strength, effective modulus, failure strain and energy absorption. The ANOVA test resulted that

there is no significant change in the peak strength with the chemical treatment. The test resulted that the chemical treatment has a significant effect on effective modulus with a significance level of 0.1. The ANOVA tests on failure strain and energy absorption rejected the null hypothesis with the significance level of 0.05 concluding that the chemical treatment has significant effect.

Figure 3.28: Average energy absorbed per unit volume and strain at failure of as fabricated and chemically treated samples

The increases in the volumetric energy and failure strain after the chemical treatment are related to the reduction of surface roughness. Generally, rough surfaces initiate surface cracks easily, and these cracks start to propagate under an applied load. Hence, the simple chemical acetone treatment (about 5 mins) for the *ABSplus*TM Kagome structures gave optimal surface finish leading to the increase in strength, energy absorption and the strain at failure.

3.4 Summary

In this chapter, a comprehensive study on the compressive performance of Kagome unit cell structure is presented. The effect of various geometric and printing variables on the FDM printed Kagome structure is discussed. Limited

numerical simulations using finite elements modelling was used to predict the compressive properties of Kagome structure, and the reasons for the discrepancies in the numerical and experimental results are discussed. The FDM printed ABS*plus*TM Kagome unit cells contain stairs like structures on the surface of the printed parts. Acetone of 90% by vol. was used as a chemical agent to polish the rough surface. The unit Kagome structures fabricated with the FDM were treated with the chemical and their compressive performance was investigated. The key findings include:

1. The part build orientation of Kagome unit cell affected not only the compressive properties: peak strength, elastic moduli, failure strain, etc. but also the failure behaviour.
2. The variation in the aspect ratio (change in diameter keeping the length constant) changed the failure mode of Kagome structure. With the increase in diameter, the failure mode of the structure changed from elastic buckling to the plastic buckling after the yield.
3. The presence of the voids in the printed structures and the stairs like structures resulting in surface roughness has reduced the performance of the structure leading to the discrepancies in the numerical results and experimental measurements of the strength and modulus.
4. With proper treatment time, surface roughness was minimized without excessive material removal. The staircases were eliminated after the treatment with well improved surface finish.
5. The compressive properties of the Kagome structures improved after the chemical treatment for the optimal treatment time. The major change

was observed in the failure strain of the structure which increased with the chemical treatment.

Chapter 4 Compressive properties of functionally graded Kagome lattice structure fabricated by fused deposition modelling

4.1 Introduction

Cellular lattice structures have immense application in the aerospace, automobile and defence industries due to their high specific strength, stiffness and energy absorption capacity under impact and shock type loading cases. With the advancement of additive manufacturing (AM), fabrication of complex design structures has been possible. AM provides means to produce the net shape lattice structures with design freedom.

Lattices structures are periodically distributed in three different directions. The unit cells are connected to each other and repeated in three directions to obtain a large ordered structures. In Kagome lattice structures, the unit structures are separated from each other at a certain distance and repeated to form periodic Kagome structure [4, 5, 31]. The experimental studies on the performance of the cellular lattice structures are performed on the repeated multiunit structures. In general, simulations studies in the performance of these lattice structures were performed in the unit cells or structure with periodic boundary conditions to save computational time and resources [112, 113]. In Kagome structures, the units are not connected with each other, and a unit structure is supposed to represent the performance of the multi-unit structure.

Functionally graded materials have a gradual change in their composition or the morphology over the volume which results in gradual change on its mechanical or functional properties over the thickness. They can be graded either compositionally or by geometrically. With additive manufacturing, functionally gradient structures can be obtained by two approaches. One approach can be the manipulation of various process parameters to get variation in the density of the parts. The density variation with this approach has no control over the internal architecture of the parts [114]. The second approach is to design the lattice structures with the variation in the density during the CAD modelling and fabricate the whole structure with the same process parameters. The second approach is relatively easier approach in the sense that the density distribution can be easily controlled at the design stage.

In this chapter, the compressive performance of the FDM fabricated Kagome lattice structure is presented from a unit cell level to multi-layer multiunit structure. The compressive performance of the unit Kagome structure is compared with the multi-unit structures. Similarly, the effect of the increase in the number of layers on the compressive performance of the Kagome structure was investigated. The graded density Kagome structures were fabricated by FDM using ABS-M30™ material supplied by CREATZ3D and were investigated for their mechanical properties under compression loading. The performance was compared with a uniform density structure. The deformation behaviour and the energy absorption of graded and uniform density structures were explored. This study aims to investigate the performance of graded density Kagome structure for its potential use in crash protection.

4.2 Experimental Design

4.2.1 Design and fabrication

Kagome unit cell structures with a core height of 13 mm and the inclination angle of 54.74° ($\theta = \tan^{-1}\sqrt{2}$) with 2.62 mm diameter along with two face sheets of 3 mm thickness were designed as shown in Figure 4.1.

Figure 4.1: Front and side view of a unit Kagome structure (all dimensions are in mm)

To compare the performance of Kagome unit structure with multi-unit Kagome structure, 3×3 Kagome units structure was designed with the same height, inclination angle and the diameter. Figure 4.2 shows the arrangement of the Kagome units in 3×3 lattice core structures. The units are separated at a distance of the length of the strut along the lines of the equilateral triangle formed by the base.

To study the effect of the number of layers in the compressive performance of the Kagome structure, specimens were designed to have one to three layers. The 2 mm thick face sheets were used at the interfaces between the layers. Single layer specimens have 3×3 units of Kagome whereas two layered specimens have 4×4 units in the bottom layer and 3×3 units on the top layer. The specimens with three layers have 3×3 units on the top layer, 4×4 units in the

intermediate layer and 5×5 units on the bottom layer. This is designed like this to observe any localized failure in the structure. The deformation mechanism under uniaxial compression indicates the following: from Figure 4.3 front and side views, we can clearly see that some struts near the boundary do sustain the applied load while other struts do not at the initial stages of loading [32].

Figure 4.2: (a) Front and side views and (b) the top view of the arrangement of the Kagome units in 3×3 lattice core structure

The graded structure also has three layers with the same number of Kagome units as in a normal three layered structures. The relative density of the uniform diameter Kagome truss with the given core height of 13 mm and diameter of 2.62 mm is 9%. To compare the mechanical performance of uniform and graded density lattice structures on equal mass basis, the graded structure with relative densities of 6.36%, 8.9% and 11.83% at the top, intermediate and the bottom layer respectively was designed. The average relative density of these three layers is 9% which is equal to the relative density of uniform density structures. The corresponding diameter in the graded density Kagome structures are 2.2 mm, 2.6 mm and 3.0 mm at top, intermediate and bottom layers respectively. The design of uniform density structure and graded density structure is shown in Figure 4.3.

Figure 4.3: CAD model of uniform and graded density Kagome lattice structures

The designed specimens were fabricated by fused deposition modelling (FDM) on a Stratasys® F370 using ABS-M30™ material. The manufacturer claims that ABS-M30™ material is 25-70% stronger than standard ABS and is used for manufacturing tools and production parts. The print setting parameters used for the fabrication are listed in Table 4.1. The support material was dissolved in using the detergent (Ecoworks™ cleaning agent) water. The printed model parts were treated chemically with 90% by vol. acetone for three minutes to reduce the surface roughness. To measure the diameter of the struts in Kagome

structures, individual struts oriented in same angles as in whole structures were fabricated keeping the same processing conditions.

Compression specimens (ASTM standard D695) were fabricated to measure the raw material properties of the 3D printed parts. The samples were printed with their length along the direction of the struts in Kagome unit structures. Three specimens were tested to obtain average Young's modulus, yield strength and stress-strain behaviour of ABS-M30™.

Table 4.1: Printing parameters used for the fabrication of the samples

Layer thickness (mm)	0.1778
Model part fill style	Solid
Support style	Smart
Model material	ABS-M30™ Ivory
Support material	QSR Support
Support Tip	T14

4.2.2 Mechanical Testing

Uniaxial compression testing on ABS-M30™ samples (standard samples for material properties) was conducted using a Shimadzu® Universal Testing Machine with 50 kN load cell under displacement control at a rate of 1.3 mm/min. Two lines were marked at the mid-portion of the specimens as the gauge length, and a TRviewX non-contact video extensometer was used to measure the displacement.

Compression testing of the Kagome unit structure was carried out using Instron universal testing machine equipped with 500 N load cell. Other multi-unit and multilayer graded and non-graded structures were tested with 50 kN load cell.

The compressive load was applied at the rate of 0.2 mm/min. A digital camera (Nikon D7200) was used to record the test and frames were extracted to illustrate the deformation at different stages of the compression.

4.3 Results and discussion

In this section, the compressive performances of the unit Kagome structure, multi-unit Kagome structure, multi-layer Kagome structure and functionally graded Kagome structure are presented. First, the comparison of the performance of unit Kagome structure with the performance of multi-unit Kagome structure is discussed. It is followed by the effect of the number of layers in the compressive performance of Kagome structures. Lastly, the performance is explored between the graded and uniform density Kagome structure.

Dimensional accuracy of the samples was accessed by measuring the strut diameters printed in the same orientation as they were in the whole structures using digital micrometre and are listed in Table 4.2. The average diameter of the fabricated struts was smaller than the designed diameter. It is inherent in FDM process that the variation of diameter is inevitable and is more prominent when printed in angles due to staircase effect [52]. It was found that the difference in the diameter of the modelled and fabricated struts reduced with the increase in the diameter.

Table 4.2: Variation in the fabricated and designed diameter of the struts

Designed strut diameter (mm)	Measured strut diameter (mm)	Difference (%)
2.20	1.914 ± 0.042	13.00
2.60	2.445 ± 0.013	5.96
2.62	2.506 ± 0.027	4.35
3.00	2.883 ± 0.034	3.90

The bulk compression properties of the printed material were obtained by compression test on the samples printed in the direction of struts in Kagome structures and are listed in Table 4.3.

Table 4.3: Bulk compression properties of FDM printed ABS-M30™ as per orientation of struts in Kagome structures

Young's modulus (MPa)	2% offset yield strength (MPa)
1498.53 ± 102.67	28.51 ± 0.39

4.3.1 Kagome unit structure and multi-unit structure

Kagome unit structure and single layer 3×3 unit Kagome structure with strut diameter (d) 2.62 mm were compressed, and their compressive performances are manifested through the stress-strain curve as shown in Figure 4.4. Both structures exhibited the linear elastic region at the beginning followed by non-linear plastic region before reaching the peak strength. The average peak strength and the effective moduli of single unit and 3×3 units structure are listed in Table 4.4. The peak strength and the effective moduli of the multi-unit structure were higher by 11% and 20% respectively. Unlike other lattice structures, the unit structures in multi-unit Kagome structures are not connected

with each other. They are positioned in a different location as depicted in Figure 4.2. So, the performance of unit structure should represent the overall performance of a multi-unit structure in case of Kagome structure. The numerical simulation of compression test using the bulk material properties conducted in both cases revealed the same compression properties (Figure 4.4(b)). But, the experimental results exhibited discrepancies in peak strength and effective moduli. This might occur due to the difference in the quality of the printed samples. Though all the printing parameters and conditions for both cases were maintained same, sometimes the print quality may differ from one batch to other batch [115].

Table 4.4: Compressive properties of unit cell Kagome and 3×3 units Kagome structures.

	Average effective loading moduli (MPa)	Average peak strength (MPa)
Unit cell	45.16 ± 0.12	1.88 ± 0.04
3×3 units cell	54.49 ± 1.78	2.11 ± 0.05

(a)

(b)

Figure 4.4: Compressive stress-strain curve for unit Kagome structure and 3×3 units Kagome structure (a) experimental measurements and (b) numerical simulation results

After the peak strength, both structures demonstrated the softening behaviour till the failure near the joints with face sheets. Unit structure and 3×3 structure exhibited the failure near the joints of struts with the face sheets as shown in Figure 4.5. The sudden decrease in load in the unit structure is due to this failure (Figure 4.4(a)). The decrease in the strength is continuous in multi-unit structure as all the units did not fail simultaneously. While some units fail at the beginning, other units still supported the load leading the continuous decrease in the strength.

Figure 4.5: The initial failure region of (a) unit Kagome structure and (b) 3×3 units Kagome structure

Figure 4.6 shows the force-displacement curve for the Kagome structures with a different number of layers. As the number of units in the top layer of the double layer, as well as triple layer structure, was the same as 3×3 single layer structure, only the first peak load was compared. The measured average peak loads were 4.18 kN, 4.31 kN and 3.99 kN for a single layer, double layer and triple layer respectively, indicating no significant effect of a number of layers. But the stiffness decreased with the increase in the number of layers as measured from the initial slope of the force-displacement curves in Figure 4.6. The double layer and triple layer structure also displayed a similar failure as described in the single layer, from near the joints to the face sheet of the top layer. As the area of the top layer is low (with 3×3 units) in a multi-layered structure, hence top layer struts experienced higher stress. Thus, the top layer failed first. After reaching the peak load, the load decreased gradually due to the gradual failure of the struts at the top layer.

Figure 4.6: Force-displacement curves of Kagome structure with a different number of layers

4.3.2 Uniform density and graded density Kagome structure

4.3.2.1 Deformation Behaviour

(a)

(b)

Figure 4.7: Load-displacement curve for (a) uniform and (b) graded density Kagome structure

Compression tests were carried out on the uniform as well as graded samples with three layers. The top layer has 3×3 units; the middle layer has 4×4 units, and the bottom layer has 5×5 units of Kagome structures. As there were

different numbers of Kagome unit in different layers (resulting different area for each layer), the compression behaviour of uniform and graded density lattice were analysed through the force-displacement curve. Figure 4.7 shows the force-displacement curves of both uniform and graded density Kagome structures with the number 1-5, which indicates the position where images of Figure 4.8 and

Figure 4.9 were captured. Both the structures exhibited linear behaviour in the initial stage of the compression followed by non-linear deformation to reach the peak load. The load decreased with further compression.

Figure 4.8 shows the deformation pattern in uniform density Kagome structure at different displacement (as numbered in the force-displacement curve). In uniform density structures, the displacement of the inter-face sheets along with the inner core (especially area beneath 3×3 core) can be observed in the early stages of the deformation. With further loading, the bending of the core can be noticed on the top layer along with the deformation in the inner core of middle and bottom layers (Figure 4.8 image 2). The deformation is localised at the central units of Kagome, without any predominant deformation in the outer units of middle and bottom layers. As the area of top layer (3×3) is low, the struts of Kagome in top layer experience higher stress than the struts of other layers leading to its failure. The failure of the top units was resembled in the force-displacement curve in Figure 4.7(a) as the lowest load of 1 kN after the first peak load. With the contact of failed struts of the top layer with face sheets, the load again increased. With further compression, the middle layer core supported the load to reach the second peak load of 5 kN. The drop in the load in the graph again resembled the collapse of the second layer. With the

contribution of the bottom layer, the load again increased to reach the third peak. Further loading caused the densification of the Kagome structures which increased the load significantly from 31.5 mm onwards. Images 3, 4 and 5 of Figure 4.8 show the uniform density Kagome structure after the collapse of each layer.

In graded density lattices, the load-displacement curve started with smaller peaks corresponding to the lowest density core in the top layer. The subsequent peaks were increasingly higher with greater load resistance due to higher core density. After reaching the first peak load of 2.16 kN, the top layer of Kagome with relative density of 6.36% started to deform without any change in other layers. Subsequently, the core of the top layer failed with the fracture near the joints to face sheet. The significant reduction in load after the peak load was due to the collapse of the top layer core. The second and third peaks were due to the load resisted by the middle and bottom cores and the subsequent reduction in the loads were due to the collapse of these layers respectively. The images of progressive collapse of graded density Kagome under compression loading at different displacement are shown in

Figure 4.9. Images 3, 4 and 5 show the graded density Kagome after the collapse of each layer.

Displacement (mm)	Captured image during compression	Image No
0	A photograph of a uniform density Kagome structure in its initial state, showing a regular lattice of interconnected struts forming diamond-shaped voids.	1
3.65	A photograph showing the structure at 3.65 mm displacement. Three red circles highlight areas of deformation in the inner core. Red arrows point from the text 'deformation in inner core' to these circles.	2
8.77	A photograph showing the structure at 8.77 mm displacement. A red bracket on the right side indicates the collapse of the top layer.	3
24.51	A photograph showing the structure at 24.51 mm displacement. A red bracket on the right side indicates the collapse of the middle layer.	4
32	A photograph showing the structure at 32 mm displacement. A red bracket on the right side indicates the densification of the material.	5

Figure 4.8: Deformation of uniform density Kagome at different displacement during the compression test

Displacement (mm)	Captured image during compression		Image No
0		initial stage	1
1.4		deformation in top layer	2
8.15		collapse of top layer	3
21.3		collapse of middle layer	4
32		densification	5

Figure 4.9: Deformation of graded density Kagome sample at different displacement during the compression test.

4.3.2.2 Compressive properties

The representative load-displacement response curves of both uniform and graded density structures are shown in Figure 4.10. The first maximum compressive load of the graded density samples was smaller than for the uniform density samples as graded samples failed from the lowest core density and gradually increased with an increase in core density. The second peak load for both structures was the same as the middle layer core density (0.09) was equal.

Table 4.5: Average compressive properties of uniform and graded density Kagome structure

Specimens	First peak load (kN)	Displacement at densification, δ (mm)	Total energy absorbed to densification (J)
Uniform density	3.99 ± 0.14	31.55 ± 0.05	121.24 ± 1.02
Graded density	2.16 ± 0.16	32.26 ± 0.26	164.25 ± 0.09

Figure 4.10: Representative load-displacement curve of compression testing on a uniform and graded density Kagome structures

The cumulative energy absorption of the lattice structures under compression was calculated by numerically integrating the load-displacement curves and is shown in Figure 4.11. It was found that the graded density structures absorbed less energy than uniform density structures at low deformation. The second layer supported the load with the collapse of the first layer. At around 22 mm, the last layer which has highest relative density supported to load increasing the energy absorption at higher rate which can be seen in Figure 4.11. With further displacement beyond 24 mm (24 mm was the breakeven displacement for energy absorption for uniform and graded density structure), the graded density structures had more energy absorption than uniform density structures. The total energy absorbed is calculated to the densification displacement of the curve and are presented in Table 4.5. For the experimented samples with an average relative density of 9%, the total energy absorption to densification increased by 35% when graded density design was incorporated instead of uniform density lattice structure.

Figure 4.11: Cumulative energy absorption versus displacement curves for uniform density and graded density Kagome lattice structure

Galehdari et.al found that the total amount of deformation in both the low velocity impact and the quasi static compression of graded honeycomb structure is nearly same [116]. The number of load drops (onset of collapse) curve was same as the number of strata as witnessed in quasi-static and low velocity impact testing of the graded structure. In the current study, quasi static compression of graded Kagome sandwich structure revealed that each layer demonstrated clear distinct peaks prior to the overall densification of the multi-core sandwich structure. This means that each stratum acts as a redundancy for the subsequent strata improving its crashworthiness. The progressive collapse of the graded structure (from low density to high density layer) as seen in Figure 4.7(b) and

Figure 4.9 can be utilized in the potential applications in elevators, infant car seat and helicopter seat for improving for crashworthiness during emergency events [116].

4.4 Summary

In this chapter, compressive properties of Kagome structure from unit structure level to multi-layer level have been studied through experiments. The performance of unit Kagome structure is compared with the performance of the multi-unit structure. The effect of the number of layers and variation in relative density across the thickness in the compressive performance Kagome structures is also investigated. The key findings include:

1. The multi-unit structure had 11% and 20% higher peak strength and effective moduli respectively, than Kagome unit cell for the designed relative density though had a similar failure.
2. The graded density Kagome structures have 35% better energy absorption over the uniform density structure for the designed relative density samples.

Chapter 5 Performance of strut-reinforced Kagome truss core structure under compression

5.1 Introduction

Lightweight, high strength and high energy absorption in materials are of interest in aerospace, automobile, and defence industries. Sandwich structures with different core morphologies like honeycomb, foam or open or closed cell regular lattice structures have immense use in these industries. The development of AM technologies has enabled the fabrication of different complex structures. With the advances in the metal printing technologies such as selective laser melting (SLM), electron beam melting (EBM), the capability to fabricate the cellular structure with engineering grade low-density material is made possible. One major objective of the cellular structure is to minimise the material usage and maximise their mechanical performance. Thus, the research and development have shifted to the new designs of cellular structures and study their mechanical performance for structural and functional applications.

In this chapter, a modified design of existing 3D Kagome lattice structure is proposed, and its compressive performance is explored. The study focuses on the change in the properties as well as the failure modes of the structure as a function of the relative density. An analytical formulation is proposed to predict the effective moduli and strength of the structure, and the results are compared with the numerical and experimental results. The performance of the modified

structure is compared to the existing Kagome structure. Finally, the effect of heat treatment on the compressive properties is investigated in terms of the effective moduli, peak strengths, failure strain and energy absorption.

5.2 Experimental Design

5.2.1 Design

The Kagome truss structure is the combination of a pair of tetrahedral structures vertically inverted with each other whereas strut reinforced Kagome (SRK) is a modification of the Kagome unit cell with an extra vertical strut in the middle as shown in Figure 5.1. The geometric parameters that define the Kagome structure are the height of the core (h), the inclination of the slant strut with the base plate (θ) and the diameter (d_s) of the strut. For SRK, the diameter of the vertical strut (d_v) should also be defined. The inclination angle is kept as of tetrahedral structures ($\theta = \tan^{-1} \sqrt{2}$), and height of the core was fixed at 11.5 mm.

Figure 5.1: Design and geometric parameters of Kagome and SRK unit structure

First, the effect of the variation of the diameter on the compressive properties of SRK is evaluated. The diameter of slanted (d_s) and vertical strut (d_v) of SRK structures were kept equal and designed with 0.4, 0.6, 0.8, and 1.0 mm, respectively in the parametric study. The performance of core structures depends on the core design and its relative density. For the comparative study of the compression properties of SRK structure, 3D Kagome unit structure was designed with the same relative density of SRK core of 1 mm strut diameter. Three samples were studied for each test case. The SRK and Kagome lattice structures were printed with the unit normal of face sheet perpendicular to the build direction as shown in Figure 5.2. With this orientation, no external support was required to fabricate the whole structure. The loose powder in the build process was self-sufficient to support the unit cells.

Figure 5.2: The build orientation of unit SRK core structure with face sheets.

5.2.2 Material

Titanium alloy, Ti-6Al-4V, has excellent corrosion resistance, high specific strength and stiffness which made it a viable material for aerospace applications and also for AM technologies. A grade 5 Ti-6Al-4V powder with a particle diameter of the range 25-63 μm supplied by SLM® was used for the fabrication of the structures. Figure 5.3 shows the SEM micrograph of as supplied powder.

It shows near spherical particles with many satellite particles. The diameter of the random particles ($n=30$) from the image were measured using the open source image processing software ImageJ®. The mean and standard deviation of the diameter are 33.79 μm and 13.07 respectively. The diameter of the particles follows normal distribution which is confirmed using Anderson-Darling test in MATLAB®.

Figure 5.3: SEM micrograph of Ti-6Al-4V powder

5.2.3 AM Process

Selective laser melting is a powder bed fusion additive manufacturing technique in which the thin layer powder is melted by the laser beam on a specific area to produce the desired cross-section. The molten powder particles coalesce with each other and solidify quickly. With the completion of a layer, the build platform lowers down which is followed by the swiping of powder by the wiper. The laser beam is directed to the area to melt the powder to get the desired cross-section selectively. This continues until a complete part is fabricated.

The fabrication of the structures was carried out on SLM 250 HL machine (SLM Solutions Group AG). This machine is equipped with a Gaussian beam

fibre laser with 400 W maximum power. The build volume of the system is 250 mm x 250 mm x 350 mm. All printing occurred in the argon environment with less than 0.05% oxygen to prevent the oxidation during the process.

There are many process parameters in SLM that can affect the physical and mechanical properties of the printed parts. The key parameters are the power of laser beam, scan speed, exposure strategy, hatch type, hatch spacing, layer thickness, etc. The energy density of selective laser melting process is influenced by the laser power (P), hatch spacing (H_s), scan speed (S) and layer thickness (L_T) as given by

$$E_d = \frac{P}{SH_sL_T} \quad (5.1)$$

The combination of laser power and scan speed is vital for process control in SLM. Each metal has specific thermal properties which dictate the amount of specific power to melt the powder for optimum material density. High laser power is generally required to get high solidified material density, but the maximum power is restricted by the metal conduction and heat transfer behaviour. The high scan speed may lead to the porosity of the part due to the low melting of the powder. So, the combination of parameters which lead to the high-density parts is required.

The process parameters used for fabrication of the structures are taken from [6] which produced the parts with low porosity and high strength and are listed in Table 5.1.

Table 5.1: SLM build parameters for the fabrication [6]

SLM Parameters	Values
Laser Power	175 W
Layer thickness	30 μm
Scan speed	710 mm/s
Hatch spacing	120 μm
Hatch type	Chess board
Energy Density	68.5 J/mm ³

5.2.4 Mechanical Testing

Universal tensile testing was carried out on dog bone tensile samples using Instron machine of 50kN load capacity under displacement control of 3.2 mm/min (according to ASTM E8/E8M) to get the material properties of the printed samples. The strain was obtained with the help of the contact extensometer.

The compression testing of the SRK structures was carried out on the same test machine at a displacement loading rate of 0.5 mm/min. The displacement readings were extracted using an external linear variable displacement transducer (LVDT) (Solartron Metrology) measuring the distance between faceplates. The total displacement given by the LVDT is the sum of the actual sample displacement and displacement of the machine [117, 118]. The machine compliance test was conducted to get the displacement of the machine as shown in Figure 5.4 which was subtracted from the LVDT reading to get the actual displacement of the samples. The engineering stress and strain were obtained by dividing the force and displacement with the cell's effective area and height respectively. The effective area (A_{eff}) is the area occupied by a stand-alone unit cell and is given in term of truss length l as $(\sqrt{3}/2)l^2$.

Figure 5.4: Machine compliance of 50 kN load cell.

5.2.5 Finite element modelling

The finite element modeling of compressive simulations on SRK structures was carried using commercial software ABAQUS/STANDARD®. SRK core structures of different diameters were modelled in Solidworks® and were imported to ABAQUS software. For the direct comparison of the analytical prediction of effective modulus and strength, two discrete rigid sheet structures are modelled along with the SRK core. These rigid plates do not undergo any deformation during the analysis but can have the rigid body motions. The rigid plates are attached to the core with the tie constraints. A reference point on each rigid plate was defined, and the boundary conditions were applied to the reference points as depicted in Figure 5.5. A displacement boundary condition was applied to the reference point of the upper rigid sheet to move in a vertical direction. This reference point was used to record the displacement of the upper sheet. The reference point on the bottom sheet was fixed in all direction. This reference point was used to record the reaction force on the structure. The truss or struts elements were discretized with ten node quadratic tetrahedral (C3D10)

elements, whereas face sheets were discretized with rigid linear quadrilateral (R3D4) elements.

Figure 5.5: SRK unit structure model for the simulation with the boundary conditions on the reference point.

The elastic-plastic constitutive model with isotropic hardening was incorporated with the material properties obtained from the tensile test of dog-bone samples, beyond the elastic limit. The elastic properties of Ti-6Al-4V are defined by Young's modulus (E) of 111.6 GPa and Poisson's ratio (ν) of 0.32. The plastic properties were extracted from the true stress-strain curve presented in Figure 5.6. The 0.2% offset yield stress was used as the yield strength. The plastic strain was calculated by subtracting the elastic strain from the total strain.

Figure 5.6: True stress-strain curve of SLM printed Ti-6Al-4V dog-bone sample for the input data in numerical simulation.

5.3 Analytical model of the effective mechanical properties

The compressive properties of SRK, as well as Kagome core structure, are predicted using force equilibrium and elastic strain energy conservation of the core. For the calculation of the effective moduli, it is assumed that the aspect ratio of the struts is adequately small such that the bending stiffness of the struts is negligible when compared to their stretching stiffness. Hence, the frictionless pin-jointed condition is assumed at the nodes for simplifying the analysis. This assumption is a verified assumption for estimating the compressive properties of lattice structures [20, 27].

When normal load P is applied to the face sheet of SRK, the axial load distribution along each of the struts can be obtained using equilibrium stiffness matrix method [119]. All slanted struts are at a same angle with the vertical, the force distribution among the slanted struts is equal. Figure 5.7 illustrates a unit SRK structure under compression, and the force distributions for the individual struts using the horizontal and vertical force equilibrium conditions are

$F_1 = F_2 = F_3 = 0.2532 * P$,	and, $F_v = 0.3798 * P$	(5.2)
----------------------------------	-------------------------	-------

where P is externally applied compressive load, and F_1, F_2, F_3 and F_v are the forces in the axial strut direction.

Figure 5.7: Configuration of unit SRK core structure under compressive load. Strain energy method was used for the prediction of the effective moduli. We considered that the bending has an insignificant effect on the stiffness of the stretch dominated structure; the total strain energy considered is of only the axial loading. Thus, this solution can only predict the initial modulus of the structure. The strain energy under axial loading can be obtained by

$$U = \frac{F^2 l}{2AE} \quad (5.3)$$

where F is an axial force along the strut, l is the length of the strut, A is an area of cross-section and E is Young's modulus of the material.

For the simplification, we use strut reinforced tetrahedral (SRT) structure for the determination of vertical displacement and double it to get the total displacement of SRK. The strain energy of slanted struts and vertical strut in SRT structure is given by

$$U_i = \frac{F_i^2 c}{2AE} \text{ and } U_v = \frac{F_v^2 h_1}{2AE}$$

where $i = 1, 2$, and 3 and c is half of the strut length ($l = 2c$) and h_1 is half the total height of SRK ($h = 2h_1$) core structure respectively.

The total strain energy of unit SRT structure is the sum of strain energy of all the struts of SRK and is given by

$$U_T = \frac{3F_1^2 * c}{2A_1 E} + \frac{F_v^2 * h_1}{2A_v E} \quad (5.4)$$

Replacing ' F ' in terms of P in Eq. (5.4) and using Castigliano's theorem, we can obtain the vertical displacement of SRT structure due to applied compressive load P , as

$$\delta_{SRT}^P = \frac{Pc}{E} \left(\frac{0.192}{A_1} + \frac{0.118}{A_v} \right) \quad (5.5)$$

The total vertical displacement of SRK due to load P is twice the displacement of SRT.

$$\delta_{SRK}^P = \frac{2Pc}{E} \left(\frac{0.192}{A_1} + \frac{0.118}{A_v} \right) \quad (5.6)$$

And the strain is obtained by dividing the vertical displacement of SRK with the core height. Replacing the core height in terms of length, we obtain

$$\varepsilon_{SRK} = \frac{\delta_{SRK}^P}{2h_1} = \frac{\sqrt{3}P}{\sqrt{2}E} \left(\frac{0.192}{A_1} + \frac{0.118}{A_v} \right) \quad (5.7)$$

The compressive stress of SRK is obtained as

$$\sigma_{cell} = \frac{P}{A_{eff}} \quad (5.8)$$

Replacing compressive stress σ_{cell} and A_{eff} in Eq. (5.8), we obtain

$$\varepsilon_{SRK} = \frac{3\sqrt{2}\sigma_{cell}c^2}{E} \left(\frac{0.192}{A_1} + \frac{0.118}{A_v} \right) \quad (5.9)$$

Rearranging the equation, the effective modulus of SRK E_{eff} is obtained as

$$E_{eff} = \frac{\sigma_{cell}}{\varepsilon_{SRK}} = \frac{E}{3\sqrt{2}c^2 B}, \quad \text{where } B = \left(\frac{0.192}{A_1} + \frac{0.118}{A_v} \right) \quad (5.10)$$

$$\text{If } A_1 = A_v = \frac{\pi d^2}{4},$$

$$E_{eff,SRK} = 0.19\pi E \left(\frac{d}{c} \right)^2 \quad (5.11)$$

The effective modulus of SRK structure can be expressed in terms of relative density as

$$E_{eff}^{SRK} = 0.563 E \bar{\rho} \quad (5.12)$$

where the relative density ($\bar{\rho}$) of SRK (with same strut diameter of slant and vertical strut) can be obtained as

$$\bar{\rho} = \frac{3\sqrt{3} + \sqrt{2}}{8\sqrt{6}} \pi \left(\frac{d}{c} \right)^2 \quad (5.13)$$

To estimate the compressive strength of the SRK core structure, it is assumed that the force is transmitted to the struts only in the axial direction acting like axial-bars (no bending moment is transmitted). We also assume that there are no local imperfections on the struts. Also, the failure of open core lattice structure (unit cell) can occur by either elastic buckling or plastic buckling after yielding. For a single strut, the critical load causing the elastic buckling and yielding are given by

$$F_{cr,elasticbuckling} = \frac{\pi^3 k^2 E d^4}{64 c^2} \quad (5.14)$$

$$F_{cr,yielding} = \frac{\pi d^2}{4} \sigma_o \quad (5.15)$$

where k is a factor depending on the boundary condition of struts: $k = 1$ for pin jointed ends, and $k = 2$ for fixed joints and σ_o is the yield strength of the strut material.

SRK structure has slanted as well as vertical struts which have two different lengths. As the areas of both the struts are the same, the vertical strut shares higher load as well as bear higher stress for the same displacement. The prediction of the failure can be based on both slanted and vertical strut. We assume that the slanted struts bear lower load than the vertical strut, the whole structure will fail ultimately after the failure of slanted struts. So, the prediction of the compression strength is based on the failure of the slanted struts.

For elastic buckling,

$$0.2532P = \frac{\pi^3 k^2 E d^4}{64 c^2}$$

$$\sigma_{cr,elasticbuckling} = \frac{3.95 \pi^3 k^2 E}{128 \sqrt{3}} \left(\frac{d}{c} \right)^4 \quad (5.16)$$

Similarly, for plastic buckling after the yield,

$$0.2532P = \frac{\pi d^2}{4} \sigma_o$$

$$\sigma_{cr,yielding} = \frac{3.95 \pi}{8 \sqrt{3}} \left(\frac{d}{c} \right)^2 \sigma_o \quad (5.17)$$

The compressive strength of SRK structures can be expressed in terms of relative density ($\bar{\rho}$) as

$$\sigma_{cr,yielding}^{SRK} = 0.845 \sigma_o \bar{\rho} \quad (5.18)$$

The compressive properties of Kagome structures are given by [19]

$$E_{eff}^{Kagome} = E \sin^4(\theta) \bar{\rho} = \frac{4}{9} E \bar{\rho} \quad (5.19)$$

$$\sigma_{cr,yielding}^{Kagome} = \sigma_o \sin^2(\theta) \bar{\rho} = \frac{2}{3} \sigma_o \bar{\rho} \quad (5.20)$$

From the above strength and stiffness relations in Eqs. (5.11) to (5.20) equations for predicting the effective modulus and strength, it is noticed that these compressive properties depend on the aspect ratio (d/c) or relative density ($\bar{\rho}$) and solid bulk material properties, Young's modulus (E) and yield strength (σ_o).

5.4 Results and discussion

First, the variation of the diameter of the fabricated struts in the Kagome structure with the designed values is discussed. It is followed by the compressive response of SRK unit structure as a function of relative density. The analytical solution and numerical simulation results of effective moduli and peak strength are compared with the experimental measurements. The performance of SRK unit cell and Kagome unit cell are compared and discussed. Finally, the effect of heat treatment on the microstructure of Ti-6AL-4V is discussed and its influence on the compressive performance of SRK and Kagome unit structures is elaborated.

5.4.1 Dimensional variation of printed samples

Before the compression testing of the SRK unit cell structures, the diameter of the struts was measured through the optical microscope as shown in Figure 5.8. The struts are focused on the edge of the strut so that the diameter of the struts can be extracted. The diameters at ten random positions in vertical struts were averaged. The slanted struts form some angles and it cannot be focused on a

plane to get the accurate measurement of the diameter. Thus, it was assumed that the diameter of the slanted struts would be the same as the vertical struts due to the difficulty in getting the accurate measure of slanted struts.

Figure 5.8: Diameter measurement of struts through an optical microscope.

Table 5.2 shows the variation of the diameter of printed samples with the designed ones. The measured diameters of the printed are larger as much as 37% for small diameter struts to 9.1% for the larger diameter (1.0 mm). This increase in diameter is mainly due to the attachment of the partially melted powder particles on the surface of the struts. As the struts are built without any external support, the heat is dissipated only through powder resulting in the partial melting of powder attached to the surface of fully melted ones. Similar increase in the thickness or diameter of the struts in SLM printed parts have been reported in many studies [120-122].

Table 5.2: Designed and measured diameter of the struts of SRK structures

Designed Diameter (mm)	Measured diameter (mm)	Difference (%)
0.4	0.527 ± 0.021	31.75
0.6	0.702 ± 0.007	17.0
0.8	0.892 ± 0.007	11.5
1.0	1.091 ± 0.009	9.1

5.4.2 Compression response of SRK unit structures

Figure 5.9(a) shows the compressive stress-strain behaviours of the unit SRK structure with different diameters of the struts. It is evident that with the increase in diameter (hence relative density), the peak strength as well as the effective modulus of the structure increases. All specimens demonstrated similar compressive behaviour except the one with the lowest relative density or the strut diameter of 0.53 mm. All other specimens exhibited distinct attainment of peak strength after initial yield point whereas the SRK with 0.53 mm diameter did not show any yield point i. e. the initial response is linear elastic to peak stress followed by softening response as shown clearly in Figure 5.9(b).

Figure 5.9: (a) Stress-strain response of SRK unit structure with a variation in diameter (mm) and (b) stress-strain response of SRK unit structure of 0.53 mm diameter showing the elastic buckling response.

Figure 5.10(b) shows the micrographs at different stages of compression response on the stress-strain curve of 0.89 mm diameter struts Kagome structure shown in Figure 5.10(a). Inset graph in Figure 5.10(a) is the magnified portion of the initial stages of the compression response of the SRK unit cell.

After the initial linear elastic region, the vertical strut attained the yielding first, after which the slope of stress-strain response changed. At the peak stress, all other struts also yielded. There was no bending of the struts till the peak stress was reached as shown in image 2 of Figure 5.10(b). As soon as the peak strength was reached, the struts started to bend, and the stress decreased simultaneously which can be seen in image 3. With further loading, the struts continued to bend followed by the appearance of cracks on the tensile side of the struts (image 4). Final failure occurred with the opening of initial cracks and creation of further cracks in the struts (image 5).

(a)

1 2 3 4 5

(b)

Figure 5.10: (a) Stress-strain response of SRK unit cell of 0.89 mm diameter and (b) pictures of 0.89 mm diameter SRK at different compressive stages.

Table 5.3 lists the analytically predicted, numerical simulated and the experimentally measured values of the effective modulus of unit SRK structure with different aspect ratio. It is observed that the simulation and the analytically predicted results match with each other within 2%. This suggests that the analytical solution correctly predicts the ideal SRK effective modulus. However, the experimental results differ by 20-32% from the analytical predicted results. The analytically predicted results and the simulation results are obtained for SRK core only whereas core along with two attached face sheets are compressed in experiments. The strain data are obtained from the LVDT which measures the movement of compression plates. We assume that the vertical loading applied on the face sheet would be directly transferred to the core and the displacement of the compression plate is the same as the displacement of the core. In fact, there is still elastic deformation of the face sheet but is small compared to the deformation of the core. If we consider both face sheets along with core during the numerical simulation, the effective moduli obtained from numerical simulation results also reduces as listed in Table 5.4. It is seen that the difference of measured and numerical analysis of SRK unit structures with face sheets is reduced to 12-24%. Other contributions to the discrepancies in the results can be the measurement of the diameter of the struts. The semi-molten powder attached to the struts increases the cross-sectional dimension of struts rather than giving the actual full solidified struts. This discrepancy caused by the powder attached on the surface has led to over-predict the stiffness.

Table 5.3: Measured, analytically predicted and numerical analysis of effective moduli of SRK unit structure

Strut diameter (mm)	Aspect ratio, (d/c)	Measured E_{eff} (MPa)	Predicted E_{eff} Eq. (5.11) (MPa)	Numerical simulated E_{eff} (MPa)
0.527	0.0748	249.55 ± 29.83	367.70	362.29
0.70	0.0994	477.16 ± 2.71	652.44	641.59
0.89	0.1264	827.54 ± 20.07	1048.70	1035.30
1.09	0.1548	1165.23 ± 60.03	1572.98	1551.60

Table 5.4: Comparison of measured and numerical analysis of effective moduli of SRK with face sheets

Strut diameter (mm)	Aspect ratio, (d/c)	Measured E_{eff} (MPa)	Numerically simulated with face sheets, E_{eff} (MPa)
0.527	0.0748	249.55 ± 29.83	326.89
0.70	0.0994	477.16 ± 2.71	586.60
0.89	0.1264	827.54 ± 20.07	944.30
1.09	0.1548	1165.23 ± 60.03	1397.20

Figure 5.11 shows the stress-strain curve obtained from the experimental measurement and finite element modelling results with truss structure of 0.7 mm and 1.09 mm diameter. It can be observed that the slope of the linear region of simulated results is steeper than the experimental results indicating the low experimental effective modulus. Both the experimental and simulation results show similar trends with an initial linear elastic region followed by the yielding to reach the peak stress. The softening after the peak stress by the experimental results matches well with the numerical predictions until the cracks start to form.

Figure 5.11: Comparison of simulated and experimental stress-strain response of SRK unit structure

Figure 5.12 shows the experimental and numerical simulation images corresponding to different strain values of SRK unit structure with 1.09 mm strut diameter. At 2% macroscopic strain, the vertical strut has already yielded whereas the remaining slanted struts are within linear elastic range. This is supported by the numerical simulation image in which the vertical strut has already reached the yield strength of material whereas other struts are still within the yield. At 4.8% strain, all struts have yielded and reached the peak strength of 21.24 MPa. After reaching the peak strength, the structure starts to bend thereby leading in geometrical softening and load carrying capacity. The images at 10% strain show the similar deformation in both experiments and numerical simulation. At this strain, the cracks started to appear on the tensile side of struts and grew with further compression which can be seen in the image at a strain of 0.12.

Strain (ϵ)	Experimental images	Numerical Simulation
0		<div data-bbox="828 380 991 752"> <p>S, Mises (Avg: 75%)</p> <ul style="list-style-type: none"> +0.000e+00 +0.000e+00 +0.000e+00 +0.000e+00 +0.000e+00 +0.000e+00 +0.000e+00 +0.000e+00 +0.000e+00 +0.000e+00 +0.000e+00 </div>
0.02		<div data-bbox="828 853 991 1227"> <p>S, Mises (Avg: 75%)</p> <ul style="list-style-type: none"> +1.490e+03 +1.300e+03 +1.192e+03 +1.083e+03 +9.750e+02 +8.667e+02 +7.584e+02 +6.501e+02 +5.417e+02 +4.334e+02 +3.251e+02 +2.168e+02 +1.085e+02 +1.357e-01 </div>
0.048		<div data-bbox="828 1323 991 1697"> <p>S, Mises (Avg: 75%)</p> <ul style="list-style-type: none"> +1.709e+03 +1.300e+03 +1.192e+03 +1.083e+03 +9.750e+02 +8.667e+02 +7.584e+02 +6.501e+02 +5.418e+02 +4.334e+02 +3.251e+02 +2.168e+02 +1.085e+02 +1.614e-01 </div>

0.1

0.12

Figure 5.12: The experimental and simulation images at different compression strain of SRK of 1.09 mm diameter.

SEM micrographs shown in Figure 5.13 illustrate the fracture surface of the failed slant strut. Few un-melted powder particles and some voids can be seen on the fracture surface. The tensile region of the failure surface shows dimples representing the ductile failure. The compression stress region shows the smooth fracture surface with many ridges.

Figure 5.13: Failed surface of slant strut in SRK structure under compression

Table 5.5 lists the compressive peak strength results of various aspect ratios obtained from analytical, numerical and experimental solution. The compressive strength of the specimen with high aspect ratio ($d/c = 0.126$ and $d/c = 0.155$) is well predicted (within 12% accuracy) by the Eq. (5.17). The 0.2% offset yield strength is considered the critical strength to predict the peak strength of the structure [31]. The strength of specimens with a low aspect ratio ($d/c = 0.075$) which shows linear elastic behaviour until it reaches peak strength is well predicted by Eq. (5.16). The experimental measurements are within the analytical result obtained with $k = 1$ and $k = 2$. The specimen with diameter 0.7 peak strength is in the transition zone, with nonlinearity observed prior reaching peak strength. Thus, both equations, Eq. (5.16) and Eq. (5.17), give a close approximation of the experimental results.

Table 5.5: Measured, analytically predicted and numerical analysis of peak strength of SRK unit structure

Strut Diameter (mm)	Aspect ratio, d/c	Predicted σ_{peak} (MPa) with $\sigma_o = \sigma_{0.2}$			Measured σ_{peak} (MPa)	Numerical simulation σ_{peak} (MPa)
		By Eq. (5.16)		By Eq. (5.17)		
		k=1	k=2			
0.527	0.0748	1.906	7.623	4.88	2.622 ± 0.18	-
0.7	0.0994	6.000	24.001	8.659	6.645 ± 0.12	7.16
0.89	0.1264	15.502	62.006	13.918	12.68 ± 0.42	12.26
1.09	0.1548	34.875	139.502	20.876	21.24 ± 0.49	19.95

Gibson and Asbhy equations can be used to predict the mechanical properties of the cellular structures.

$$\frac{E_{cell}}{E} = C_1 \left(\frac{\rho}{\rho_o} \right)^m \quad (5.21)$$

$$\frac{\sigma_{cell}}{\sigma_y} = C_2 \left(\frac{\rho}{\rho_o} \right)^n \quad (5.22)$$

Taking the logarithm on both the sides,

$$\log \left(\frac{E_{cell}}{E} \right) = m \log \left(\frac{\rho}{\rho_o} \right) + \log C_1 \quad (5.23)$$

$$\log \left(\frac{\sigma_{cell}}{\sigma_y} \right) = n \log \left(\frac{\rho}{\rho_o} \right) + \log C_2 \quad (5.24)$$

In our study, we examined the compression properties of SRK structures with four relative densities. The samples with higher relative densities failed after reaching the yield whereas the ones with low relative densities failed in the linear region itself. For modulus prediction, four readings are available to get the coefficient. But for strength prediction, as the above equation is for the failure after yielding, only two readings can be used which does not give any fair representation, thus are not included. The values of the constant obtained

are $C_I = 0.5572$ and $m = 1.07$, which are similar to the theoretical values given in Eq (5.12).

The performance of the SRK unit structure is compared to the performance of unit Kagome structure. Kagome structure itself is regarded as high performing lattice structure in terms of compressive strength and effective modulus. For direct comparison, Kagome unit structure was designed and fabricated with the same relative density of SRK structure (with 1.0 mm strut). With the fabrication, as reported in Table 5.2, the diameter of SRK has changed to 1.09 mm. We assume that the Kagome structure after the fabrication still has the same relative density as that of SRK. Figure 5.14 shows the compressive stress-strain curve of SRK and Kagome unit structures. Table 5.6 shows the average peak strength and effective modulus of both the structures. It is observed that for this specific case SRK has better effective modulus (12.87%) and peak strength (13.42%) than Kagome unit structure. The presence of the vertical strut (which shares higher amount of load) in SRK unit structure has led to the increase in the strength and the effective modulus. Similar better performances have been obtained due to the presence of vertical struts in BCCZ [63, 65] and strut reinforced tetrahedral structures [56]. After the initial linear elastic region, the Kagome structures reach the peak with smooth hardening curve. However, as explained earlier in section, SRK unit has a change in the slope after the yielding of the vertical strut. After the peak strength, SRK unit structure loses its load carrying capacity at a faster rate than Kagome indicated by the steeper slope of the post-peak stress response.

Figure 5.14: Stress-strain response of SRK and Kagome unit structure with a same relative density

Table 5.6: Average effective moduli and peak strength of SRK and Kagome unit structure

Structures	Effective modulus, E_{eff} (MPa)	Peak Strength, σ_{peak} (MPa)
SRK	1165.23 ± 60.03	21.24 ± 0.49
Kagome	1015.23 ± 48.28	18.39 ± 0.09

5.5 Heat Treatment of SRK and Kagome structure

The mechanical properties of the Ti-6Al-4V parts fabricated by SLM are different from those of conventional methods. The objective of heat treatments after SLM process is to achieve the mechanical properties that can be achieved by traditional methods by modifying the microstructure and reducing the residual thermal stresses. Due to the rapid cooling process in SLM, the microstructure of the parts printed by SLM is different than fabricated by the conventional casting method which results in dissimilar mechanical properties.

The parts produced by the SLM have high strength and modulus but have low ductility compared to the parts produced by conventional metal casting. Hence, the major goal of the heat treatment is to increase the ductility of the parts and reduce the internal stress.

Ti-6Al-4V is obtained by alloying pure Ti with 6 wt% Al (α stabiliser) and 4 wt% V (β stabiliser). Figure 5.15 shows the equilibrium phase of Ti-6Al-4V at a different temperature. At low temperature, the microstructure consists of $\alpha + \beta$ equilibrium phase whereas, with increasing temperature, β phase % increases and it will change to complete β phase after 950 °C. The transition temperature in which complete transformation of microstructure to β phase is known as β transus temperature. The final microstructure of the heat-treated samples can be controlled with the designed heat treatment process. Mainly, the maximum temperature of the treatment, residence time, cooling rate and environment affect the final microstructure of heat treated parts as well as the mechanical properties.

Figure 5.15: Phase transformation diagram of Ti-6Al-4V [123]

In this study, the SRK and Kagome unit structures are heat treated to below β transus temperature and their compressive properties are studied. The

microstructure of as fabricated and heat treated samples are investigated, and their implications on the overall compressive properties are studied.

5.5.1 Heat treatment and material characterisation

The SRK samples were enclosed in the vacuum tube and heated at a rate of 5 °C/min. Vrancken et al. [124] studied the influence of various heat treatment processes on SLM components considering residence time, temperature and cooling rates. They concluded that heating temperature below β transus temperature followed by furnace cooling to room temperature provided the best tensile properties. Thus, 850 °C was considered for the peak temperature of the heat treatment on SRK unit structures. After reaching 850 °C, they were kept at the same temperature for 2 hrs and were furnace cooled to room temperature.

For the study of the microstructures, the samples were grinded with SiC grinding paper with a grit size of 320 and followed by fine grinding with an abrasive 9 μm diamond suspension. Colloidal Silica (OP-S) with 0.04 μm abrasive was used for final polishing of the samples. Kroll's reagent was used to reveal the microstructure of the samples. Optical microscope and Joel SEM were used for the extraction of micrographs of microstructures.

5.5.2 Microstructures of Ti-6Al-4V parts

Micro-structures of as fabricated Ti-6Al-4V samples produced by SLM show fully acicular α' martensitic structures [125, 126] as shown in Figure 5.16. The side view of the microstructure sample shows long columnar prior β grains oriented on the build direction (arrows in Figure 5.16(a) show the elongated grains direction). They grow epitaxially due partial remelting of previous layers acting as the nucleus of strongly textured grains. The size of the needle

structures is very fine (Figure 5.16 (b)) due to the high cooling rate during the SLM print process.

Figure 5.16: (a) Optical micrograph of side surface illustrating the wide columnar grains (arrows shows the grain direction) with α' martensitic structure of as fabricated samples and (b) SEM image showing the fine acicular α' structures

Figure 5.17 shows the microstructures of the heat treated samples below β transus. The fine martensitic structures have transformed into the mixture of α and β [124, 127]. The β fraction of the mixture increases with the increase in the temperature. It is reported that the equilibrium α fraction is 73% at 850 °C [128].

Figure 5.17: Microstructure of Ti-6Al-4V SLM printed samples heat-treated at 850 °C at (a) lower magnification and (b) higher magnification. (Lighter zones indicate β phase and dark zones are α phases)

After the sub- β -transus heat treatment, fine acicular α' structure decomposes into a coarser mixture of α and β .

5.5.3 Compression properties after the heat treatment

To study the effect of the heat treatment on the SRK unit structures, the specimens were heat treated to 850 °C, below β transus temperature (980 - 995 °C) [124, 129] of Ti6Al4V, and were furnace cooled. Three samples of each treated and non-treated SRK unit structures with various diameter and Kagome structures were subjected to uniaxial compression test at a strain rate of $7.25 \times 10^{-4} \text{ s}^{-1}$. Figure 5.18 shows the representative stress-strain curve of as fabricated and heat treated sample of SRK unit structure with strut diameter of 0.89 mm. The higher slope of the initial linear region and lower peak strength is observed in the heat-treated sample. The distinct difference on the curves is higher failure strain of the heat treated sample than of as-fabricated sample. The average effective modulus and peak strength of as fabricated and heat treated specimens of SRK unit structures of various diameters, and Kagome structure are shown in Figure 5.19. It is observed that the peak strength of the structures was reduced whereas the effective modulus of the structures has increased. The average effective moduli have increased by 40-48% whereas the average peak strengths have decreased by 11-15% after the heat treatment of the structures.

Figure 5.18: Representative stress-strain curves of as fabricated and heat treated sample of SRK unit structure with strut diameter of 0.89 mm with the inset graph of linear region.

Figure 5.19. Average (a) effective modulus and (b) peak strength of as fabricated and heat treated samples with various diameters

Figure 5.20 shows the average energy per unit volume (area under the stress-strain curve) and an average failure strain of raw as well as heat treated samples. After the heat treatment, the average energy absorption has increased by 19-35% whereas the failure strain has increased by 37-70%. Though the

ductility has increased by a significant amount, the similar increase in energy absorption was hindered by the reduction in the peak strength. It is also observed that the energy absorption of Kagome structures is higher than the SRK structures of the same relative density. Though SRK structures have higher peak strength and modulus, Kagome has better energy absorption capacity due to its higher failure strain. After the peak strength, SRK unit structure loses its load carrying capacity at a faster rate than Kagome indicated by the steeper slope of the post-peak stress response which contributes to have less energy absorption as seen in Figure 5.14. Two sample t-tests were carried out to analyze the results of heat treatment on compressive strength, compressive modulus, energy absorption and failure strain in Kagome structure and SRK structure with 1.09 mm diameter (same relative density with unit Kagome) with the significance level of 0.05. All the t-tests rejected the null hypothesis for equal means for strength, modulus, energy absorption, and failure strain. This supported that the heat treatment has significant effect on the compressive properties of SRK and Kagome unit structure. The t-tests results are presented in Appendix C.

Figure 5.20: Average (a) energy absorbed per unit volume and (b) strain at failure of as fabricated and heat treated samples of SRK unit structures with various diameters and Kagome structures

The decomposition of the fine acicular martensitic α' structure to a coarser mixture of α and β with sub- β -transus heat treatment has led to the decrease in the peak strength and increase in the ductility of the material. With the increase in the ductility, the energy absorption of the structures also increases as depicted in Figure 5.20.

The different phases of Ti6Al4V have different moduli. The α , α' and β phases have higher modulus respectively among each other [130]. After the heat treatment, α' transform to $\alpha + \beta$ phases. With a higher fraction of the α phase in the mixture at 850 °C, the stiffness of heat treated part has increased as seen in Figure 5.19(a). Sallica-Leva et al. [127] obtained a similar increase in the effective modulus of the SLM printed porous structure with sub- β -transus heat treatment.

5.6 Summary

In this chapter, a new lattice structure design is proposed, and its compressive properties are explored. The modification on the existing 3D Kagome structure with the inclusion of vertical strut has led to a new structure named strut reinforced Kagome structure. The unit SRK and Kagome structures were successfully fabricated through selective laser melting (SLM) without any additional support structure. The compression properties of SLM printed Ti-6Al-4V SRK was explored with the variation in the aspect ratio. An analytical prediction of the SRK structure is proposed and is compared with the numerical simulation and experimental measurements. Similarly, the performance of SRK is compared with Kagome structures with the same relative density. At last, the

effect of the heat treatment on the compressive performance of SRK and Kagome structures has been explored.

Based on the results, the key findings can be summarised as:

1. The force distribution on the struts of SRK structure was used to develop the analytical solution which was able to predict the effective modulus and peak strength of unit SRK structure.
2. The SRK unit structures have better performance than Kagome unit structures in terms of peak strength and modulus for same relative density. The presence of vertical strut, which supports higher load than slant struts in the direction of loading has led to better properties.
3. The sub- β -transus heat treatment has led to the increase in the effective modulus, failure strain and energy absorption and a decrease in the peak strength of SRK and Kagome truss structures.

Chapter 6 Flexural performance of Kagome lattice sandwich beam

6.1 Introduction

Sandwich structures have immense advantages in the applications that require high bending stiffness and strength with low weight. The concept of sandwich beam is that the stiff faces carry in-plane (axial) and traverse bending loads whereas the lightweight core carries the shear loads. Generally, metallic and polymeric foams are used as core structures for such light weight applications.

The close-cell foam structures are bending dominated structure whose stiffness and strength scales as $\bar{\rho}^2$ and $\bar{\rho}^{1.5}$, respectively. The cellular lattice core structure being stretch dominated structure scales as $\bar{\rho}$. The stretch dominated structures are stiffer and stronger than the bending dominated structures. Kagome, being as near ideal stretch dominated structure, has better stiffness and strength than other bending dominated structures [10].

A sandwich beam fails by a number of competing failure mechanisms. The failure mode of the sandwich structure depends on the geometric parameters of the beam and material properties of the core and face sheets. The desired properties and failure modes can be achieved by playing with the different geometric parameters.

Bending properties of the sandwich beam with metallic or polymeric foams or corrugated structures are determined through three-point or four-point bending tests. Steeves and Fleck [131] had developed analytical failure load equations

for the face sheet failure, core indentation, core shear failure for CFRP composite face sheet with polymeric foam core and developed a failure mode map. Then in a subsequent study verified the models with instrumented experiments and finite element simulations [79]. Similar work on the metal foams and Al alloy face sheets were done by Bart-Smith, Gibson, Fleck and Chen [132-134]. Deshpande and Fleck [20] investigated the collapse response of sandwich beam with the tetrahedral core through the analytical and experimental solution. The use of effective properties for tetrahedral core gave an acceptable solution in predicting the beam response. Lee and Kang [80] derived the analytical solutions for collapse strength for metal wire woven Kagome structure under bending and carried out few case studies through experiments and numerical simulations to check its accuracy [81]. The analytical solutions were effective and accurate to predict the performance under bending. The samples with the core shear failure mode and the specimen with the geometric parameter at the confluence of the three failure modes namely, face sheet buckling, plastic indentation and core shear mode B were considered for the numerical simulations. Still, there is a need of the numerical simulation study with the samples which have other failure mechanisms for Kagome lattice structure and assess the accuracy of analytical prediction.

In this chapter, various failure modes of sandwich structures under bending and their failure load is reviewed. Initially, the normal compressive and shear failure load of the Kagome unit cell are derived and in turn, these estimates are used to predict the failure loads of failure mechanisms. The failure mode map in terms of normalised thickness and core height for Kagome sandwich structure is constructed using these failure equations. A few selected Kagome sandwich

beams with different geometric parameters are modelled to predict each of the failure modes under three-point bending. The mechanical properties of SLM printed Ti-6Al-4V tensile samples [6] were used for numerical modelling. The failure mode and the peak load obtained from the numerical simulations are compared with the analytical solutions.

6.2 Analytical solution for stiffness and strength in three-point bending

To derive the failure loads due to the bending of the sandwich beam with Kagome core, we need to derive the compressive and shear properties of Kagome unit cell. To estimate the mechanical properties of Kagome structure, we assume that the trusses are connected with ball joints, and the force is transmitted along the axial direction only. Kagome struts fail either by elastic buckling or plastic buckling after the yield of the strut. The critical force causing the elastic and plastic buckling after the yield of the strut can be obtained by

$$F_{cr,elasticbuckling} = \frac{\pi^3 k^2 d^4}{64c^2} E_o \quad (6.1)$$

$$F_{cr,yielding} = \frac{\pi d^2}{4} \sigma_o \quad (6.2)$$

where E_o and σ_o are Young's modulus and yield stress of the strut material. Figure 6.1 shows the Kagome unit structure under compression as well as shear load. The force experienced by the struts due to normal and shear force can be obtained by resolving the force distribution. The inclination angle of the struts with the face sheet ($\theta = \tan^{-1}\sqrt{2}$) is considered same as with tetrahedral structures. The critical force experienced by the strut due to normal load P is

$F_{cr} = \frac{P}{\sqrt{6}}$. The normal compressive strength of a given Kagome structure can be obtained by dividing the normal force 'P' applied on the structure by the effective area of the structure which is given by $2\sqrt{3}c^2$.

Figure 6.1: (a) Kagome unit core structure and (b) the configuration of Kagome unit cell under compression and shear loads

The strength to predict elastic or plastic buckling of unit cell can be expressed as [80]

$$\sigma_{cell,elasticbuckling} = \frac{\sqrt{2}}{128} \pi^3 k^2 \left(\frac{d}{c} \right)^4 E_o \quad (6.3)$$

$$\sigma_{cell,yielding} = \frac{\sqrt{2}}{8} \pi \left(\frac{d}{c} \right)^2 \sigma_o \quad (6.4)$$

where $k = 1$ for pin joint and $k = 2$ for clamped condition. The critical ratio (d/c) can be obtained by equating Eq. (6.3) and Eq. (6.4).

The shear strength of Kagome core are given by

$$\tau_{cell,elastic} = \alpha \frac{\pi^3}{128\sqrt{3}} \left(\frac{d}{c}\right)^4 E_o \quad (6.5)$$

$$\tau_{cell,yielding} = \alpha \frac{\pi}{8\sqrt{3}} \left(\frac{d}{c}\right)^2 \sigma_o \quad (6.6)$$

where α is an index indicating the orientation of Kagome structure [80]. Kagome core in sandwich beams can be placed in two orientations. The orientation which predicts higher shear strength of the core is considered in our modelling and the value of $\alpha = 1$ is used for this orientation.

6.2.1 Stiffness of sandwich beams

Consider a simply supported sandwich structure loaded in three-point bending as shown in Figure 6.2. Let L be span length, H be the height of the core, b be the width of the beam, t_f be the thickness of the face sheet and D be the overhang length. The relative elastic deflection of the top and bottom rollers under three-point bending is given by the sum of deflection due to the flexural and shear deformation as given by [75]

$$\delta = \frac{PL^3}{48(EI)_{eq}} + \frac{PL}{4(AG)_{eq}} \quad (6.7)$$

where $(EI)_{eq}$ and $(AG)_{eq}$ are equivalent flexural and shear rigidities respectively, of the sandwich beam.

where

$$(EI)_{eq} = \frac{bt_f(H+t_f)^2 E_f}{2} + \frac{bt_f^3 E_f}{6} + \frac{bH^3 E_c}{12} \approx \frac{bt_f(H+t_f)^2 E_f}{2} \quad (6.8)$$

$$(AG)_{eq} = \frac{b(H+t_f)^2 G_c}{H} \approx b(H+t_f) G_c \quad (6.9)$$

where G_c is the equivalent shear modulus of the core as given by [80]

$$G_c = \frac{\sqrt{2}}{48} \pi \left(\frac{d}{c} \right)^2 E_c \quad (6.10)$$

Figure 6.2: Sandwich structure under three-point bending

6.2.2 Strength of sandwich beam

A sandwich beam with low relative core density has five different failure modes under bending [135]. Face sheet yielding, face sheet elastic wrinkling, local indentation, core shear in mode A and mode B are the failure modes under bending load. The different failure modes and their failure strength are described briefly here under.

6.2.2.1 Face sheet yielding

When the face sheet of the sandwich panel attains the yield strength before the yielding of the core, face yield determines the limit load. The collapse load is obtained by equating the maximum bending moment with the collapse moment of the section [75].

$$P_{FY} = \frac{4bt_f(H+t_f)}{L}\sigma_y^f + \frac{bH^2}{L}\sigma_y^c \quad (6.11)$$

where σ_y^f and σ_y^c are the yield strength of the face sheet and core materials respectively.

Generally, the contribution of the second term due to the core yield failure is negligible (as $\sigma_y^c \ll \sigma_y^f$) and hence Eq. (6.11) can be approximated for simplicity as

$$P_{FY} = \frac{4bt_f(H+t_f)}{L}\sigma_y^f \quad (6.12)$$

6.2.2.2 Face sheet wrinkling

Unlike closed-cell foam core sandwich structure, sandwich with open core structure or honeycomb structure, the core does not provide a continuous support across the face sheet surface area. The buckling of the face sheet which wavelength may scale upto the cell size of the core is known as intercellular buckling. The collapse load in this case [80] is given by

$$P_{FW} = \frac{4bt_f(H+t_f)}{L}\sigma_w^f \quad (6.13)$$

where,
$$\sigma_w^f = 0.58 \left(\frac{3\sqrt{2}\pi}{40} \right)^{\frac{2}{3}} \left(\frac{d}{c} \right)^{\frac{4}{3}} E_f$$

where E_f is the elastic modulus of facesheet material and σ_w^f is the wrinkling strength.

6.2.2.3 Indentation

The indentation collapse load is set by the compressive yield of the core structure beneath the central loading roller. This indentation model assumes that the compressive side of the sandwich beam face behaves as an elastic beam

column with the core as a rigid-ideally plastic foundation. The collapse load for indentation mode of failure is given by [131]

$$P_I = bt_f \left(\frac{\pi^2 (H + t_f)}{3L} \sigma_{cell}^2 E_f \right)^{\frac{1}{3}} \quad (6.14)$$

The material properties of both face sheet and core structures are assumed to be the same in our study. Thus, the material properties are both are represented by E_o and σ_o . Replacing the value of compressive strength σ_{cell} of unit cell for both elastic buckling and plastic buckling from Eqs. (6.1) and (6.2), the indentation load can be expressed for two failure mechanisms of the core as

Core collapse under elastic buckling:

$$P_I^E = \frac{1}{16} bt_f \left(\frac{\pi^8 \left(\frac{d}{c} \right)^8 (H + t_f)}{L} \right)^{\frac{1}{3}} E_o \quad (6.15)$$

Core collapse under plastic yielding

$$P_I^P = \left(\frac{1}{96} \pi^4 \right)^{\frac{1}{3}} bt_f \left(\frac{(H + t_f)}{L} \right)^{\frac{1}{3}} \left(\frac{d}{c} \right)^{\frac{4}{3}} (E_o \sigma_o^2)^{\frac{1}{3}} \quad (6.16)$$

6.2.2.4 Core shear

The core of the sandwich panel carries the shear force when a sandwich beam is subjected to traverse shear force. Two competing shear collapse mechanism can occur in case of three-point bending. Core shear A occurs when there is only the formation of the hinge at the middle of the sandwich panel. In the core shear B collapse mechanism, the formations of hinges occur not only at the mid-span but also at the outer supports with no deformation beyond them. The collapse load for core shear modes A and B are given by

$$P_{CSA} = \frac{2bt_f^2}{L} \sigma_y + 2bH \left(1 + \frac{2D}{L} \right) \tau_{cell} \quad (6.17)$$

$$P_{CSB} = \frac{4bt_f^2}{L} \sigma_y + 2bH \tau_{cell} \quad (6.18)$$

respectively. In the Eq. (6.17), D is the overhang length. Replacing the value of τ_{cell} from Eqs. (6.5) and (6.6), the collapse loads are given by:

$$P_{CSA}^E = \frac{2bt_f^2}{L} \sigma_o + \frac{\pi^3}{64\sqrt{3}} bH \left(1 + \frac{2D}{L} \right) \left(\frac{d}{c} \right)^4 E_o \quad (6.19)$$

$$P_{CSA}^P = \frac{2bt_f^2}{L} \sigma_o + \frac{\pi}{4\sqrt{3}} bH \left(1 + \frac{2D}{L} \right) \left(\frac{d}{c} \right)^2 \sigma_o \quad (6.20)$$

$$P_{CSB}^E = \frac{4bt_f^2}{L} \sigma_o + \frac{\pi^3}{64\sqrt{3}} bH \left(\frac{d}{c} \right)^4 E_o \quad (6.21)$$

$$P_{CSB}^P = \frac{4bt_f^2}{L} \sigma_o + \frac{\pi}{4\sqrt{3}} bH \left(\frac{d}{c} \right)^2 \sigma_o \quad (6.22)$$

The Kagome structure can fail by either elastic buckling or plastic buckling after the yield of the strut under normal stress. Under the shear load, the structure also fails either by elastic buckling or plastic buckling after the yield. Thus, under bending load, the structure can fail by local indentation, core shear mode A and mode B with elastic buckling or plastic yielding in addition to face sheet yielding and wrinkling. Therefore, there are altogether eight failure modes.

6.3 Failure mode maps for sandwich panels

The above-stated formulae for the competing failure modes of a sandwich panel under bending load (Section 6.2.2) can be used to construct the failure map mode. For this, a non-dimensional load parameter is introduced.

$$\bar{P} = \frac{P}{Lb\sigma_o} \quad (6.23)$$

All the collapse loads are re-expressed in terms of $\bar{P}$ with the use of the non-dimensional geometrical and material parameters. The face sheets and core strut are considered to be of the same material in our study. σ_o and E_o are used for yield strength and Young's modulus of the material. The non-dimensional parameters are

$$\bar{t} = \frac{t_f}{L} \quad (6.24)$$

$$\bar{h} = \frac{H}{L} \quad (6.25)$$

$$\bar{d} = \frac{d}{c} \quad (6.26)$$

$$\bar{D} = \frac{D}{L} \quad (6.27)$$

Converting all the equations in terms of $\bar{P}$, we obtain the following equations.

Facesheet yielding

$$\bar{P}_{FY} = 4\bar{t}(\bar{t} + \bar{h}) \quad (6.28)$$

Facesheet wrinkling

$$\bar{P}_{FW} = 1.115\bar{t}(\bar{t} + \bar{h})\bar{d}^{\frac{4}{3}} \frac{E_o}{\sigma_o} \quad (6.29)$$

Indentation

$$\bar{P}_I^E = \frac{1}{16}\bar{t} \left(\frac{\pi^8}{6} (\bar{t} + \bar{h})\bar{d}^8 \right)^{\frac{1}{3}} \frac{E_o}{\sigma_o} \quad (6.30)$$

$$\bar{P}_I^P = \left(\frac{1}{96} \pi^4 \right)^{\frac{1}{3}} \bar{t}(\bar{t} + \bar{h})^{\frac{1}{3}} \bar{d}^{\frac{4}{3}} \left(\frac{E_o}{\sigma_o} \right)^{\frac{1}{3}} \quad (6.31)$$

Core shear A

$$\bar{P}_{CSA}^E = 2\bar{t}^{-2} + \frac{1}{64\sqrt{3}}\pi^3\bar{h}\bar{d}^{-4}(1+2\bar{D})\frac{E_o}{\sigma_o} \quad (6.32)$$

$$\bar{P}_{CSA}^P = 2\bar{t}^{-2} + \frac{1}{4\sqrt{3}}\pi\bar{h}\bar{d}^{-2}(1+2\bar{D}) \quad (6.33)$$

Core shear B

$$\bar{P}_{CSB}^E = 4\bar{t}^{-2} + \frac{1}{64\sqrt{3}}\pi^3\bar{h}\bar{d}^{-4}\frac{E_o}{\sigma_o} \quad (6.34)$$

$$\bar{P}_{CSB}^P = 4\bar{t}^{-2} + \frac{1}{4\sqrt{3}}\pi\bar{h}\bar{d}^{-2} \quad (6.35)$$

For a given geometric parameter of the sandwich beam, the non-dimensional collapse load $\bar{P}$ is calculated for every possible failure modes. The failure mode which gives the least value of $\bar{P}$ for a given geometrical parameters is considered as the possible failure mechanism of that sandwich beam. With the change in various geometric parameters, the failure modes also change. We just plot the boundary position in which the failure mode changes from one to other with the non-dimensional axes $\bar{t}$ and $\bar{h}$ for a given aspect ratio $\bar{d}$. A Matlab® program (see Appendix D) was used to draw the failure mode map with $\bar{t}$ as x-axis and $\bar{h}$ as y-axis for a given slenderness ratio. Figure 6.3 shows a representative failure map mode for the $\bar{d} = 0.1706$ and $\bar{D} = 0.15$ which is used later in the case studies for the given aspect ratio and overhang length. From the failure mode, it can be observed that indentation failure mode is active for high core thickness with low face sheet thickness. The face sheet yielding is active for low core and thin face sheets with long span length. The sandwich beam with a thicker face sheet is expected to fail by core shear mechanism. Face sheet wrinkling mechanism was not observed in the failure mode map. Ti-

6Al-4V alloy has high strength and stiffness such that the face sheet should have very low thickness to have the failure wrinkling failure.

Figure 6.3: Representative failure map of structures with $\bar{d} = 0.1704$ and $\bar{D} = 0.15$ in terms of non-dimensional face sheet thickness and core height

6.4 Finite element modelling

Finite element analysis has been used to model the behaviour of the sandwich beams with 3D Kagome core under three-point bending load using commercially available finite element package ABAQUS®. The Kagome core structure in the beam was modelled in SOLIDWORKS® and was imported to ABAQUS CAE environment as a .SAT file and assembled with the face sheets. The compressive load was applied through a rigid roller (modelled as shell) which is placed above the upper face sheet, and two rollers below the lower face sheet were fully constrained by assigning all degrees of freedom to zero as shown in Figure 6.4. A penalty friction with 0.1 frictional coefficients was used in the surface to surface contact between rollers and face sheets [136]. The use of friction coefficient in the contact between the rollers and sandwich beams would help to achieve numerical convergence and precise value of μ has a

negligible effect on the response [79]. Tie constraint was used as the bonding between the face sheets and the core of the sandwich beams. The self-contact was set to on for the Kagome core struts. The Kagome core was discretised with quadratic tetrahedral elements (C3D10) whereas the face sheets were discretised with linear quadratic brick elements with reduced integration (C3D8R). Bilinear quadrilateral 3D rigid elements (R3D4) were used for meshing the rigid rollers (modelled as shell). The areas of face sheets near to the contact with rollers were partitioned, and the number of elements in those areas was increased. The elastic-plastic constitutive behaviour of SLM printed Ti64 was incorporated in the model. The elastic modulus of $E_o = 110 \text{ GPa}$ and Poisson's ratio $\nu = 0.32$ was used for defining the elastic properties. The plastic properties were taken from true tensile stress-strain data subtracting the elastic strain from the work of Ullah et al. [6].

Figure 6.4: Sandwich structure with Kagome core showing the boundary conditions applied in numerical simulation

6.5 Case studies

We studied the bending performance of sandwich beams with four different geometric parameters listed in Table 6.1, to identify various failure mechanisms. The samples were chosen such that the expected failure mechanisms differ from each other. Sample S1 has relatively thick face sheet

and is expected to fail by core shear mode A. Sample S2 has thicker core height with thin face sheet thickness which is expected to fail by core indentation. S3 has all geometric parameters same as S1 except it has higher overhang length. Thus, it is expected to fail by core shear mode B. S4 also has similar geometric parameters as S1 except it has low expect ratio. Thus, S4 is expected to fail by core shear with elastic buckling.

Table 6.1: Different geometric parameters of the sandwich beam models used for the three point bending analysis

Case study	t_f (mm)	H (mm)	L (mm)	(d/c)	D (mm)	Expected failure mode
S1	2	11.5	112.7	0.1704	17.0	Core shear with plastic yielding
S2	0.6	24.2	98.6	0.1704	17.0	Indentation with plastic buckling
S3	1.5	11.5	112.7	0.1704	31.7	Core shear with plastic yielding
S4	2	11.5	112.7	0.1136	17.0	Core shear with elastic buckling

Figure 6.5 shows the load-displacement curve obtained for model S1. The numerical simulation resulted in the maximum load of 10.14 kN. Figure 6.6 shows the images at different stages of the simulation in load-displacement curve. The image 3 shows the deformed shape of the model at the peak load. In the simulation, core shear failure is considered when traverse shear reaches the shear strength of the material. The shear strength of SLM printed Ti-6Al-4V is estimated to be 625 MPa [7]. Contours of traverse shear stress on the struts at the displacement with peak load showed higher shear stress than the shear strength of the material revealing the core shear failure mechanism. The

deformed shape indicates that the model failed by the typical core shear in mode A with shear deformation in the area of overhang length too. The maximum load predicted by the Eq. (6.20) $P_{max} = 10.07$ kN which is almost equal to the solution given by FEA. The failure mechanism can also be estimated using the failure mode map as shown in Figure 6.7 which also predicts the core shear mode 'A' failure mechanism.

Figure 6.5: Load-displacement curve obtained for numerical simulation of sample S1

Figure 6.6: Deformed shapes of the model S1 at different positions marked on the load-displacement curve shown in Figure 6.5

Figure 6.7: Failure map for $\bar{d} = 0.1704$ and $\bar{D} = 0.15$ predicting failure mechanism for samples S1 and S2.

To model the specimens with a thicker core height of the structure, two layer Kagome with 2D Kagome as an interface between two layers was designed. This design would help to have a greater core height without the change in aspect ratio of the struts. Figure 6.8 shows the load-displacement curve of sample S2 under three-point bending. The maximum load obtained through numerical simulation ($P_{max} = 5.16$ kN) is within 10% predicted by Eq. (6.16) .

The corresponding image of the peak load in the curve (image 2 of Figure 6.9) shows the initial global deflection along with the localized indentation below the roller. The sandwich beam undergoes the global deflection in the beginning followed by the local indentation. Figure 6.8(b) shows contours of plastic strain in the sandwich beam beneath the roller (marked in the image 2 of Figure 6.9) at position 2 in Figure 6.8(a). The plastic strain is only observed in the core beneath the roller confirming the plastic deformation of the core due to the local indentation. Beyond the peak load, there is a drop in the load, in response the reduction in the stiffness of the beam due to overall reduction in net-section thickness. The failure map also predicts that with the given geometrical parameters, S2 should fail by indentation mechanism as shown in Figure 6.7.

Figure 6.8: (a) Load-displacement curve obtained from FEA for model S2 and (b) the plastic strain contour at the core beneath the roller at position 2 in load-displacement curve

Similarly, numerical modelling was carried out for S3 which has longer overhang length than S1. With the longer overhang, the failure map mode also changes with the increase in the region of core shear failure mode B which can be observed in Figure 6.10 compared to Figure 6.7. Figure 6.11 shows the load-displacement curve obtained for S3 under three-point bending load. The

corresponding image of the simulation at the peak load is shown in Figure 6.12.

The deformation behaviour observed was similar to S1 which has failure mechanism of shear failure mode A.

Figure 6.9: Deformed shapes of the model S2 at different positions marked on load-displacement curve shown in Figure 6.8

The contour of shear stress in the image (Figure 6.12) reveals that the struts have experienced shear stress more than the shear strength of the material. Thus, design S3 failed by core shear. The overhang of the core does not exhibit any shear deformation beyond the bottom rollers depicting shear core failure mode B. The peak load obtained from numerical solution $P_{max} = 8.12$ kN is well predicted by Eq. (6.22) which gives $P_{max} = 7.94$ kN. The failure mechanism can also be obtained through the failure map mode which indicates

the core shear mode B as the failure mechanism of the S2 as seen in Figure 6.10.

Figure 6.10: Failure map of sandwich beams with $\bar{d} = 0.1704$ and $\bar{D} = 0.28$ predicting the failure mechanism for S3

Figure 6.11: Load-displacement curve for model S3 obtained from FEA

Figure 6.12: Deformed shapes of the model S3 at peak load marked as (1) in a load-displacement curve in Figure 6.11

Similarly, FEA was carried out for three-point bending of sample S4. The failure mechanism for the given geometric parameters obtained from the failure map predicts the core shear failure mode A with elastic buckling as shown in Figure 6.13. At first, the general static formulation was used for the numerical simulation which predicted failure mode as core shear as seen in Figure 6.14. As d/c is less than the critical value (0.123), the elastic buckling is the major failure mechanism. For the elastic buckling, the peak load obtained through the simulation with general static formulation did not match with the load predicted by Eq. (6.15). Instead, linear perturbation buckling formulation was used for the simulation, and the load was determined through the first eigenvalue and was 4.68 kN which is comparable to the load predicted by Eq. (6.15) ($P_{max} = 4.86$ kN).

Figure 6.13: Dimensionless failure map as a function of $\bar{t}$ and $\bar{h}$ for an aspect ratio $\bar{d} = 0.1136$ and overhang ratio $\bar{D} = 0.15$.

Figure 6.14: The failure initiation of sample S4 under three-point bending illustrating shear failure mechanism.

6.6 Summary

The flexural performance of the Kagome lattice structure was investigated through numerical simulations. The analytical solution for different failure modes under bending for Kagome structure was derived. The failure mode map was constructed in terms of non-dimensional face sheets thickness and core height with the help of the failure load of different failure mechanisms. The failure mechanism of Kagome sandwich structure with different geometrical parameters under bending was numerically investigated and compared with the failure map and analytical solutions. Two different approaches were used to predict peak load through numerical simulations. For the struts with bigger

aspect ratio than a critical value, general static formulation was utilized. With small aspect ratio, linear perturbation formulation was used. The maximum load and the failure mechanism predicted by the finite element modelling were in good agreement with the analytical solutions and the failure map for various samples with different geometries.

Chapter 7 Conclusions and Future Work

This chapter summarises the major conclusions from the predominantly experimental work carried in the thesis. Also, scopes for future work are elaborated.

7.1 Conclusions

In this thesis, first, the compressive performance of ABS Kagome structure fabricated by fused deposition modelling was explored. The effect of the build orientation, strut aspect ratio, and the surface roughness were investigated. The deformation and the compressive performance of graded density Kagome structure was explored and compared with the uniform density structure. Kagome structure was modified with an inclusion of vertical strut and manufactured through selective laser melting process with Ti-6Al-4V. The deformation and compressive properties of the strut reinforced Kagome structure was investigated with the change in the aspect ratio analytically, numerical simulation and experimental measurements. The performance of SRK is compared with Kagome structure with the same relative density. Heat treatment was carried out to influence the properties of the Kagome and SRK structures. Lastly, the flexural performance of the sandwich beams with Kagome structure as a core was investigated by numerical simulations. The failure map modes were created with the help of analytical solutions and the failure modes are verified by numerical solutions.

The key contributions of this research are presented in the following sections.

7.1.1 Printing and characterisation of Kagome lattice structures by fused deposition modelling.

The compressive performance of Kagome structure fabricated by fused deposition modelling is investigated in the view of using the Kagome core structure in UAV wings to increase the specific strength and stiffness. Unit cell approach was adopted to simplify the study of the effect of different geometric and build variation on the compressive properties. The change in the part build orientation affected not only the strength and moduli but also the failure behaviour of the Kagome unit cells. The variation in the aspect ratio of the struts of Kagome structure also changed the failure mode of the structures from elastic buckling to plastic buckling after the yield.

The surface roughness was minimized through the post process treatment with the acetone with proper treatment time. The staircases which are an integral part of FDM fabricated parts are eliminated with well improved surface finish after the treatment. Considerable increase in the failure strain and energy absorption (under compression loading) was resulted after the acetone treatment of Kagome structures.

The compressive performance of unit Kagome structure fabricated by FDM not only represented the performance of multi-unit Kagome structures. The initial failure of the unit as well as multi-unit structures was also similar and failed around the joints of the struts with the face sheets. For multi-layer Kagome

structure, the overall energy absorption of the Kagome structures was improved by the graded density design over the uniform density structure.

7.1.2 Performance of strut reinforced Kagome truss core structure under compression

The performance of cellular solids depends on the design of the structure. To enhance the compressive performance, the existing design of the Kagome truss core was modified with the inclusion of a vertical strut. The unit SRK structures with different struts diameters were successfully fabricated by selective laser melting without external support structures using Ti-6Al-4V. The compression properties were analytically predicted and compared with the numerical simulations and experimental measurements. The analytical solution was able to predict the compressive strength (within 12% accuracy) and effective moduli (within 12-24%) with the experimental measurements. SRK unit structures performed better than existing Kagome structures of the same relative density in terms of the compressive strength and moduli. Heat treatment on the SRK and Kagome structure at 850 °C followed by the furnace cooling improved the effective moduli, failure strain and energy absorption of (Ti-6Al-4V) SRK and Kagome structure with a small decrease in the peak strength. The decomposition of fine acicular martensitic α' structure to a coarser mixture of α and β phases after the heat treatment were observed which led to the change in the properties of the Kagome structures.

7.1.3 Flexural performance of Kagome lattice sandwich beams

Bending performance of sandwich beams with Kagome structure as a core was investigated by numerical simulations. The analytical solutions for three point

bending of sandwich structures with different failure modes were derived, and failure map mode was constructed in non-dimensional facesheet thickness and core height. Two different approaches were utilized in predicting the peak load through numerical solutions. For the structures with a bigger diameter than the critical aspect ratio, general static formulation was used. For the small diameter, linear perturbation formulation was utilized. The failure mode of the samples used in the numerical simulation matched with the one predicted by failure mode map and the peak loads were found to be within 10% of the analytical solution. Thus, the analytical solution and failure map successfully predicted the peak load and failure modes respectively.

7.2 Original contributions in this research

- A comprehensive study on the compressive behaviour of Kagome unit structure fabricated by fused deposition modelling was carried through experiments. Chemical treatment by 90% vol. of acetone was used to reduce the surface roughness and enhance the compression properties of the FDM printed lattice Kagome structure. Also, the graded density design was employed to improve the energy absorption of the multilayer Kagome structure.
- A new design of lattice core structure, strut reinforced Kagome, is proposed and fabricated by selective laser melting. The analytical solution for peak strength and effective modulus is developed for SRK and is verified by numerical simulation and experimental measurements. The SRK unit cell outperformed the Kagome unit cell with same relative density in terms of peak strength and effective moduli.

7.3 Scope for future work

The current dissertation work scope can be enhanced by studying the following:

- In chapter three, the numerical simulation for compression testing on Kagome structure was carried out using the tensile property of the material printed on the same orientation of Kagome strut. To capture the entire structural behaviour more precisely, FEA simulation can be carried out by implementing constitutive equation. For this, tensile properties and the shear properties must be investigated in three orientations.
- In chapter three, Kagome structures were designed to have a uniform diameter of struts. Under compression, the lattice core has varying stress states along the truss length. Diameter optimization along the strut can be carried out to achieve uniform stress, thereby improving the structural performance.
- In chapter four, the uniaxial compressive performance of graded density structure was compared with the performance of uniform density structure with a solid ABS sheet as the interface between two layers. This structures can be further optimised by replacing the solid sheets with 2D Kagome structure as interfaces between the layers.
- Chapter five was more focused on the performance of the SRK structures in relation to the aspect ratio of the struts. The comparison of the performance of SRK and Kagome structure was carried out for a single relative density. To further compare the performance, the study on the samples with other relative density is recommended. Additionally, in SRK unit structure, vertical strut and slanted struts were

designed with the same diameter. As the load carried out by vertical and slanted struts are different, the performance of the structure can be improved by finding the optimum diameters of slanted and vertical struts.

- The flexural behaviour of sandwich beams with Kagome structures was studied through analytical modelling and numerical simulations. Experimental verification of the results is recommended. Further, the optimal or minimum mass design for the strength and stiffness constraints should be solved for.

List of Publication

Journals

1. Gautam, R., Idapalapati, S., & Feih, S. (2018). "Printing and characterisation of Kagome lattice structures by fused deposition modelling". *Materials & Design*, 137, 266-275.
<https://doi.org/10.1016/j.matdes.2017.10.022>
2. Gautam, R. and Idapalapati, S. (2019). "Compressive performance of strut-reinforced Kagome truss core structure fabricated by selective laser melting". *Materials & Design*, 164, 107541.
<https://doi.org/10.1016/j.matdes.2018.107541>
3. Gautam, R., Idapalapati, S. (2019). "Compressive properties of additively manufactured functionally graded Kagome lattice structure". *Metals*, (Accepted)

Conference Papers

1. Rinoj, G., Idapalapati, S., & Feih, S. (2016). "Failure Mode Analysis of Kagome Lattice Structures". *Proceedings of the 2nd International Conference on Progress in Additive Manufacturing (Pro-AM 2016)*, 91-96.
2. Gautam, R., & Idapalapati, S. (2017). "Processing and characterisation of Kagome unit cell through fused deposition modelling". *SAMPE Technical Conference Proceedings*.

3. Gautam, R. and Idapalapati, S. (2018). "Compressive behaviour of strut reinforced Kagome structure fabricated by fused deposition modelling".
Proceedings of the 3rd International Conference on Progress in Additive Manufacturing (Pro-AM 2018), 220-225.

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Appendix A Tensile Sample for Plastic material.

The orthographic views of the tensile sample for plastic material with the dimension are given below:

Figure A1: Orthographic views of the standard tensile specimen with dimensions. All dimensions are in mm.

Appendix B Statistical analysis of effect of chemical treatment on surface roughness and mechanical properties

This appendix contains two sample t-tests for the mean of surface roughness before and after the chemical treatment.

t-Test: Two-Sample Assuming Unequal Variances
Surface Roughness

	<i>0 min</i>	<i>3 min</i>
Mean	16.49183	10.04633
Variance	35.2608	12.12319
Observations	6	6
Hypothesized Mean Difference	0	
df	8	
t Stat	2.293593	
P(T<=t) one-tail	0.025489	
t Critical one-tail	1.396815	
P(T<=t) two-tail	0.050978	
t Critical two-tail	1.859548	

t-Test: Two-Sample Assuming Unequal Variances
Surface Roughness

	<i>0 min</i>	<i>5 min</i>
Mean	15.18433	6.894833
Variance	7.819099	5.875413
Observations	6	6
Hypothesized Mean Difference	0	
df	10	
t Stat	5.486946	
P(T<=t) one-tail	0.000133	
t Critical one-tail	1.812461	
P(T<=t) two-tail	0.000267	
t Critical two-tail	2.228139	

t-Test: Two-Sample Assuming Unequal Variances

Surface Roughness

	<i>0 min</i>	<i>7 min</i>
Mean	18.3175	7.255333
Variance	24.07059	5.958352
Observations	6	6
Hypothesized Mean Difference	0	
Degree of freedom	7	
t Stat	4.944767	
P(T<=t) one-tail	0.000833	
t Critical one-tail	1.894579	
P(T<=t) two-tail	0.001666	
t Critical two-tail	2.364624	

For the effect of the chemical treatment on the effective modulus, peak strength, energy absorption per volume and failure strain, single factor ANOVA was carried out.

Peak Strength				
<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
0 min	5	4055.625	811.1251	4475.133
3 mins	5	4108.113	821.6225	4253.782
5 mins	5	4140.492	828.0983	3080.235
7 mins	5	4017.609	803.5218	826.2861

Peak Strength (ANOVA)						
<i>Sources</i>	<i>Sum of Squares</i>	<i>Degree of freedom</i>	<i>Mean square</i>	<i>F</i>	<i>P-value</i>	<i>F critical</i>
Between Groups	1787.092	3	595.69	0.189	0.902	3.24
Within Groups	50541.75	16	3158.86			
Total	52328.84	19				

Effective modulus				
<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
0 min	5	141.675	28.335	9.355914
3 mins	5	156.495	31.299	2.474911
5 mins	5	161.563	32.3126	7.273087
7 mins	5	152.072	30.4144	3.247627

Effective modulus (ANOVA)						
<i>Sources</i>	<i>Sum of Squares</i>	<i>Degree of freedom</i>	<i>Mean Squares</i>	<i>F</i>	<i>P-value</i>	<i>F critical</i>
Between Groups	42.93	3	14.31	2.56	0.091	2.46
Within Groups	89.41	16	5.59			
Total	132.34	19				

Volumetric Energy				
<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
0 min	5	0.521326	0.104265	5.46E-05
3 mins	5	0.654004	0.130801	0.00019
5 mins	5	0.671804	0.134361	0.000131
7 mins	5	0.646353	0.129271	0.000309

Volumetric Energy (ANOVA)						
<i>Sources</i>	<i>Sum of Squares</i>	<i>Degree of freedom</i>	<i>Mean Squares</i>	<i>F</i>	<i>P-value</i>	<i>F critical</i>
Between Groups	0.002845	3	0.000948	5.54	0.008	3.239
Within Groups	0.002736	16	0.000171	6	36	
Total	0.005581	19				

Failure Strain				
<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
0 min	5	0.66081	0.132162	0.000128
3 mins	5	0.838121	0.167624	0.000243
5 mins	5	0.872708	0.174542	0.000125
7 mins	5	0.880637	0.176127	0.000631

Failure Strain (ANOVA)						
<i>Sources</i>	<i>Sum of Squares</i>	<i>Degree of freedom</i>	<i>Mean Square</i>	<i>F</i>	<i>P-value</i>	<i>F critical</i>
Between Groups	0.006387	3	0.002129	7.557	0.002279	3.239
Within Groups	0.004507	16	0.000282			
Total	0.010894	19				

Appendix C Statistical analysis for performance of Ti-6Al-4V unit Kagome and SRK cells

This appendix contains the two sample t-test of means of peak strength and effective moduli of SRK and Kagome structure.

Effective modulus		
	<i>Kagome</i>	<i>SRK</i>
Mean	1015.23	1165.233
Variance	3496.06	5406.093
Observations	3	3
Hypothesized Mean Difference	0	
Degree of Freedom	4	
t Stat	-2.75368	
P(T<=t) one-tail	0.02559	
t Critical one-tail	1.533206	
P(T<=t) two-tail	0.05118	
t Critical two-tail	2.131847	

Peak Strength		
	<i>Kagome</i>	<i>SRK</i>
Mean	18.39333	21.236
Variance	0.014533	0.373333
Observations	3	3
Hypothesized Mean Difference	0	
Degree of Freedom	2	
t Stat	-7.90579	
P(T<=t) one-tail	0.007813	
t Critical one-tail	2.919986	
P(T<=t) two-tail	0.015626	
t Critical two-tail	4.302653	

Effect of heat treatment on the properties of Kagome and SRK structure are analyzed with two sample t-test for means of peak strength, effective modulus, energy absorption, and failure strain.

Kagome unit cell

Effective modulus

	<i>As fabricated</i>	<i>Heat treated</i>
Mean	1015.23	1432.967
Variance	3496.06	3943.863
Observations	3	3
Hypothesized Mean Difference	0	
Degree of Freedom	4	
t Stat	-8.3884	
P(T<=t) one-tail	0.000553	
t Critical one-tail	2.131847	
P(T<=t) two-tail	0.001105	
t Critical two-tail	2.776445	

Peak Strength

	<i>As fabricated</i>	<i>Heat treated</i>
Mean	18.39333	15.81
Variance	0.014533	0.0259
Observations	3	3
Hypothesized Mean Difference	0	
Degree of Freedom	4	
t Stat	22.25212	
P(T<=t) one-tail	1.21E-05	
t Critical one-tail	2.131847	
P(T<=t) two-tail	2.41E-05	
t Critical two-tail	2.776445	

Energy Absorption

	<i>As fabricated</i>	<i>Heat treated</i>
Mean	2.118457	2.586163
Variance	0.039226	0.015489
Observations	3	3
Hypothesized Mean Difference	0	
Degree of Freedom	3	
t Stat	-3.46325	
P(T<=t) one-tail	0.020272	
t Critical one-tail	2.353363	
P(T<=t) two-tail	0.040544	
t Critical two-tail	3.182446	

Failure Strain

	<i>As fabricated</i>	<i>Heat treated</i>
Mean	0.259693	0.4254
Variance	0.001232	0.002515
Observations	3	3
Hypothesized Mean Difference	0	
Degree of Freedom	4	
t Stat	-4.68899	
P(T<=t) one-tail	0.004692	
t Critical one-tail	2.131847	
P(T<=t) two-tail	0.009385	
t Critical two-tail	2.776445	

SRK unit cell (1.09 mm strut diameter)

Effective Modulus

	<i>As fabricated</i>	<i>Heat treated</i>
Mean	1165.233	1641.767
Variance	5406.093	8064.213
Observations	3	3
Hypothesized Mean Difference	0	
Degree of Freedom	4	
t Stat	-7.11156	
P(T<=t) one-tail	0.001033	
t Critical one-tail	2.131847	
P(T<=t) two-tail	0.002066	
t Critical two-tail	2.776445	

Peak Strength

	<i>As fabricated</i>	<i>Heat treated</i>
Mean	21.236	18.17
Variance	0.373333	0.5701
Observations	3	3
Hypothesized Mean Difference	0	
df	4	
t Stat	5.467355	
P(T<=t) one-tail	0.002722	
t Critical one-tail	2.131847	
P(T<=t) two-tail	0.005444	
t Critical two-tail	2.776445	

Energy absorption

	<i>As fabricated</i>	<i>Heat treated</i>
Mean	1.743967	2.220977
Variance	0.022524	0.039657
Observations	3	3
Hypothesized Mean Difference	0	
df	4	
t Stat	-3.31329	
P(T<=t) one-tail	0.014782	
t Critical one-tail	2.131847	
P(T<=t) two-tail	0.029563	
t Critical two-tail	2.776445	

Failure strain

	<i>As fabricated</i>	<i>Heat treated</i>
Mean	0.150943	0.241747
Variance	7.44E-06	0.000304
Observations	3	3
Hypothesized Mean Difference	0	
df	2	
t Stat	-8.91225	
P(T<=t) one-tail	0.006179	
t Critical one-tail	2.919986	
P(T<=t) two-tail	0.012357	
t Critical two-tail	4.302653	

Appendix D Code for failure mode map

```
close all;

clear all;

% Values declaration

E=110e3; %in MPa

sy=1028; %in MPa

x3=0.1136; % d/c

x5=0.15; % D/l

alpha=1

failureMode = {'FE', 'FP', 'AE', 'AP', 'BE', 'BP', 'IE', 'IP'};

x1vals = 0.001:0.0001:0.04;

x2vals = 0.02:0.001:0.4;

[x1, x2] = meshgrid(x1vals, x2vals);

fID = failureID1([x1(:)'; x2(:)'], x3, x5, alpha, E, sy);

fID = reshape(fID, size(x1));

figure(1),

h = pcolor(x1, x2, fID);

h.EdgeColor = 'none';

hold on;

% figure(1), imshow(fID, []), hold on;

% h = gca;

% set(h,'YDir','normal')

% axis on;

% h.XTickLabel = x1vals(h.XTick);

% h.YTickLabel = x2vals(h.YTick);
```

```

fIDx = fID;
fIDx(2:end, :) = fID(1:end-1, :);
fIDy = fID;
fIDy(:, 1:end-1) = fID(:, 2:end);

edgex = abs(fID - fIDx)>0;
edgey = abs(fID - fIDy)>0;
edge = edgex | edgey;

[yID, xID] = find(edge == 1);
figure(1), plot(x1vals(xID), x2vals(yID), 'k.');
```

function fm = failureID1(x, x3, x5, alpha, E, sy)

```

f = [ 1.115*(E/sy)*x(1, :).*(x(1, :)+x(2, :))*(x3^(4/3));
      4*x(1, :).*(x(1, :)+x(2, :));
      (2*x(1, :).*(x(1, :)+x(2, :)).*(x3^4).*(1+2*x5)) + ((2*alpha*(pi^3)./(128*sqrt(3)))*(E/sy)*x(2, :).*(x3^4).*(1+2*x5));
      (2*x(1, :).*(x(1, :)+x(2, :)).*(x3^2).*(1+2*x5)) + ((2*alpha*(pi)./(8*sqrt(3)))*(E/sy)*x(2, :).*(x3^2).*(1+2*x5));
      (4*x(1, :).*(x(1, :)+x(2, :)).*(x3^4)) + ((2*alpha*(pi^3)./(128*sqrt(3)))*(E/sy)*x(2, :).*(x3^4));
      (4*x(1, :).*(x(1, :)+x(2, :)).*(x3^2)) + ((2*alpha*(pi)./(8*sqrt(3)))*(E/sy)*x(2, :).*(x3^2));
      (E/(16*sy))*x(1, :).*(((pi^8)/6)*(x(1, :)+x(2, :)).*(x3^8))^(1/3);
      x(1, :).*(((2*(pi^4))/(3*64))*(E/sy)*(x(1, :)+x(2, :)).*(x3^4))^(1/3) ];

%fm = f;

[~, fm] = min(f);
```