INFLUENCE OF FDM BUILD PARAMETERS ON TENSILE AND COMPRESSION BEHAVIORS OF 3D PRINTED POLYMER LATTICE STRUCTURES

A thesis submitted in partial fulfillment of the requirements for the degree of
Master of Science in Mechanical Engineering

By
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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY **Sai Avinash Yadlapati** ENTITLED **Influence of FDM Build Parameters on Tensile and Compression Behaviors of Three-Dimensional Printed Polymer Lattice Structures** BE ACCEPTED IN PARTIAL FULLFILLMENT OF THE REQUIREMENT FOR DEGREE OF Master of Science in Mechanical Engineering.

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ABSTRACT

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This research focuses on the compression and tensile behavior of three-dimensional printed polymer lattice structures with different printing parameters such as build orientation, infill density, and layer thickness. The body-centered cubic (BCC) lattice unit cell, which has been extensively investigated for energy absorption applications, is considered here to create compression and tensile specimens. Special test fixture was designed and developed to perform the tensile tests. The specimens were printed using Acrylonitrile Butadiene Styrene (ABS) polymer material on a Stratasys uPrint 3D printer. The printing parameters considered in this case are: (a) Three different build orientations (0, 45 and 90 degrees); (b) Two different infill densities (Sparse High and Solid); and (c)Two different layer thicknesses (0.010 and 0.013 inch). Once fabricated, the specimens were imaged using an optical microscope (OM) to capture their surface characteristics. Strut dimensions of all specimens are measured to understand their build accuracy. In addition, fabrication time for each configuration were recorded for comparison. The specimens were then tested under quasi-static compression and tension to determine the stiffness, failure loads, and energy absorption behaviors. Specific properties were also calculated by dividing the test properties by the specimen mass. All the test data obtained from OM and mechanical tests were then compared and interpreted with respect to all the three build parameters.

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LIST OF NOMENCLATURE

F	Applied force, N
h	Height, m
K	Stiffness, N/mm
M	Mass, Kg
SEA	Specific Energy Absorption, Joule

LIST OF ACRONYMS

3D	3-Dimensional
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
ASTM	American Society for Testing and Materials
BC	Boundary Condition
BCC	Body Centered Cubic unit cell
CAD	Computer Aided Design
STL	Stereo Lithography
UTM	Universal Testing Machine
SLM	Selective Laser Melting
FDM	Fused Deposition Modeling

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Dedicated to my mother and father

CHAPTER 1: INTRODUCTION

1.1 Additive Manufacturing (AM)

Additive Manufacturing (AM) which is known as 3D printing has recently grown in last few years and is being widely used in many applications. Additive manufacturing or 3D printing is a process of making a three-dimensional solid object of virtually any shape from a digital model. 3D printing can be achieved using Additive manufacturing processes, where successive layers of material are laid down in different shapes. Additive Manufacturing has lot of technologies behind it out of which Fused Deposition Modelling (FDM) is mostly used in wide range of applications. This technology needs a CAD file in Stereo Lithography (STL) format to build the complex models. From this STL file, FDM creates a toolpath and prints the model needed layer by layer as shown in Figure 1. The print head extrudes the filament through the heated nozzle. The material solidifies when it is printed on the tray. The structure is built by the specific toolpath which is obtained by software i.e. set up by the 3D Printer. In this research Acrylonitrile Butadiene Styrene (ABS) has been used to create lattice structure. There are several parameters that affect part quality such as mechanical robustness, surface conditions and accuracy. The major parameters that can be controlled on a Stratasys FDM printer are build orientation, layer thickness or resolution and infill density.

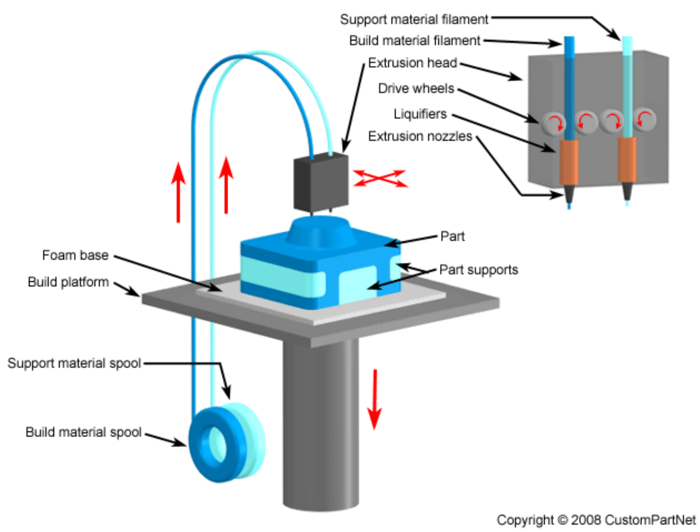


Figure 1.1: FDM

1.2 Build Orientation

Designers often ignore the importance that part orientation during build, plays role in final quality of a 3D printed part. Here we discuss about, how part orientation effects the part quality, manufacturing time, strength and surface finish of 3D printed parts. It also describes the importance of build orientation by technology.

Part accuracy

Think about a tube with a hole (10 mm outer diameter, 6 mm inner diameter, 30 mm length) that is printed with FDM with its center axis up and down. The 3D printer would construct this part as a series of concentric circles layered on top of one another. This would produce a final tube with a relatively smooth outer surface.

If the same tube is readjusted with its center axis left and right, the part will be built as a series of rectangles (with a little different width) layered on top of each other. Also, the surface of the tube that touches the build platform will be flat, because the material would as the first layers were printed.

By orientating the part in different directions, there is a big difference in the print quality, as can be seen in the figure below. Two identical tubes printed at the same layer height in different orientations (left: up and down, right: left and right)

Build time

Orientation can also really affect print time.

Using as an example the tube of the previous section, the left right orientation will take significantly less time to print than the up down, as the total number of layers is reduced: at a 100 μm layer height, the horizontal cylinder will be printed with 100 total layers and the vertical with 300 layers. This can add up to significant time differences for large parts.

Part strength

Some 3D printing especially FDM build parts that have inherently anisotropic properties, meaning they are much stronger in the XY direction than the Z direction. For functional parts, it is important to think about the application and the direction of the loads. For example, FDM parts are much more likely to delaminate and break when placed in tension in the Z direction compared to the XY directions (up to 4-5 times difference tensile strength).

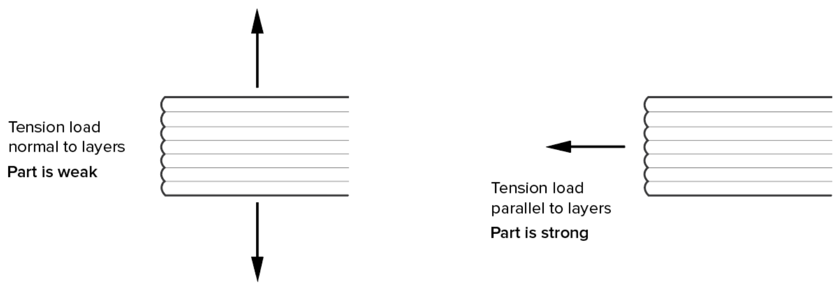


Figure 1.2: Example of Part Accuracy

3D printing technologies generally are much stronger in one direction compared to another

Support Structures

Support material adds extra time and cost to a 3D print.

Often a lot of designing time is spent to the best part orientation to reduce the chance of print failure and the amount of required support

Surface finish

Generally, the top or upward facing surfaces of a 3D printed part will have the best surface finish, but this differs from process to process:

For FDM, the top surface is smoothed by the extrusion tip, the surface in contact with the print bed will usually be glossy and the surfaces above support structures will have support marks.

For SLA, the lower surfaces will have support marks and require post-processing, while the top surfaces will be smooth and free of support marks.

Parts printed with a powder bed 3D printing processes, like SLS and Binder Jetting, will have a grainier finish on their lower surfaces.

Parts printed with Material Jetting will have a matte finish at surface printed on supports and a glossy finish otherwise (a homogeneous matte finish is also available).

1.3 Infill Densities and Layer Resolution

The most important setting here is the fill density, which defines the amount of plastic inside the print. A higher fill density means that there's more plastic on the inside of your print, leading to a stronger object.

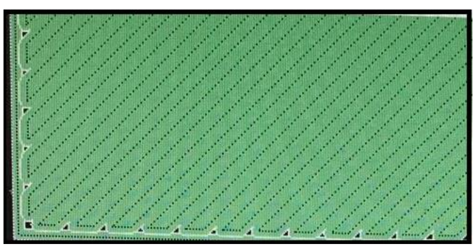
Layer resolution means height of each layer of material extruded to produce a part. Available resolutions are based on printer type.

- 0.010 inch (.254 mm)
- 0.013 inch (.330 mm)

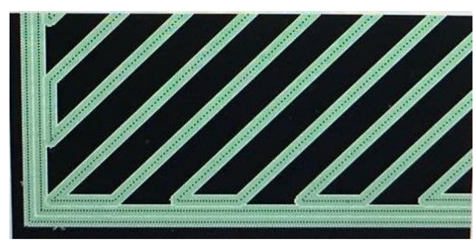
Resolution will affect build time and surface finish - A shorter height creates a smoother finish, but will take longer to build.

Solid - used when a stronger, more durable part is desirable. Build times will be longer and more material will be used.

A



B



C

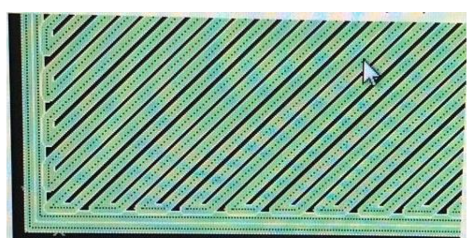


Figure 1.3: Infill densities A: Solid; B: Sparse high; C: Sparse low

Sparse - high density (Elite, 1200es, uPrint 3D Printers only) - this is the default model interior style and it is highly recommended. Build times will be shorter, less material will be used, and the possibility of part curl for geometries with large mass will be greatly reduced.

Sparse - low density - the interior will be "honeycombed/hatched". This style allows for the shortest build times and lowest material use

Support fill - support material is used to brace the model material during the build process. It is removed when the part is complete. Support fill options will affect the support strength, the amount of support material used, and the build time of the print.

Our software which processes part files has two different ways to create the internal structure of parts. These two modes are called Solid and Sparse. A solid model is exactly what the printer will create when the part is processed in solid mode. The entire part is solid ABS plastic. The solid mode is more expensive due to two reasons. The first one being that it takes longer for a part to print. The second reason is because the part contains more ABS material. If structural integrity and part functionality are important then this mode is the best choice.

The Sparse mode does not create a model that is solid. From the outside of the part the model will look as if it was entirely solid. While the inside has a honeycomb type pattern. This pattern also can be compared to a spider's web. When printing a sparse part all outside surfaces are the same as solid model would appear. The outside walls usually .06" and the internal sparse pattern helps keep the part structurally strong, similar to how trusses support a bridge. The sparse mode can cut build times and model material over 30% in most cases which greatly reduces the part cost. If part appearance and cost is important, this is the mode to use.

1.4 Lattice Structures

With advancements in additive manufacturing technology, lattice structures are becoming more widely used for applications in aerospace and transport. Characterized by low density and high strength, lattice structures offer a higher efficiency than conventional materials. Unit cells make up lattice structures and are classified by their shape and orientation of structural members. Types of shape classifications include cubic, tetragonal, monoclinic, orthorhombic, rhombohedral, hexagonal, and triclinic. Within these shape classifications are the following sub-classifications based on member orientation: simple, body centered, face centered, and end centered. Often, body centered cubic (BCC) unit cells are used when designing lattice structures due to their ability to be scaled and built easily. This is due to their numerous lines of symmetry and simplicity. A BCC unit cell is characterized by four struts that all meet at a central node in the middle of the cubic region they encompass. BCC unit cells balance strength and density which make them fairly universal for all applications. The lattice structure used in this research uses a BCC unit cell. An example of the BCC unit cell used for this research can be seen in Figure 1.4.

Most other research of lattice structures is focused on compressive behavior or response to impact rather than tensile behavior, although several groups have performed research on tensile behavior of lattice structures. Some examples of lattice structures are shown in Figure 1.5.

Figure: 1.4 BCC Unit Cell

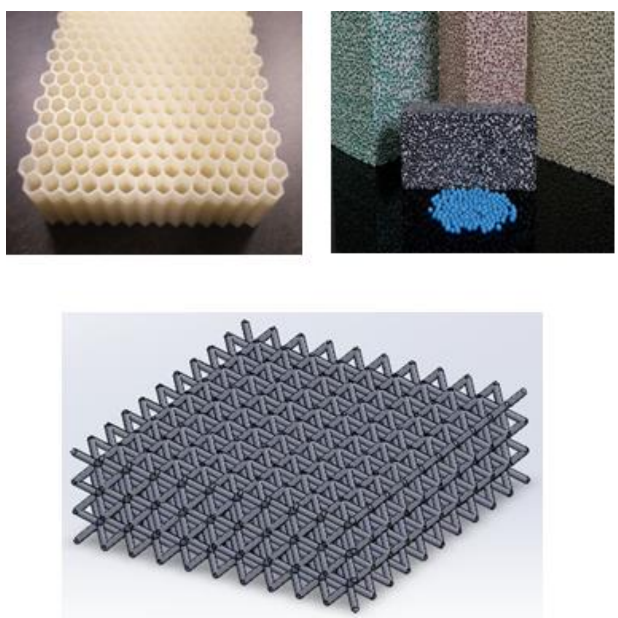


Figure 1.5 lattice structures

1.5 Energy Absorption:

Energy absorption is main attribute in many applications. Reducing the weight of structure is very much needed. SEA became a main objective in mechanical field to carryout experiments and study modelling analysis.

It is the absorbed energy per unit mass [1]. The total energy absorbed W represents the area under the curve of the Load Displacement curve.

$$W = \int F \, dx$$

$$SEA = W/m$$

F is the load, x is the deflection & m is mass [2], [3], [4]

SEA is obtained by integrating the area under load displacement graph up to second failure of lattice core structures while doing quasi static loading. The reason for having till the end of second stage of failure is material starts to be solid instead of having unit cells and load keeps increasing. This topic is discussed back in results of SEA Calculations.

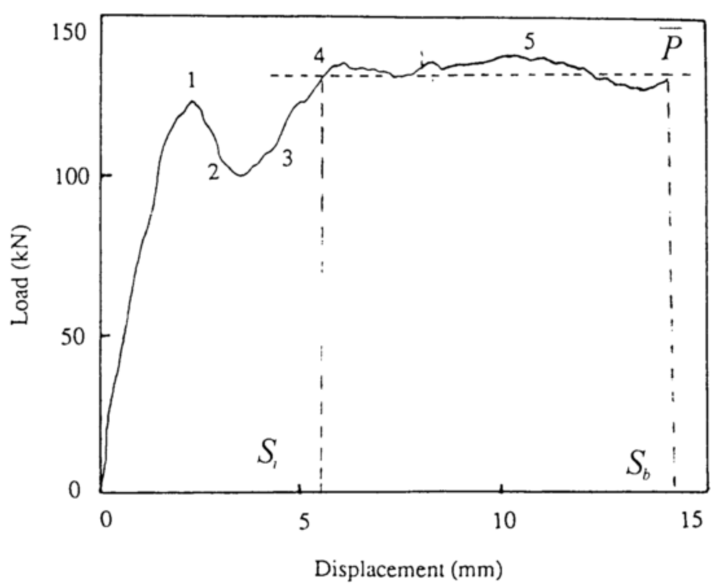


Figure: 1.6 Load Displacement Curve [1]

1.6 Aim and Scope

The aim of this study was to find out the effect of FDM build parameters such as Build Orientation, infill density, and layer resolution on tension and compression behaviors of BCC lattice structures. BCC unit cell is used to study the behavior of the structure under quasi static compression loading and tensile loading. BCC cells are printed with same dimensions in different conditions: (a) Three different build orientations (0, 45 and 90 degrees); (b) Two different infill densities (Sparse High and Solid); and (c) Two different layer thicknesses (0.010 and 0.013 inch). These print orientations were discussed back in chapter 3. The compression test is done on INSTRON 5500R and whereas the tensile test is done on INSTRON 5800R under an extension control of 0.02 mm /min. Load displacement curve is taken to find out stiffness, failure loads, SEA and compare the results. Also stress strain curve is taken to find out yield strength and ultimate strength.

Chapter 2: Literature Review

2.1 Introduction

Here the previous research done is discussed to know what has been written in past related to these topics. Topics discussed are Compression Test, Tensile Test and Energy Absorption & Lattice Structures.

2.2 Compression Test & Tensile Test

Many researches that are done previously used Compression test to compare mechanical properties among different geometries and materials. Some of them did compression tests to evaluate energy absorption capability and stiffness. **Frida Johansson [5]** investigated and characterized 30 different trabecular structures of Ti-6Al-4V, fabricated by Selective Laser Melting. That includes investigation the effect on the morphology and porosity fraction caused by the manufacturing and the effect on mechanical and physical properties due to the different characterizations of the structures. The result stated that the porosity fraction was lower than the designed porosity, and that is was strongly influenced by size of the voids and struts. The strut thickness was higher than the design values, especially on the lateral surface, while the voids size were approximately as designed. Result from the compression test showed a trend of decreasing stiffness and strength with increasing porosity fraction. Also structures with same porosity fraction could have a wide range in mechanical properties which indicates high dependence on the morphological geometry i.e. pore size and shape, strut size and pore distribution. Comparisons between tensile and compression behavior stated that the structures had a lower strength but a significant higher stiffness in tensile load. All structures from the wear test showed a good resistance while the results from the friction test needs further investigation to be fully understood**. Olaf Andersen [6]** did experimental and numerical evaluation of the mechanical behavior of strongly anisotropic light-weight metallic fiber structures under static and dynamic compressive loading. She did study mechanical behavior of rigid sintered fiber structures under quasi-static and dynamic loading. Special attention is paid to the strongly anisotropic properties observed for different directions of loading in relation to the main fiber orientation. Basically, the structures show an orthotropic behavior; however, a finite thickness of the fiber slabs results in moderate deviations from a purely orthotropic behavior. Depending on the direction of loading, the fiber structures show a distinctively different deformation behavior both experimentally and numerically. Based on these results, the prevalent modes of deformation are discussed and a first comparison with an established polymer foam and an assessment of the applicability of aluminum fiber structures in crash protection devices is attempted. **Ahmed A d Sarhan [7]** investigated the effects of geometrical structure and layer orientation on strength of Rapid Prototyped specimens figure 2.1. Tensile strength and compressive strength resistance are identified for different specimen structures and different layer orientations of ABS rapid prototype solid models. The specimens are fabricated by a FDM rapid prototyping machine in different layer orientations with variations in internal geometrical structure. The 0° orientation where layers were deposited along the length of the specimens displayed superior strength and impact resistance over all the other orientations. The anisotropic properties were probably caused by weak interlayer bonding and interlayer porosity. Dimension SST 1200es" was the FDM machine model used in the experiment. This machine is easy to operate, and it is suitable for RP manufacturing purposes. It is suitable to fabricate small and medium size of ABS product. Pro ENGINEER was used to prepare the specimens drawing and Catalyst Ex Version 4.2 was the software used to arrange and test the specimens before fabrication. Crest ultrasonic generator was used to remove the supporting material attached to the specimens as a post-processing process. The universal testing machine model INSTRON 4469 was used for both tensile and compression testing of the specimen. One of the conclusions is suitable structure design and layer orientation are important factors needed to be considered in FDM technology which is related to one of the build parameters in my research. **R Umer [8]** did an analysis on compression behavior of different composite lattice designs. He designed 4 composite lattice structures named BCC, BCCz, FCC, F2BCC using lost mold procedure where he inserted carbon fiber tows into holes of the core. He then performed compression tests on all the 4 lattice structures which gave a result that F2BCC have the better compression strength out of all the lattice structures and when normalized by relative density the BCCz structure out performed other structures as shown in Figure: 2.4 Different Composite lattice Structures [8]

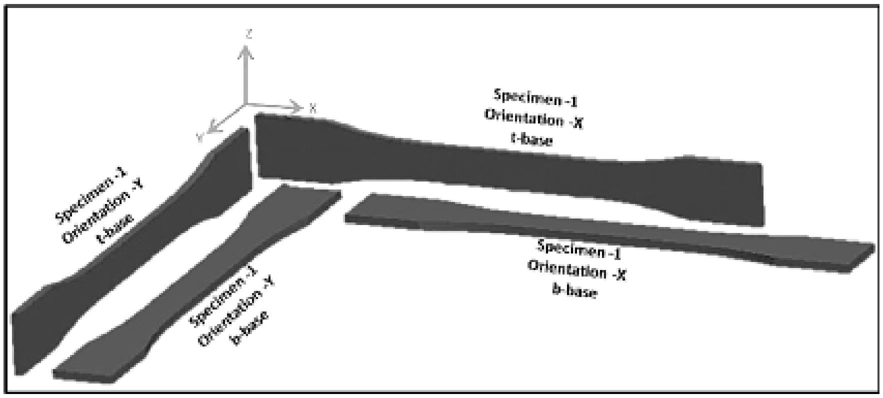


Figure 2.1: Specimen Orientation [6]

2.3 Energy Absorption

George C Jacob [2] did research on energy absorption in composite materials for automotive crashworthiness. In passenger vehicles the ability to absorb impact energy and be survivable for the occupant is called the ‘‘crashworthiness’’ of the structure. Energy absorption is dependent on many parameters like fiber type, matrix type, and fiber architecture, specimen geometry, processing conditions, fiber volume fraction, and testing speed. Changes in these parameters can cause subsequent changes in the specific energy absorption (ES) of composite materials up to a factor of 2. He in detailed mentioned review of the energy absorption characteristics in polymer composite materials. He also gave a description about various methods to test composites structures and various crushing modes in composite tubes. Finally, he raised certain design issues related to keep deceleration below 20g during impact by finding out the work rate decay. **N A Endut & M H F Al Hazza [9]** studied on energy absorption behavior of aluminum foam sandwich shown in Figure 2.2. Metal foams are one of the idea to evolve new material in automotive industries since it can absorb energy when it deformed and good for crash management. Recently, new technology had been introduced to replace metallic foam by using aluminum foam sandwich (AFS) due to lightweight and high energy absorption behavior. So he took an aluminum foam sandwich and conducted 6 different compression tests varying the thickness of aluminum foam. He then took stress strain curves to look the behavior of the foam and he found that the energy absorption of aluminum foam increases from 12.74 J to 64.42 J. **Thomas Tancogne Dejean [10]** did a study on Additively-manufactured metallic micro-lattice materials for high specific energy absorption under static and dynamic loading in which an octet truss material(Figure 2.3) is designed for energy absorption purposes featuring an exceptionally high specific energy absorption, a constant plateau stress between initial yield and densification, and zero plastic Poisson's ratio. Prototype materials are built from stainless steel 316L using Selective Laser Melting. The basic building element of the micro-lattices are 2.2 mm long beams with a 500 μm diameter cross-sections. Detailed micro- and meso-structural analysis including tomography, microscopy and EBSD analysis revealed substantial local material property variations within the lattice structure. Compression experiments are performed under static and dynamic loading conditions confirming the anticipated exceptional energy absorption material characteristics for strain rates of up to 1000/s. Finally, research has revealed that the mechanical properties of the basis material vary substantially within the SLM-made lattice structures. The comparison of the results for thin and thick SLM made structures (mini-versus standard specimen) reveals that the differences in grain morphology and texture (mostly due to different cooling conditions) can result in a yield stress difference of more than 20%.

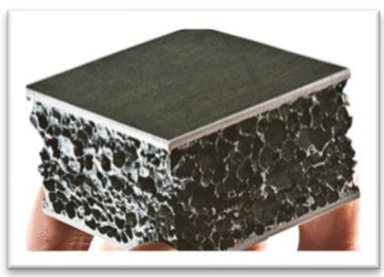


Figure: 2.2 Aluminum Foam sandwich [8]

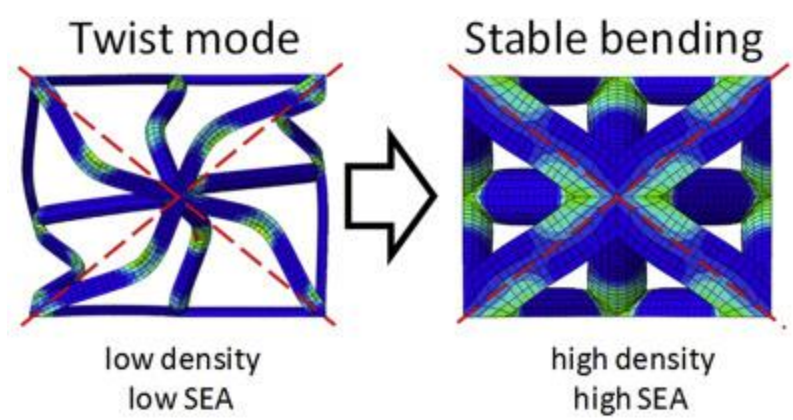


Figure: 2.3 Octet structure on which SEA is studied [9]

2.4 Lattice Structures

R Umer [8] carried out compression tests on 4 composite lattice design structures. Figure 2.3 shows all configurations that are used for their study, BCC, BCC with vertical bars BCCz, FCC and doubled BCC (F2BCC). A number of manufacturing techniques have been used to produce these metallic structures, including a rapid processing and brazing procedure, investment casting, and selective laser melting and for carbon fiber-reinforced sandwich structures, the lost-mold technique has been used.

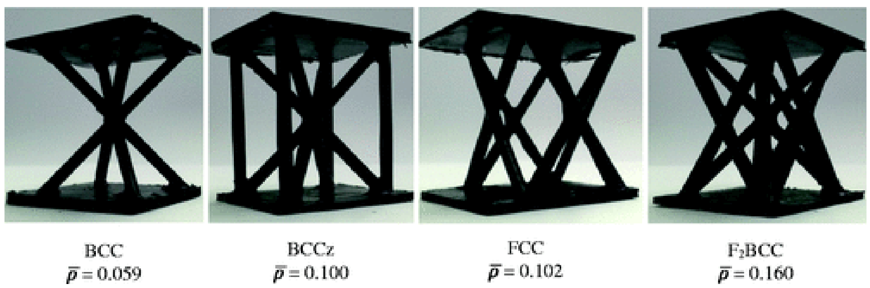


Figure: 2.4 Different Composite lattice Structures [8]

A study was done on Evaluations of cellular lattice structures manufactured using selective laser melting [11]. Cellular lattice structures shown in Figure 2.5 are generated by a novel unit cell type called “Schoen Gyroid”. The lattice structures with a wide unit cell size range were manufactured by SLM. Struts within the lattice structures with smaller unit cell sizes have higher densities. The yield strengths and Young's moduli both decrease with the increase in unit cell size.

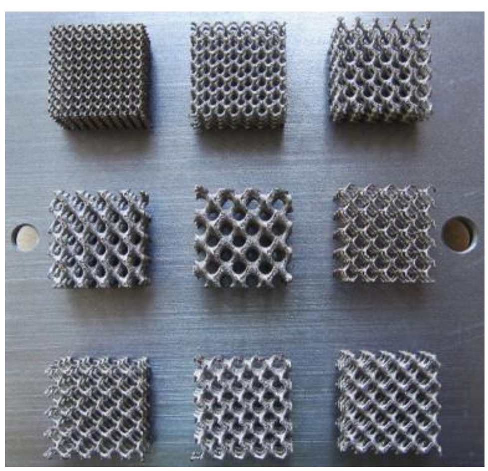


Figure 2.5 Cellular lattice structures manufactured by SLM [11]

Study on Evaluation of light-weight AlSi10Mg periodic cellular lattice structures fabricated via direct metal laser sintering [12] where there used a unique style of unit cell called Diamond Cell shown in Figure 2.6 to create lattice structures shown in Figure 2.7. The AlSi10Mg lattice structure is made directly by Direct Metal Laser Sintering shown in Figure 2.7.

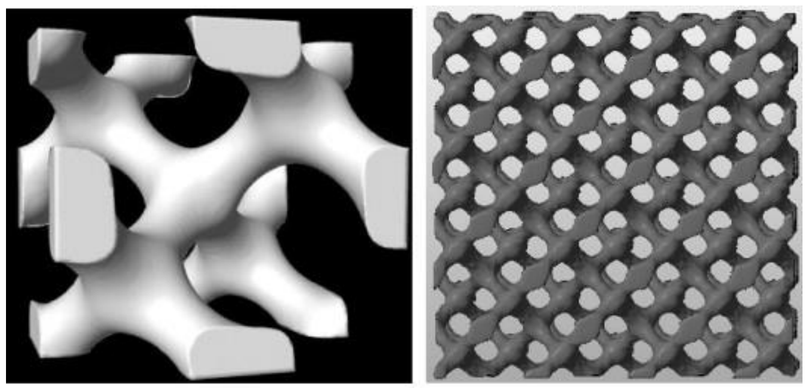


Figure 2.6: Unit Diamond Cell and Its Periodic lattice structure [12]

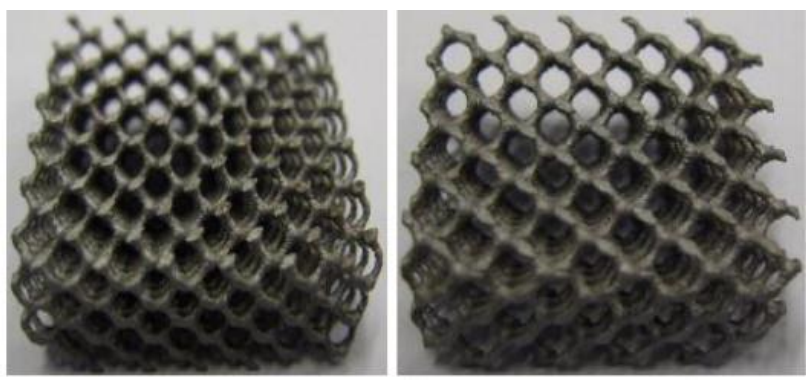


Figure 2.7: Lattice Structure made by Direct Metal Laser Sintering (DMLS) [12]

Al Rifaie, Mohammed Jamal [13] did a study on resilience and toughness behavior of 3d-printed polymer lattice structures. A BCC structure is modified by adding vertical bars in different arrangements and created three new configurations. So, this study is done on totally four set of configurations. BCC, BCC with vertical bars added to all nodes BCCV, BCC with vertical bars added to alternate nodes BCCA, BCC with gradient arrangements of vertical bars BCCG. These configurations are shown in Figure 2.8. SEA was calculated in both compression and impact tests of all configurations which resulted in showing BCCV has highest SEA in both configurations.

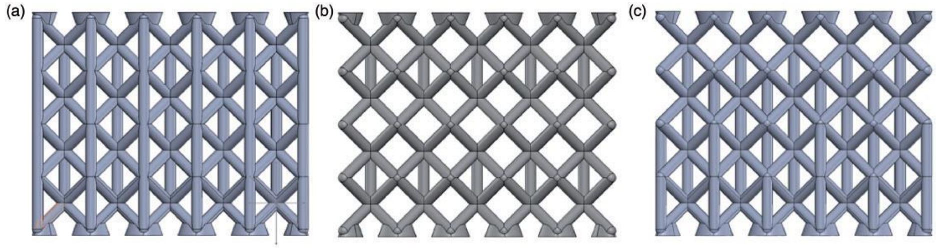


Figure 2.8: a) BCCV b) BCCA c) BCCG

Study on Low-Velocity Impact Behavior of Sandwich Structures with Additively Manufactured Polymer Lattice Cores [14]. Impact test is done on sandwich panel lattice structures. These structures consist of solid face sheets and low-density cellular core structures, which are traditionally based upon honeycomb folded-sheet topologies as shown in Figure 2.9 In this work, the sandwich core is comprised of lattice truss structures (LTS). Two different LTS designs are 3D-printed using acrylonitrile butadiene styrene (ABS) and are tested under low velocity impact loads. Absorption Energy and failure loads are investigated. It is observed that selective placement of vertical support struts in the unit-cell results in an increase in the absorption energy of the sandwich panels. BCC unit cell was chosen for the first (baseline) configuration and the second unit-cell configuration consists of a BCC unit cell with an alternating vertical strut (BCCAV). They removed the vertical members in alternate layers in the BCCAV structure, allowing both failure modes and increasing the amount of energy absorbed during impact loading.

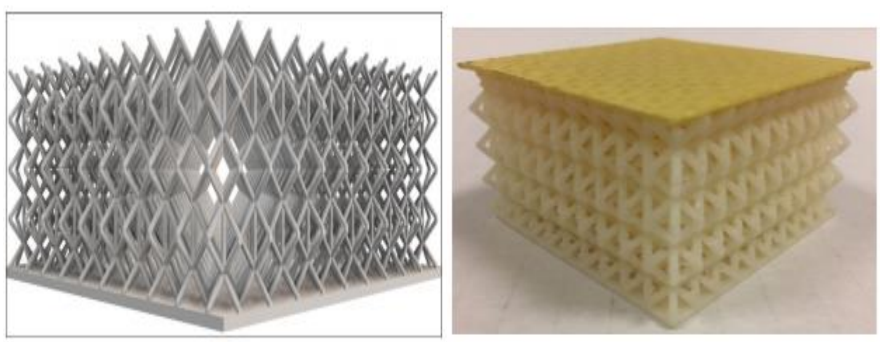


Figure 2.9: BCCAV structure

Limited research work is going on different lattice structures as we can see there are few studies that are done on polymer structures and there is no work going on build parameters. Doing research on different lattice structures gives the best structure that absorbs more energy. There will be an effect of build parameters also on the structure.

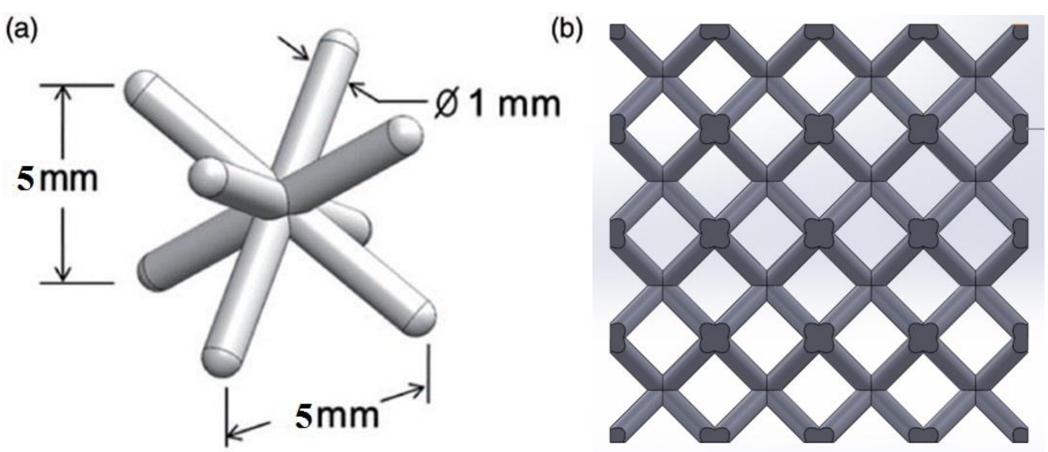
Chapter 3: Design and Fabrication

3.1 Overview

In this chapter, design of the lattice structures that are used for both compression and tensile tests are discussed. Solid Works Computer Aided Software (CAD) is used to design the specimens. Stratasys uPrint 3D [15] printer is used to fabricate the specimens in all required orientations including build parameters. The material used was an ivory colored production grade thermoplastic ABSplus-P430 which shows elastic plastic behavior at room temperature. [16, 17]

3.2 Compression Test Specimen

As discussed earlier BCC unit cell is used to study the differences between energy absorption ability. A BCC specimen have an average weight of 1.8 grams. This is designed using Solid works. The Dimensions of a unit cell is 5mm x 5mm x 5mm and the overall dimensions of the BCC structure is 20mm x 20mm x 20mm with diameter of the truss elements as 1mm. After the structure is printed it is found out that the diameter is not exactly 1 mm it is somewhere around 0.9 mm - 1.1 mm. The total number of unit cells in each structure is 64. There are 4 unit cells copies in each x, y & z direction. There are a number of studies on a BCC unit cell. All the compression tests are done Instron 5500R universal testing machine, seen in Figure 5.1, which has a maximum load capacity of 150 KN.



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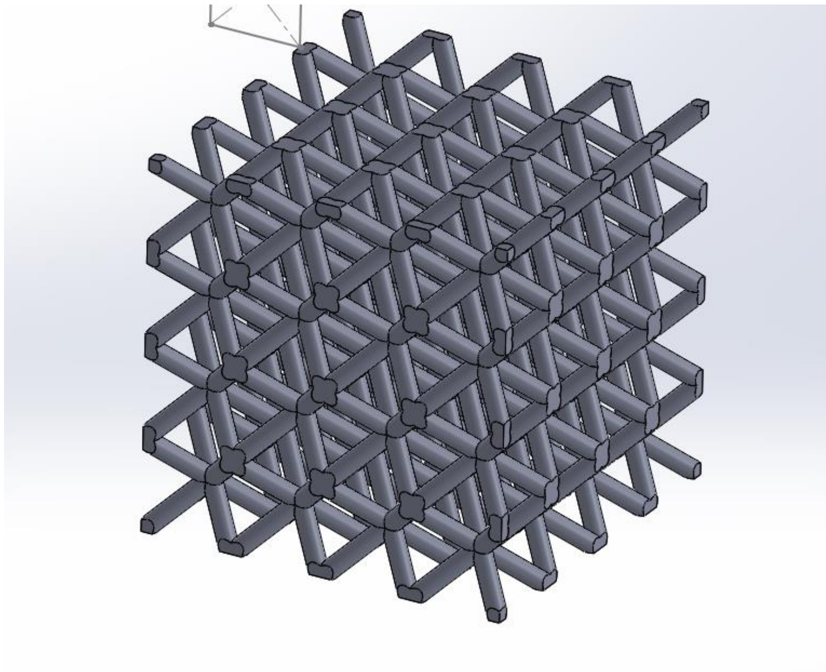


Figure 3.1: (a) BCC Unit Cell, (b) Side View of BCC lattice structure

(c) 3D view of BCC Lattice Structure

3.3 Tensile Test Specimen

As discussed above regarding the compression specimen the same BCC unit cell has been used for the tensile specimens too. Using Solid works a CAD model of the lattice structure was created by assembling unit cells into a cubic lattice with flat plates as shown in figure 3.2 for mounting in the test fixture. Each unit cell is 5mm x 5mm x 5mm with diameter of truss as 1mm. It results in the overall dimensions of lattice structure to be 26mm x 26mm x 26mm and the dimensions of the plates are 50mm x 26mmx 5mm.

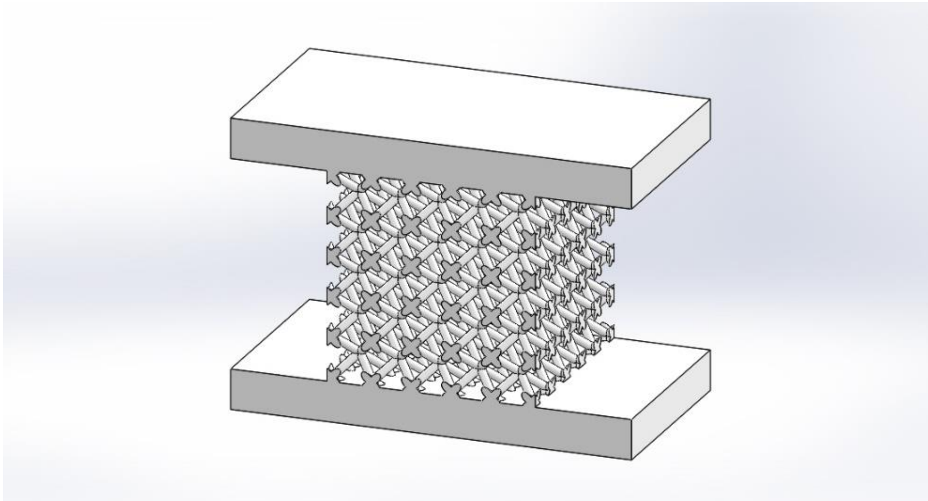


Figure 3.2: Tensile Test Specimen

3.4 Tension Test Fixture

Special fixtures, seen in Figure 3.3, had to be designed and built to perform tensile tests on the test specimens. Dimensioned drawings of the fixtures are in the appendix attached to the end of this report. All the lattice structures were tested using an Instron 5800 R, universal testing machine, seen in Figure 5.2, which has a maximum load capacity of 150 KN. The testing machine is equipped with Bluehill2® control and data acquisition software.

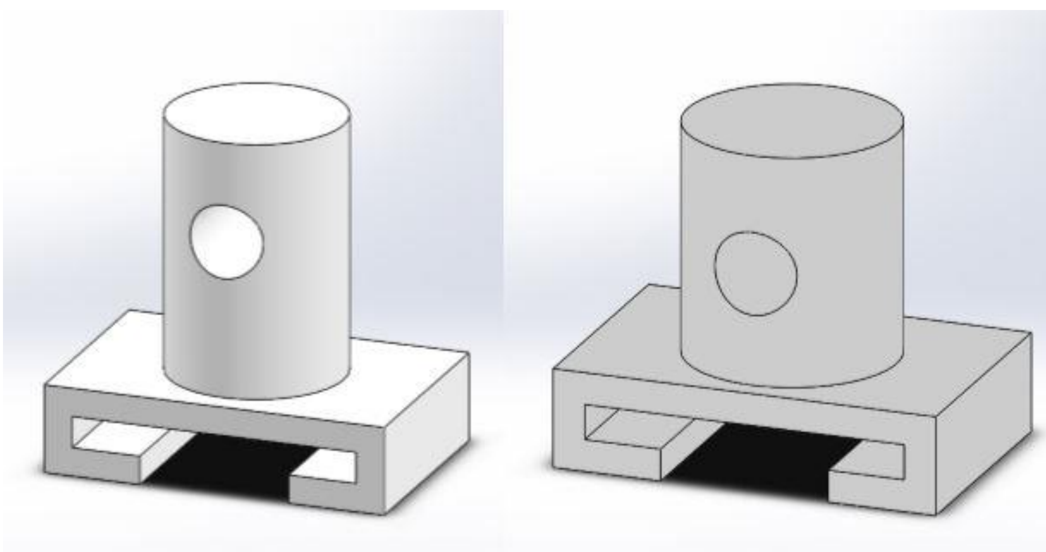


Figure 3.3: (Left) top tension test fixture; (right) bottom tension test fixture

3.5 3D Printer used for Fabrication

A Stratasys uPrint SE plus 3D printer has been used to print all the lattice structures as seen in figure 3.5. It uses STL file as the input using CatalystEX software provided by Stratasys. The maximum layer thickness capability of the printer is 0.33 mm. It uses FDM technology to build up the model. The default temperature settings were used while printing where the printer head temperature is 300°C and chamber temperature is 77°C. It has a limited space of 200 x 200 x 150 mm. This printer have an ability to print specimens in different angle orientations like 0°, 30°, 45°, 60° and 90°. It also has 2 different type of thicknesses that it can print the material a) 0.010 mm b) 0.013mm. In addition it has an option to choose one among the three different infill densities (Sparse Low Density, Sparse High Density, and Solid).

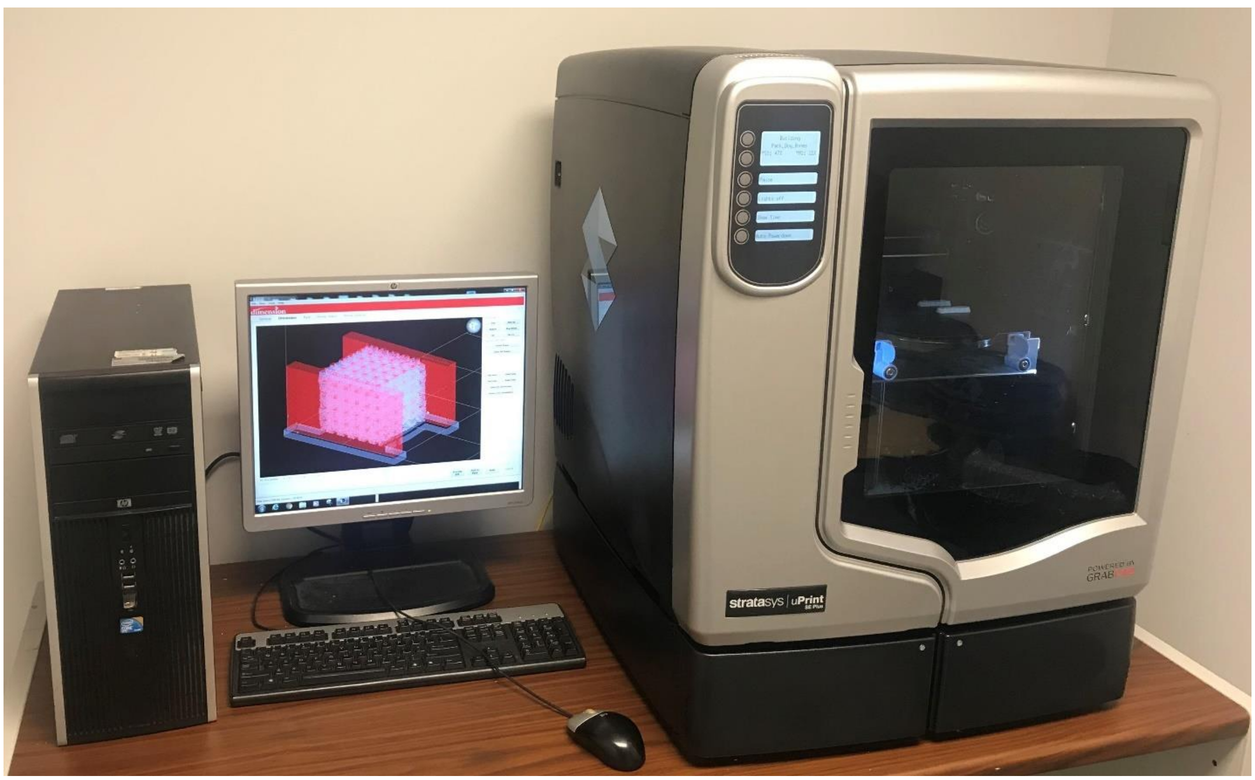


Figure 3.5: Stratasys uPrint SE plus 3D Printer.

3.6 Parameters used for Fabrication of both Compression and Tensile Specimens

Both the compression and tensile specimens were printed in different orientations. So Solid and Sparse High-Density infill densities are used with layer thickness of both 0.010 inch & 0.013 inch and each specimen is printed in 0°,45°,90° orientation.

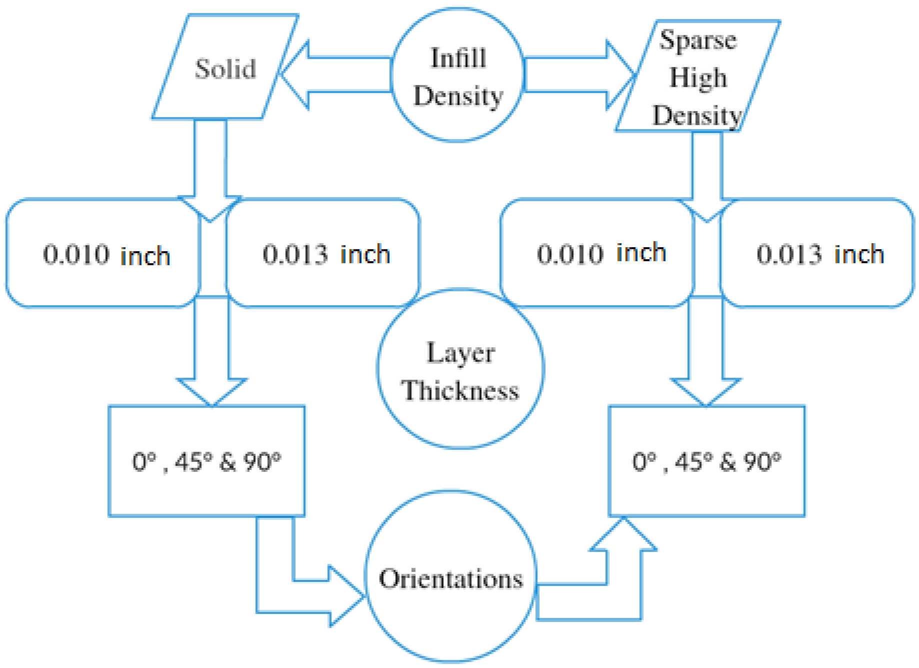


Figure 3.6: Figure showing all build parameters that are taken to print specimen

Specimens that are printed in 0° orientation didn't require much support material except at bottom whereas the specimens printed in 45° orientation required a great amount of support material. To remove the support material a cleaning apparatus by Stratasys was used where the specimen was soaked in the heated chemical bath for approximately 8 hours. The tank heats and circulates the chemical solution to accelerate the support structure removal process. After removing the material, the specimens were washed in water at room temperature and are dried [18]. Images of specimens printed in each build orientation are shown in figures 4.1-4.3 in next chapter.

Chapter 4: Physical Attributes

4.1 Original and microscopy images of specimens printed in all orientations.

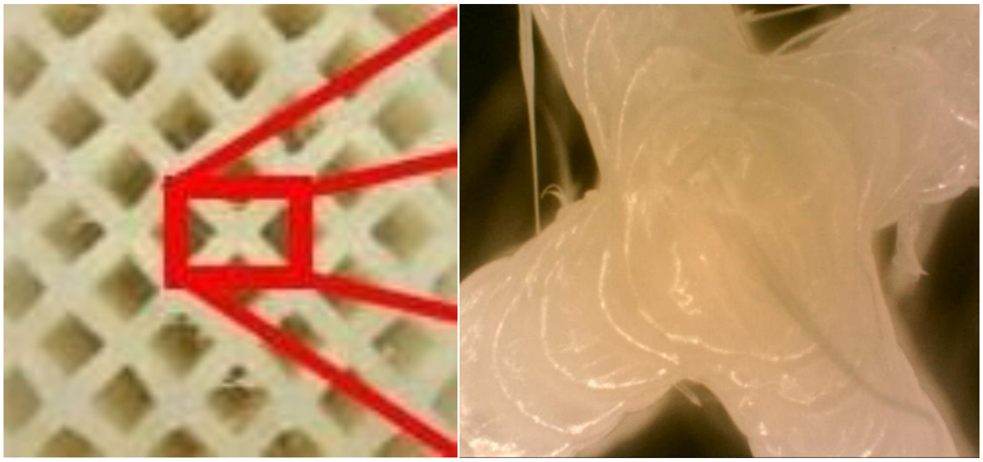


Figure 4.1: Specimen printed in 0° & 90°

The microscope view of the specimens printed for compression test are same for 0° & 90°since the lattice is symmetrical with dimensions of 20mm x 20mm x 20mm.

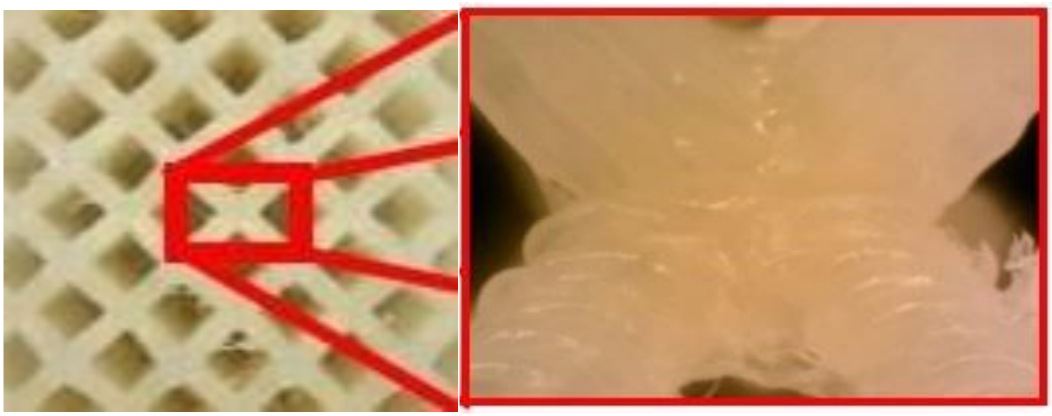


Figure 4.2: Specimen printed in 45°

If we compare the printing of layers in both 0° & 45° when we see the truss elements 2 of them were having straight linear layers in 45° orientation which may affect the behavior. The remaining 2 truss elements have layers printed in 45° angle.

There is a change in print style of layers as we discussed earlier changing the print angle. The only thing that can't be explained by the microscopy image is the infill density whether the material used is sparse high density or solid.

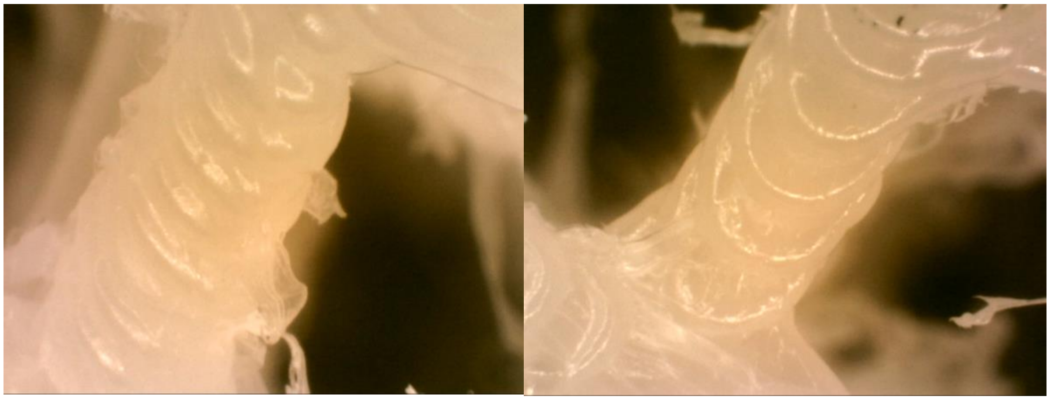


Figure 4.3: Images of truss elements printed in 0° & 45°

We can observe the difference between the layer pattern for 0° and 45 ° angle printing.

4.2 **Build Time and Accuracy**

4.2.1 Introduction

Here, we discuss about the print accuracy and build time of each specimen of different configurations. The diameter of each truss element given in design is 1.0 mm. Even though the design says it is 1.0 mm, sometimes due to printer clearance i.e. by calibration error it sometimes might build less than the given input diameter. Build times may vary depending on the infill density, layer thickness and printing orientation(angle).

4.2.2 Build Time

It means the time taken to build each specimen

Compression Test Specimens

Configuration	Build Time
Solid 0.010 0^0	1 hr 23 mins
Solid 0.010 90^0	1 hr 23 mins
Solid 0.010 45^0	2 hr 15 mins

Solid 0.013 0^0	2 hr 10 mins
Solid 0.013 90^0	2 hr 10 mins
Solid 0.013 45^0	2 hr
Sparse high density 0.010 0^0	1 hr 23 mins
Sparse high density 0.010 90^0	1 hr 23 mins
Sparse high density 0.010 45^0	2 hr 16 mins
Sparse high density 0.013 0^0	2 hr 10 mins
Sparse high density 0.013 90^0	2 hr 10 mins
Sparse high density 0.013 45^0	2 hr

Table 1: Build Time for Compression Test Specimens

Tensile Test Specimens

Configuration	**Build Time**
Solid 0.010 0^0	4 hr 08 mins
Solid 0.010 90^0	5 hr 22 mins
Solid 0.010 45^0	5 hr 44 mins
Solid 0.013 0^0	4 hr 47 mins
Solid 0.013 90^0	4 hr 59 mins
Solid 0.013 45^0	5 hr 48 mins
Sparse high density 0.010 0^0	4 hr 06 mins
Sparse high density 0.010 90^0	5 hr 21 mins
Sparse high density 0.010 45^0	5 hr 58 mins
Sparse high density 0.013 0^0	4 hr 04 mins
Sparse high density 0.013 90^0	4 hr 58 mins
Sparse high density 0.013 45^0	5 hr 47 mins

Table 2: Build Time for Tension Test Specimens

If we observe the specimens build times the build times vary from configuration to configuration it is due to the amount of support material required for the lattice structure. Some configurations need more support which results in taking more time print the specimen.

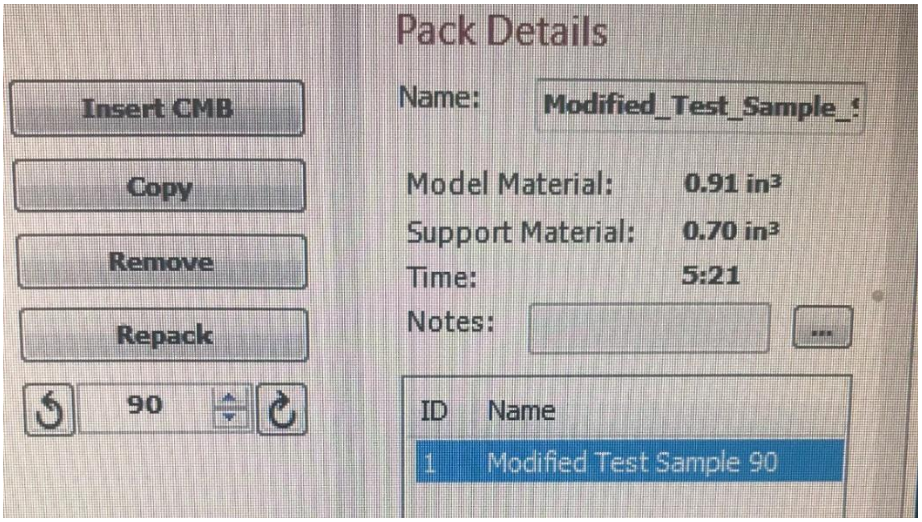


Figure 4.4: Build Time shown in 3D printer

4.3 Accuracy

As discussed earlier in introduction due to some errors in printer there are some variations in part diameter.

Compression Test Specimens

Configuration	**Average Diameter of truss elements**
Solid 0.010 0^0	0.9 mm
Solid 0.010 90^0	0.9 mm
Solid 0.010 45^0	1.0 mm
Solid 0.013 0^0	0.9 mm
Solid 0.013 90^0	0.9 mm
Solid 0.013 45^0	1.0 mm
Sparse high density 0.010 0^0	0.9 mm
Sparse high density 0.010 90^0	0.9 mm
Sparse high density 0.010 45^0	1.0 mm
Sparse high density 0.013 0^0	0.9 mm
Sparse high density 0.013 90^0	0.9 mm
Sparse high density 0.013 45^0	1.0 mm

Table 3: Diameter of truss elements Compression Test Specimens

The overall height of each lattice structure is 20 mm. Due to change in diameter the height after measuring is approximately 20 mm for every specimen.

Tensile Test Specimens

Configuration	Average Diameter of truss elements
Solid 0.010 0^0	1.0 mm
Solid 0.010 90^0	1.0 mm
Solid 0.010 45^0	1.0 mm
Solid 0.013 0^0	1.0 mm
Solid 0.013 90^0	1.0 mm
Solid 0.013 45^0	1.0 mm
Sparse high density 0.010 0^0	1.0 mm
Sparse high density 0.010 90^0	1.0 mm
Sparse high density 0.010 45^0	1.0 mm
Sparse high density 0.013 0^0	1.0 mm
Sparse high density 0.013 90^0	1.0 mm
Sparse high density 0.013 45^0	1.0 mm

Table 4: Diameter of truss elements Tension Test Specimens

For tensile specimens the diameter is accurate.

All the diameters are measured by Digital Vernier calipers. The error might be due to printer and there is a possibility of some support material that is remained on the structure at some points.

There is a possibility that since the unit cell have so minute dimension of 1.0 mm the printer prints it layer by layer where there might be some temperature drop which results in contrast of material. Sometime sit print 0.9mm sometimes it prints 1.1 mm. sometimes accurate, so the height of specimen is accurate.

Chapter 5: Experimental Work

5.1 Material Properties

The material properties of ABS are shown in Table 5 which are taken from Stratasys [16]. There might be a change of properties after printing since there are reasons like printing conditions, type of toolpath, porosity and layer thickness. In this research standard compression and tensile test has been done. Stress Strain curve is taken from both the tests to study on properties like yield strength, ultimate strength (Tensile and Compressive).

Mechanical properties	**Tensile (ASTM D638) [12]**
Yield strength (MPa)	31
Ultimate strength (MPa)	33
Elongation at yield (%)	2
Elongation at break (%)	6
Modulus (GPa)	2.2

Table 5: Properties of ABS

5.2 Compression Test

There are 16 specimens that are tested using INSTRON 5500R, universal testing machine, which has a maximum load capacity of 150KN [17]. Figure 6.1 describes the machine. It has a software called Bluehill2 provided by Instron which can post process the data. This data is saved in an EXCEL file in CSV format which has load, Displacement, Compressive Stress, Compressive strain and Deformation results. Each configuration has 3 specimens to consider the uncertainty which results in testing of 48 specimens.

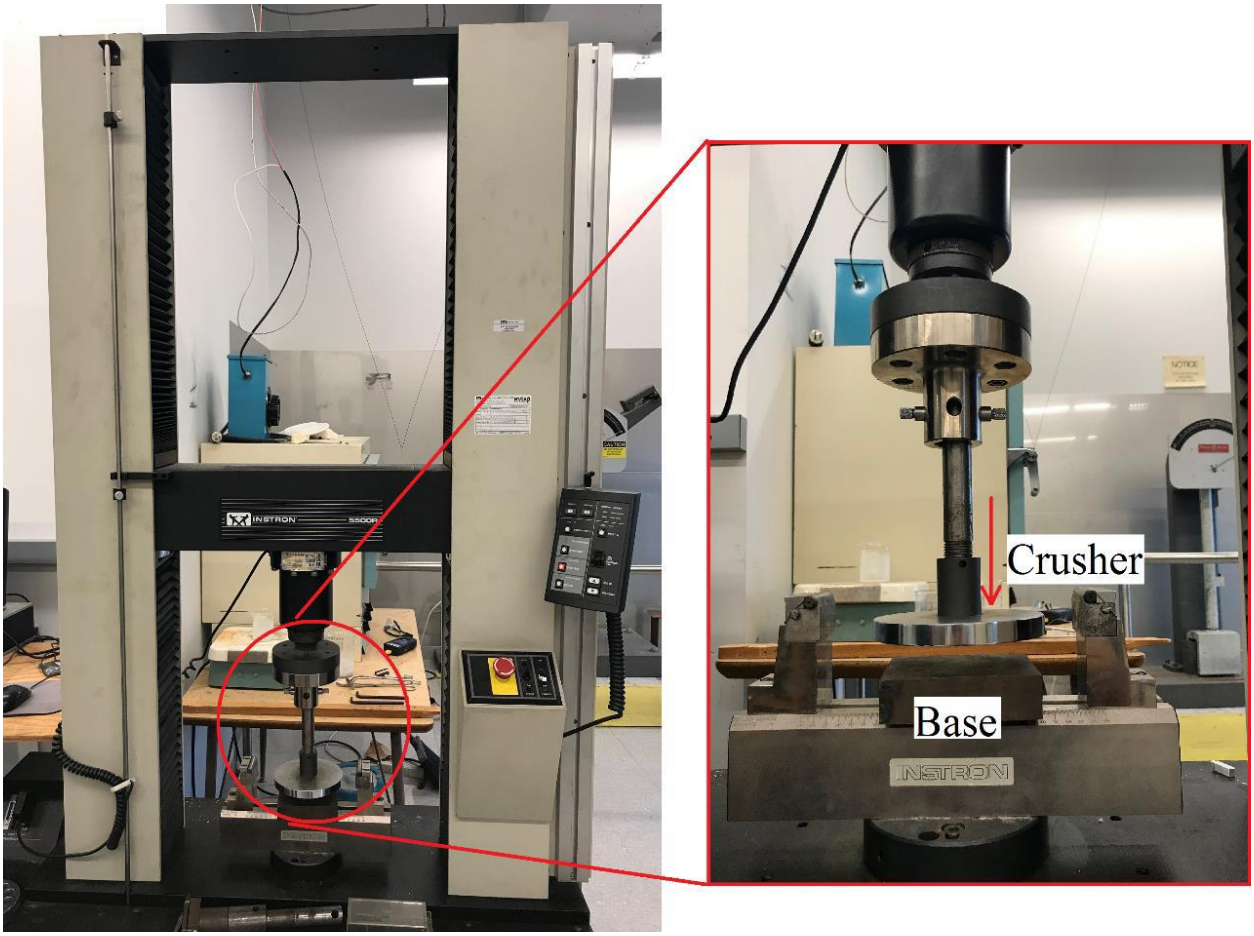


Figure 5.1 INSTRON 5500R

Quasi static compression test was performed on the specimens under displacement control of 0.5mm/min. The specimens were compressed up to 8mm crush length, up to 40% of the total height. The Yield Strength, Ultimate Strength, Young's Modulus are calculated from the Stress Strain Curve, whereas the Specific Energy Absorption (SEA) & Stiffness are calculated from Load Displacement Curve. As discussed earlier SEA is the area under load-displacement curve divide by weight. To calculate the area the cumulative trapezoidal integration is done by using excel worksheet. Here sand paper which has rough surface in the interior is used on both top and bottom of the specimen as shown in Figure 5.2. The boundary condition was almost fixed on both top and bottom for all the specimens. This observation of boundary condition has been captured using Time lapse Video. The crusher that pushes the top face of specimen is made from stainless steel to avoid friction.

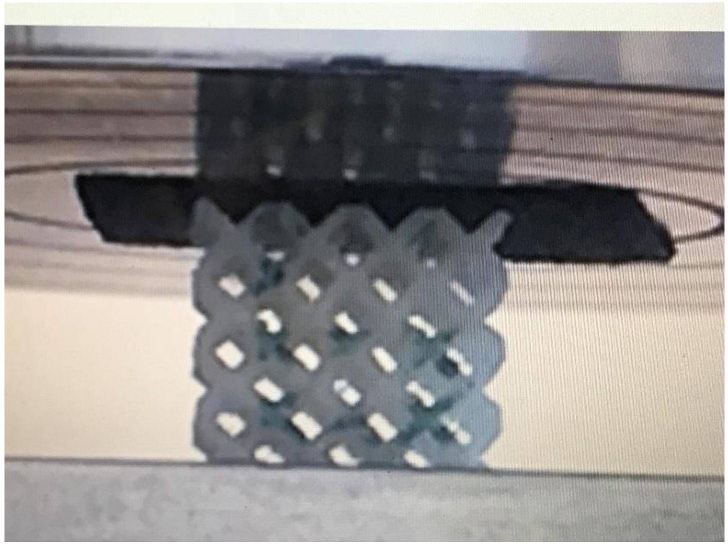


Figure 5.2: Sand paper used on top of the specimen.

Sand Paper is used on top and bottom of the Compression Specimen as shown in Figure 5.2 to avoid sliding of the specimen since the crusher has smooth surface. Out of all the specimens printed in 45° orientation shown in Figure 5.3 the specimens were tested on both directions of the structure the face that they were printed, and opposite direction of printing as shown in Figure 5.4.

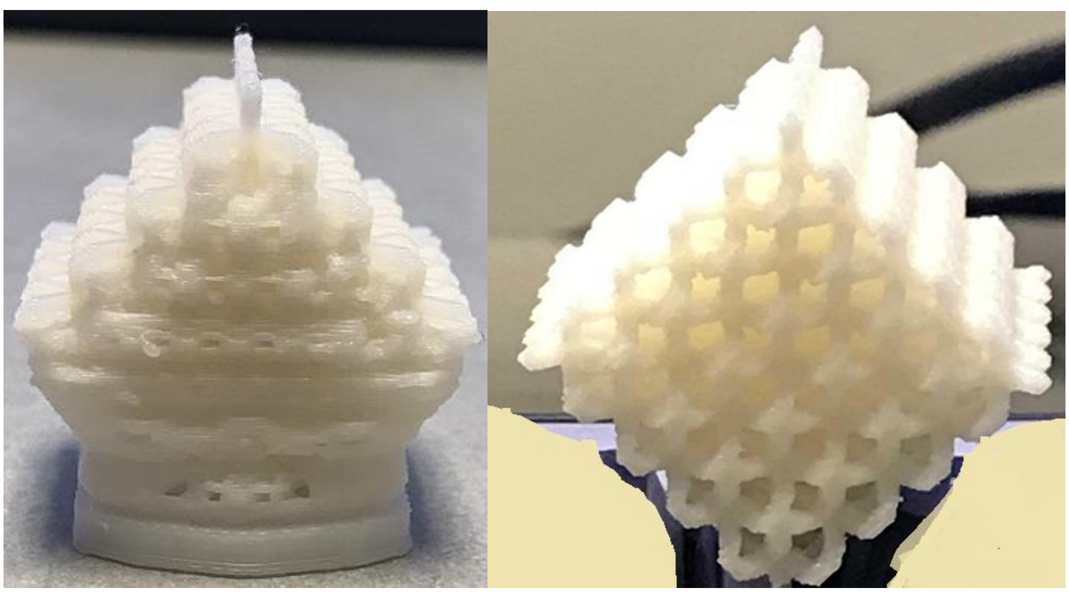


Figure 5.3 Specimen printed in 45° before and after support material removal

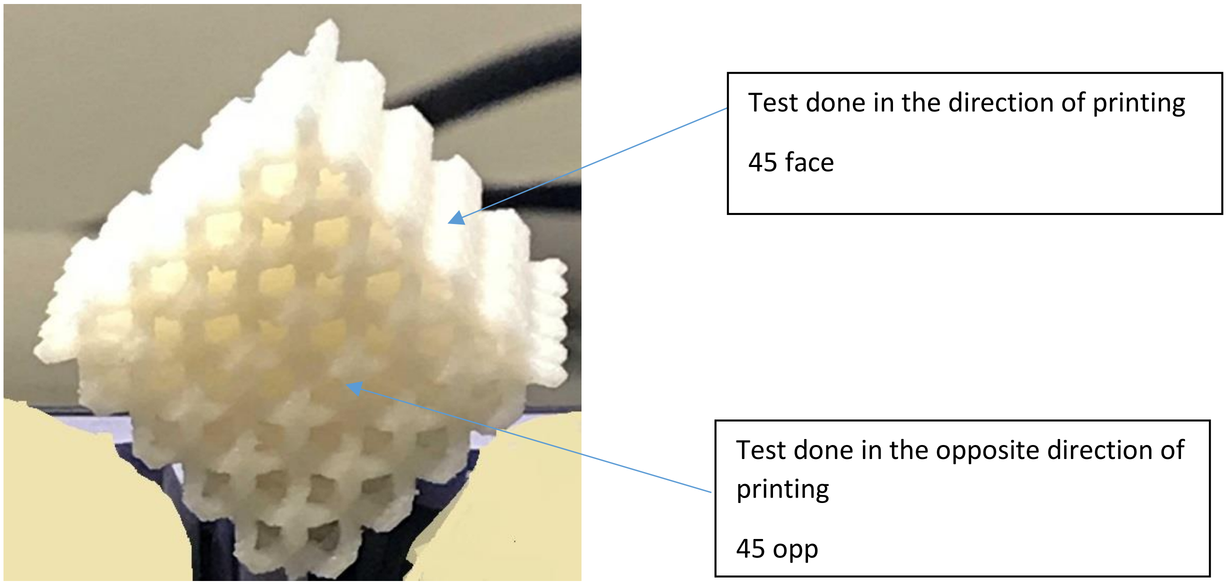


Figure 5.4: Image showing the test directions of 45°

5.3 Tension Test

For Tension test there are 12 specimens that are tested using INSTRON 5800R which has a max load capacity of 150 KN. Figure 5.6 describes this testing machine. It even has the Bluehill2 Industrial software provided by INSTRON. Tensile test was performed on specimen under extension control of 0.2 mm/min. The specimens were pulled up to 4mm.The Specific Energy Absorption (SEA) and Stiffness (K) are calculated using load displacement curve. Yield Strength is calculated from Stress Strain Curve. Since there is no other option to hold the specimen for tensile test additional plates are attached on the top and a fixture is created accordingly to hold the specimens. Figure 5.5 shows the specimen image of a Tensile Specimen.

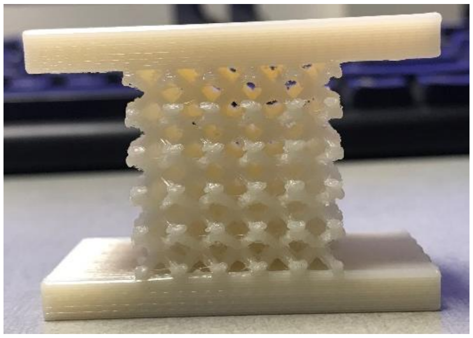


Figure 5.5 Tensile Specimen

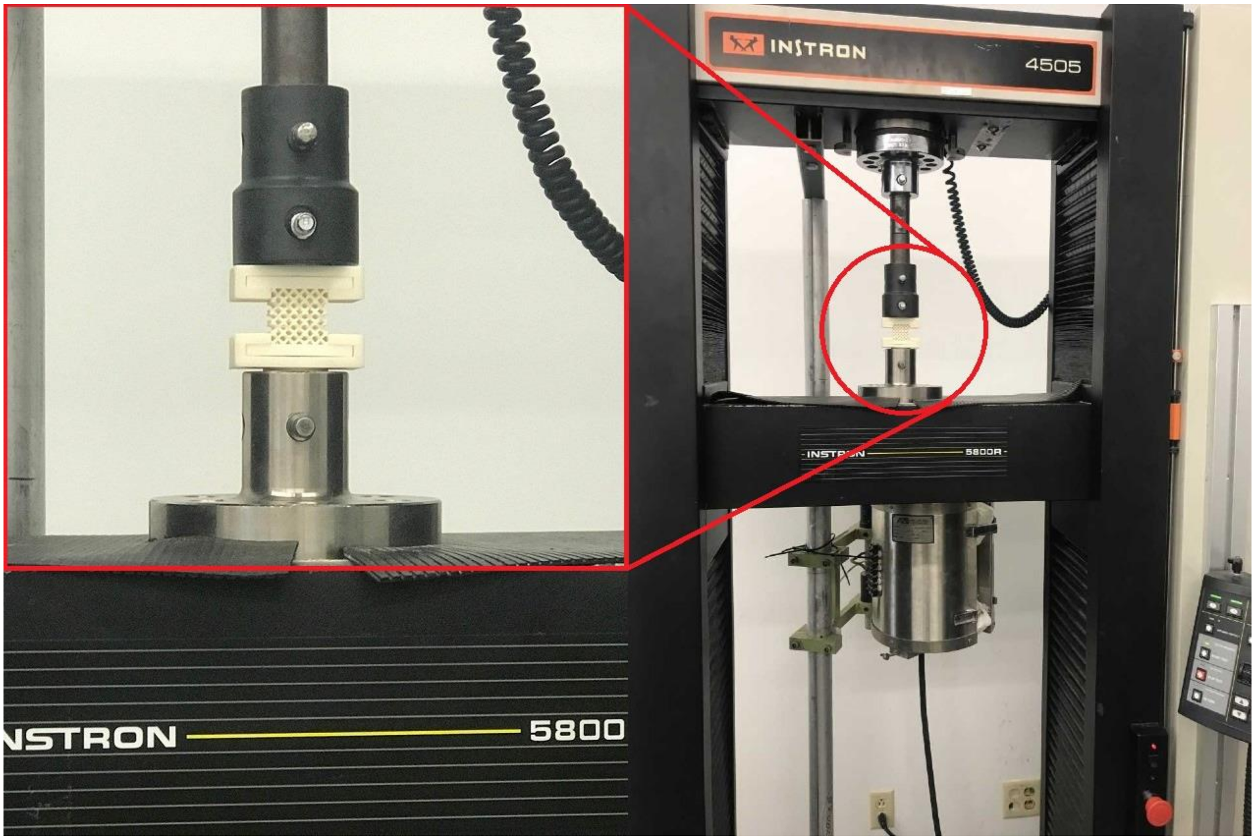


Figure 5.6 INSTRON 5800R

Each configuration has 3 specimens to consider the uncertainty which results in testing of 36 specimens.

CHAPTER 6: RESULTS AND DISCUSSION

6.1 Overview

This chapter presents all the experimental work results. Load Displacement curve is very important to evaluate the Specific Energy Absorption (SEA). 48 specimens for Compression and 36 specimens for Tension Test are used. Comparisons of all the Specimens were done using SEA, Stiffness (K), yield Strength, Ultimate Strength. The comparison between 3 specimens of same configuration were also considered.

6.2 Points considered to calculate the results

For Compression Test, SEA was calculated at 3 points

- point at start of first failure
- point at end of first failure
- point at end of second failure

Each curve shows multiple failures since the load was rising again when the first layer of lattice structure is collapsed, and it happened to all the specimens which tells that's acceptable.

For Tension Test, SEA was calculated at only one point because there won't be that many failures for tensile as it happened in compression since it breaks away at a point.

- point at failure

Stress and Strain values are calculated by giving the specimen dimensions to the INSTRON 5500R & INSTRON 5800R machine which uses a software provided by INSTRON (Bluehill). This software auto calculates the Stress and Strain values, these values are plotted in excel sheets.

6.3 Results

As we have seen in results the configurations irrespective of layer thickness and infill density gave a same behavior in Both Load Displacement curves and Stress Strain curves. In Compression especially if we observe the behavior of Load displacement curves that have configuration of 45° face got same results where every specimen collapsed completely after first failure. Figure 6.1

describes that behavior. Configuration with 45° opposite and layer thickness of 0.010 have high values than any other configurations in all compression tests it can be seen in Figure 6.2 till first failure. They aren't even collapsed for the given maximum extension. So, when compared to all other configurations this configuration may take more time to collapse totally. All configuration with solid and sparse thickness showed the same behavior irrespective of the layer thickness. It can be seen in Figure 6.3 & Figure 6.4.

6.3.1 Comparison of Compression Test Stress Strain Curves

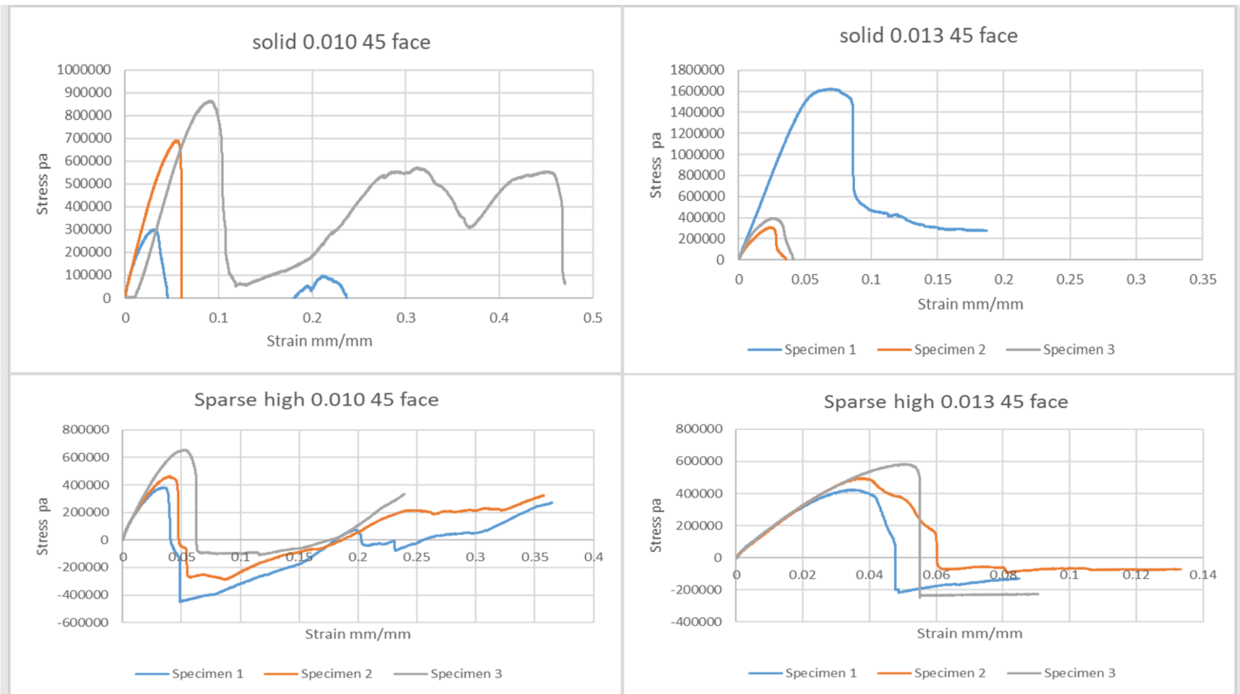


Figure 6.1: Stress Strain curves for 45° face Compression test configurations

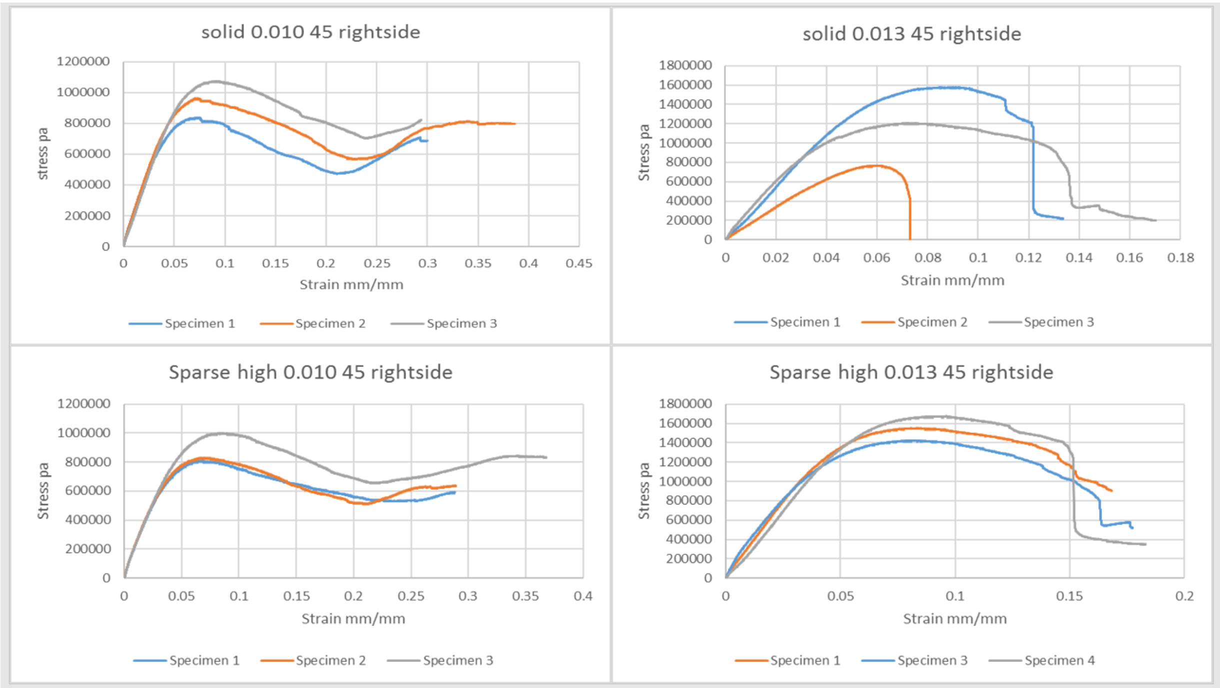


Figure 6.2: Stress Strain curves for 45° opposite Compression test orientations.

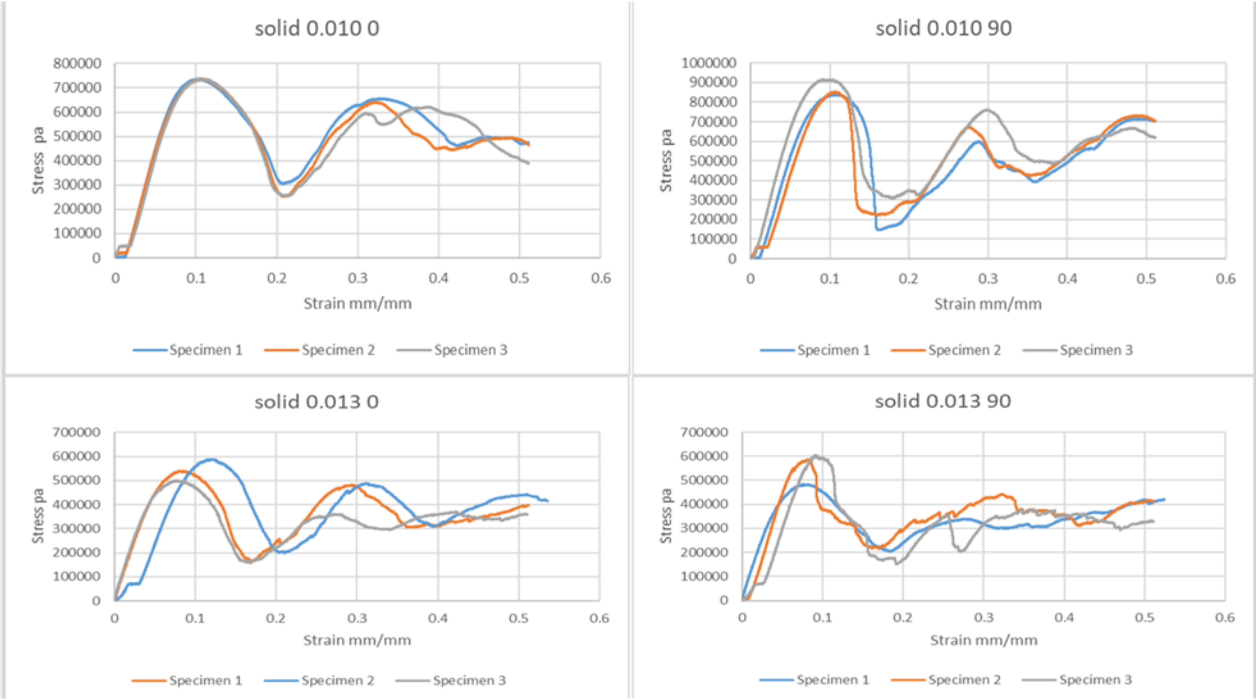


Figure 6.3: Stress Strain curve for solid 0° & 90° Compression test configurations.

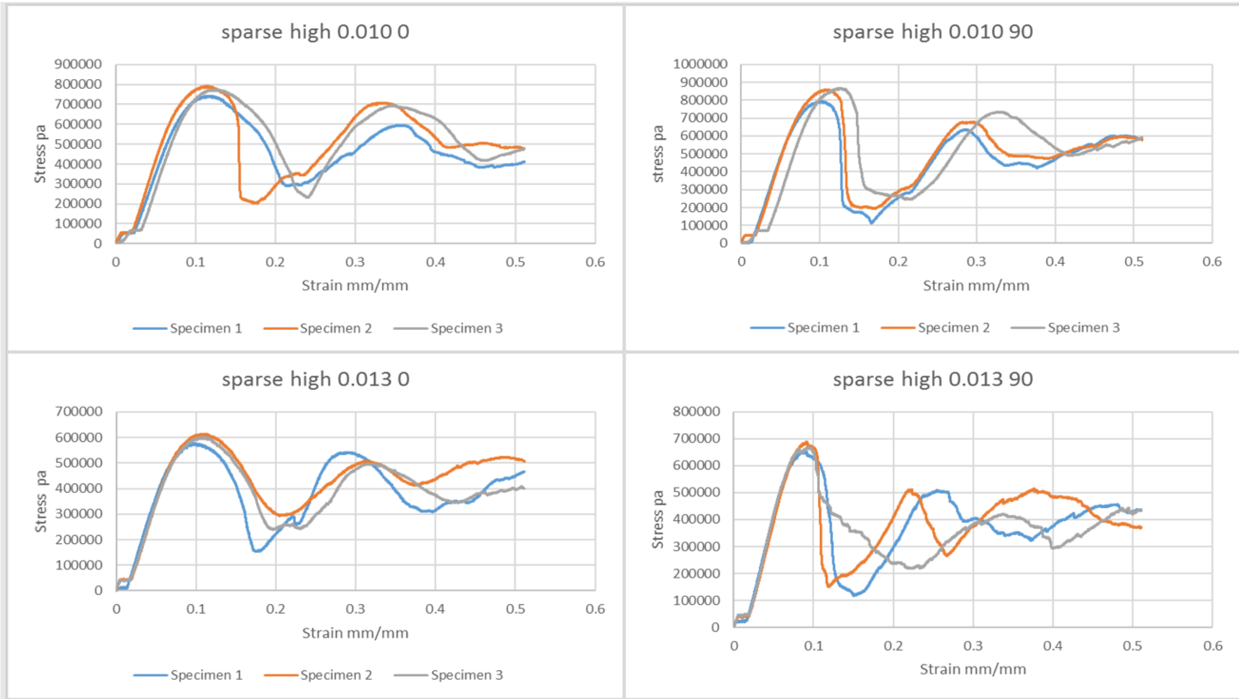


Figure 6.4: Stress Strain for sparse 0° & 90° Compression test configurations

For the tensile specimens tested with different configurations every configuration shows the same behavior since they fail at a time. Specimens having 45° angle configurations are very brittle having low values. They broke down very soon. Every other specimen printed in 0° & 90° configuration aren't too bad. Expected result is solid configuration but after experiment we got sparse high density 0.010 0° configuration with highest and better values.

6.3.2 Comparison of Tension Test Stress Strain Curves

Stress Strain curves for all tensile specimens are shown in Figure 6.5, Figure 6.6 and Figure 6.7

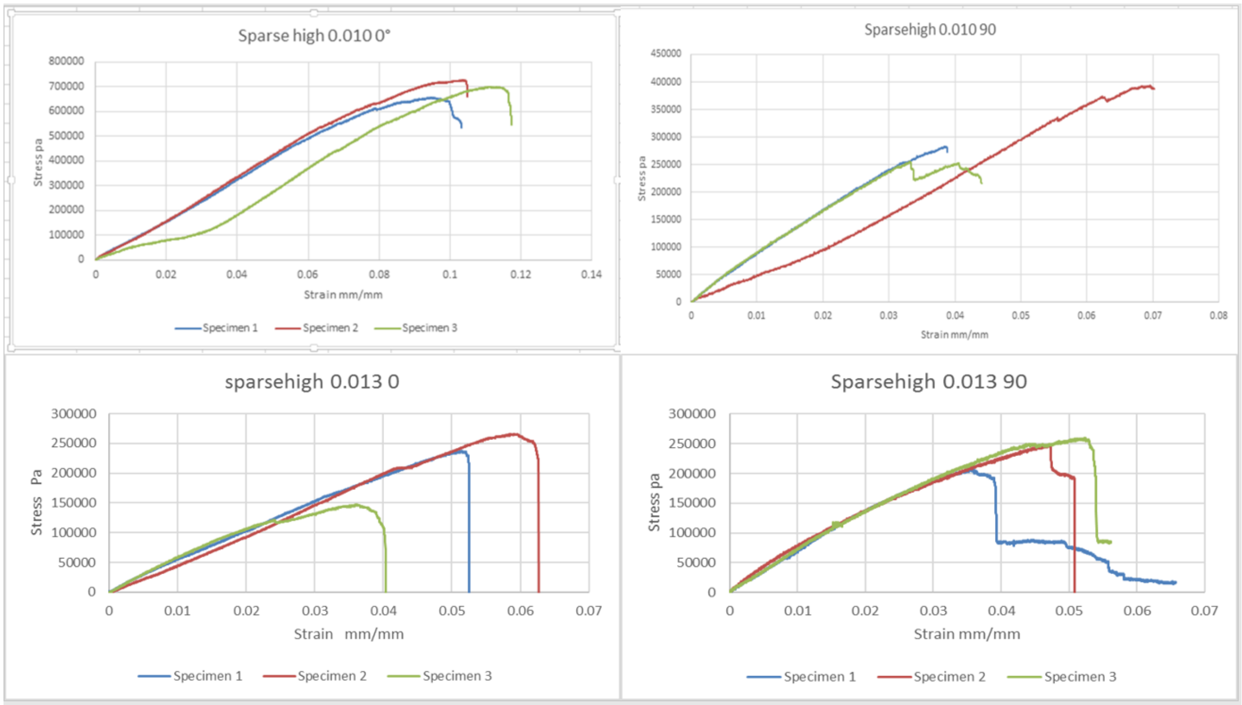


Figure 6.5: Stress Strain curve for sparse high 0° & 90° Tensile test configurations.

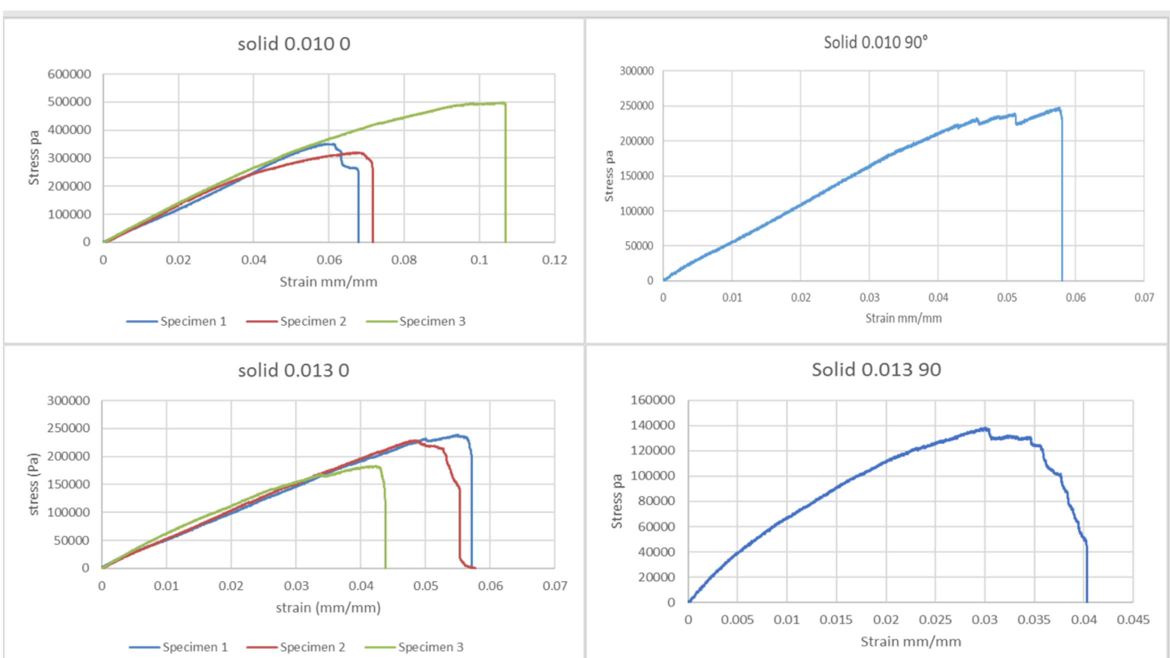


Figure 6.6: Stress Strain curve for solid 0° & 90° Tensile test configurations

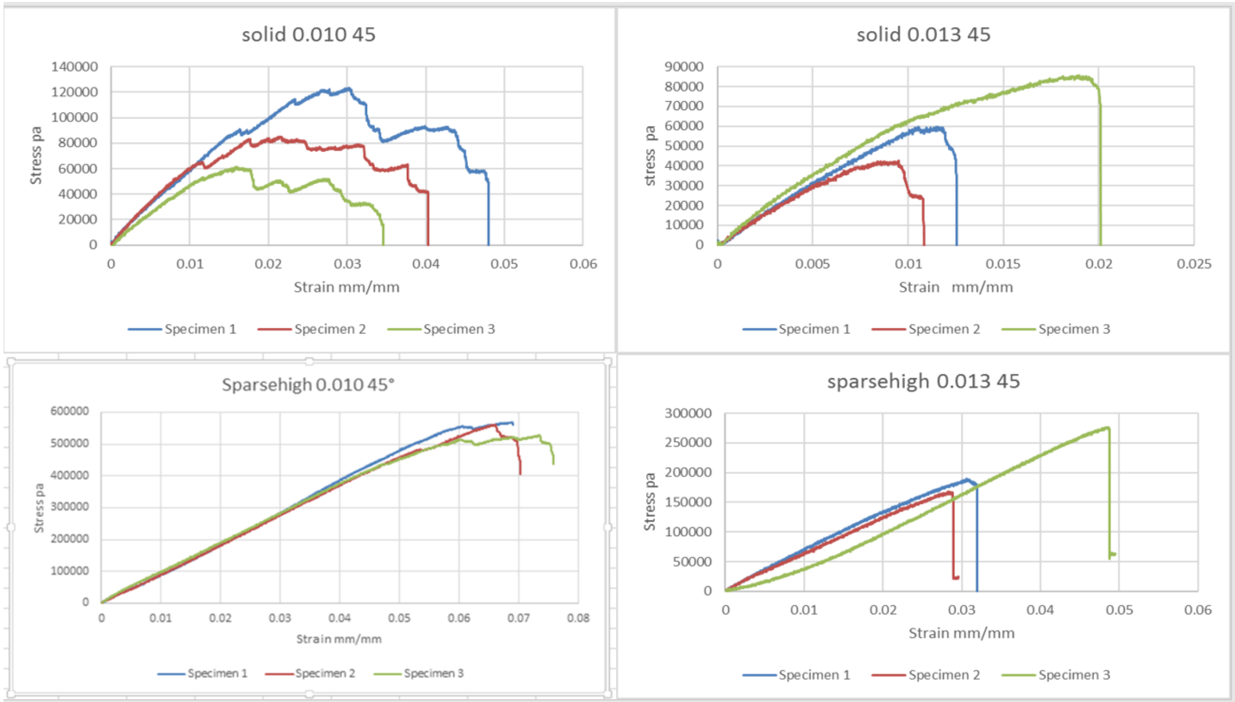


Figure 6.7: Stress Strain curve for 45° Tensile test configurations

In case of tensile 45° configuration is not at all suitable since they have very poor values.

Comparison of all results for all Compression test configurations till the start of first failure.

Configuration	SEA (J/Kg)				Stiffness (N/mm)			
	0°	90°	45° face	45° opposite	0°	90°	45° face	45° opposite
Solid 0.010	211.31	263.94	111.64	234.18	196.47	241.33	288.97	388.33
Solid 0.013	155.53	129.67	132.19	267.70	177.40	180.46	527.25	505.09
Sparse high 0.010	254.72	254.60	66.25	215.23	181.04	206.68	331.76	404.09
Sparse high 0.013	181.19	163.59	56.45	378.21	158.82	189.22	328.81	625.42

Table 6: Compression test results for all configurations.

Configuration	Young's Modulus (Mpa)				Failure Load / Ultimate Strength (Mpa)			
	0°	90°	45° face	45° opposite	0°	90°	45° face	45° opposite
Solid 0.010	8.97	11.03	13.45	12.88	0.73	0.86	0.61	0.94
Solid 0.013	7.94	8.26	24.66	23.45	0.53	0.54	0.76	1.16
Sparse high 0.010	8.10	9.87	15.56	19.53	0.75	0.83	0.41	0.81
Sparse high 0.013	7.28	8.63	15	29.56	0.59	0.65	0.49	1.48

Table 7: Compression test results for all configurations.

Configuration	SEA till start of 1st layer failure (J/Kg)				SEA till end of 1st layer failure (J/Kg)				SEA till the end of 2nd layer failure			
	0°	**90°**	**45° face**	**45° opposite**	**0°**	**90°**	**45° face**	**45° opposite**	**0°**	**90°**	**45° face**	**45° opposite**
Solid 0.010	211.3	263.9	111.6	234.1	469.1	407.4	125.1	717.8	877.5	786.75	-	-
Solid 0.013	155.5	129.6	132.1	267.7	307.1	279.2	211.4	441.9	596	481.6	-	-
Sparse high 0.010	254.7	254.6	66.25	215.23	472.5	367.8	72.86	645.8	1009.3	795.0	-	-
Sparse high 0.013	181.1	163.5	56.45	378.2	370	278.7	73.29	805.54	786.8	534.2	-	-

Table 8: SEA results for all compression test configurations

Comparison of all results for all Tension Test configurations till the start of first failure.

Configuration	SEA (J/Kg)			Stiffness (N/mm)		
	0°	**90°**	**45°**	**0°**	**90°**	**45°**
Solid 0.010	51.12	19.27	1.79	140.29	134.88	146.87
Solid 0.013	19.30	23.17	5.07	127.43	121.87	144.39
Sparse high 0.010	155.60	31.27	67.63	146.01	156.10	202.80
Sparse high 0.013	16.06	26.50	13.91	126.99	158.40	151.22

Table 9: Tension test results for all configurations.

Configuration	Young's Modulus (Mpa)			Failure Load / Ultimate Strength (Mpa)		
	0°	**90°**	**45°**	**0°**	**90°**	**45°**
Solid 0.010	5.81	5.07	5.51	0.39	0.24	0.08
Solid 0.013	5.12	5.02	5.64	0.21	0.23	0.06
Sparse high 0.010	6.52	6.66	8.53	0.68	0.30	0.52
Sparse high 0.013	4.86	6.34	5.78	0.21	0.23	0.20

Table 10: Tension test results for all configurations.

Chapter 7: Images of Specimens After Testing.

Failed Specimens in Compression Test.

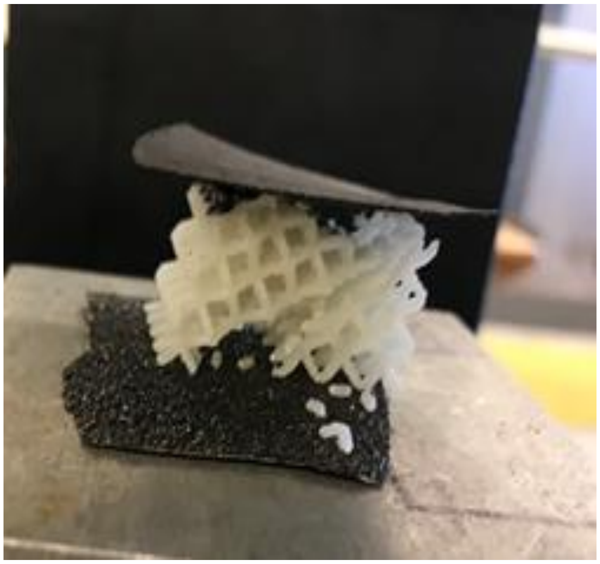


Figure 7.1 Solid 0.013 45° opposite

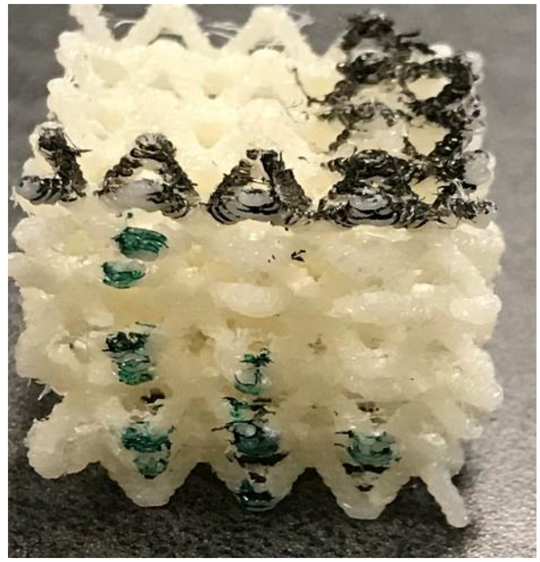


Figure 7.2 Sparse high 0.013 0°

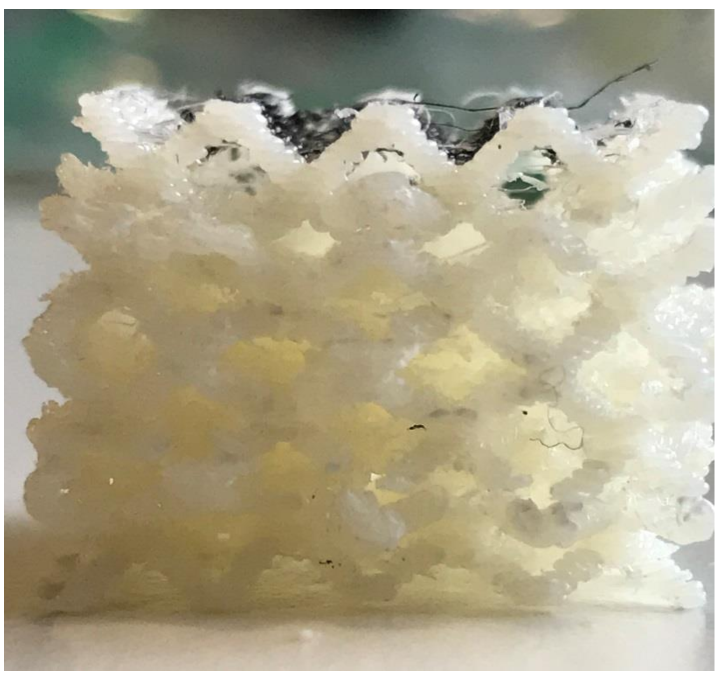


Figure 7.3 Solid 0.013 90°

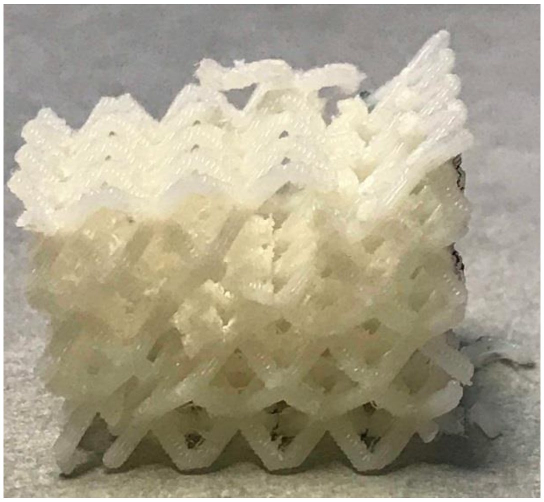


Figure 7.4 Solid 0.010 45° face

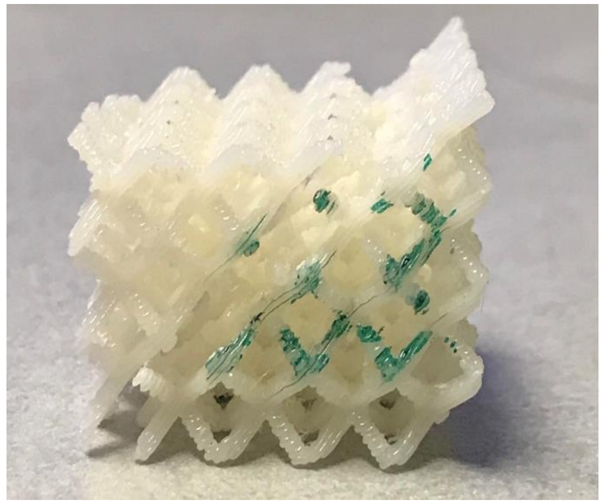


Figure 7.5 Sparse 0.013 45

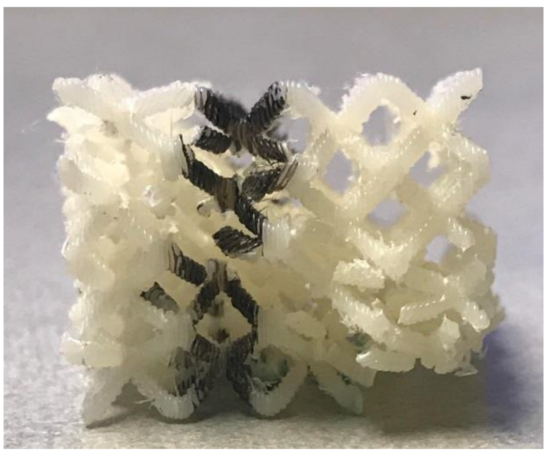


Figure 7.6 sparse 0.010 90°

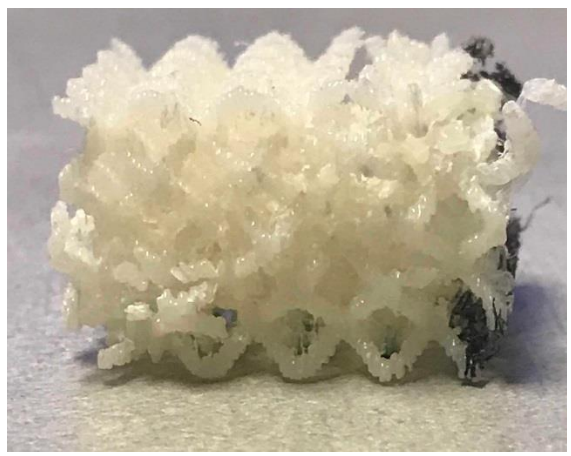


Figure 7.7 Sparse 0.013 90°

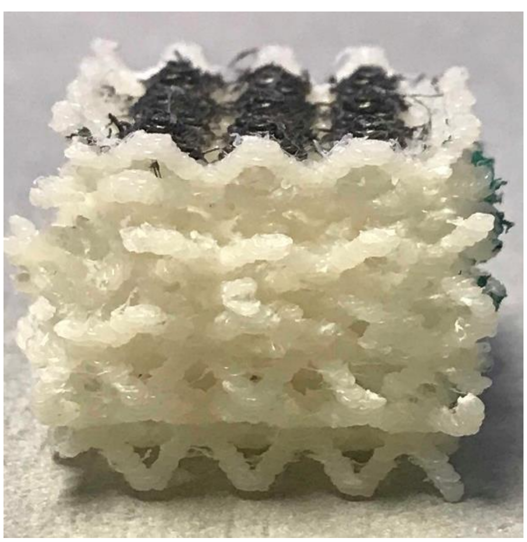


Figure 7.8 Solid 0.013 0°

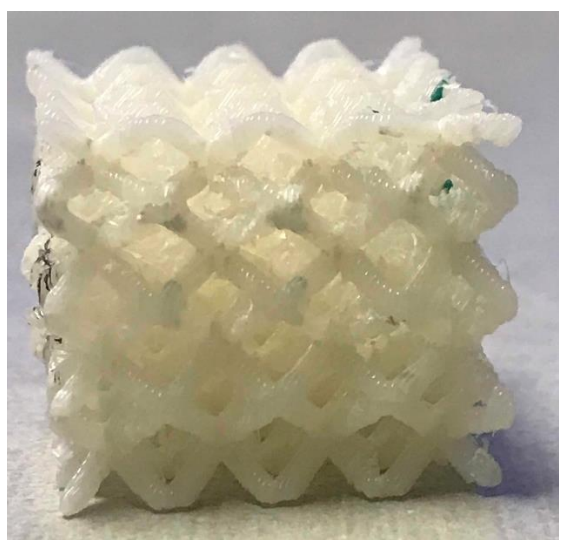


Figure 7.9 Solid 0.010 45° opposite

Failed Specimens in Tensile Test.

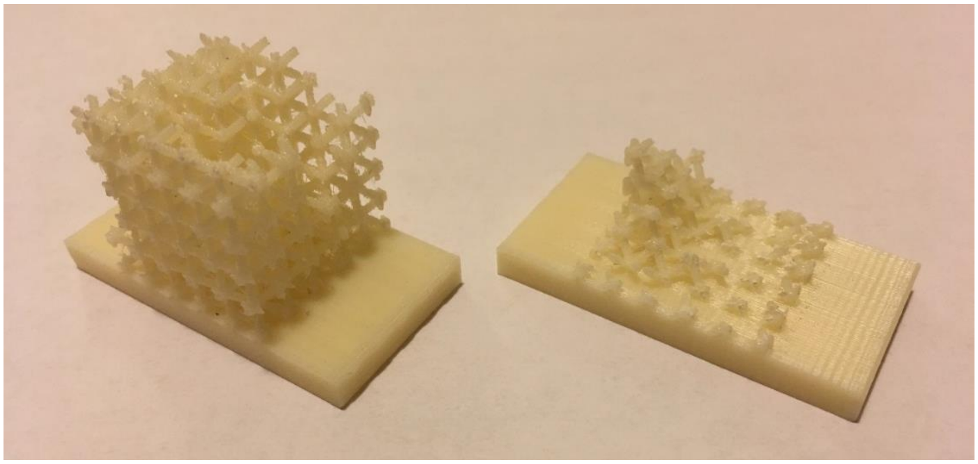


Figure 7.10: sparse high 0.010 0°

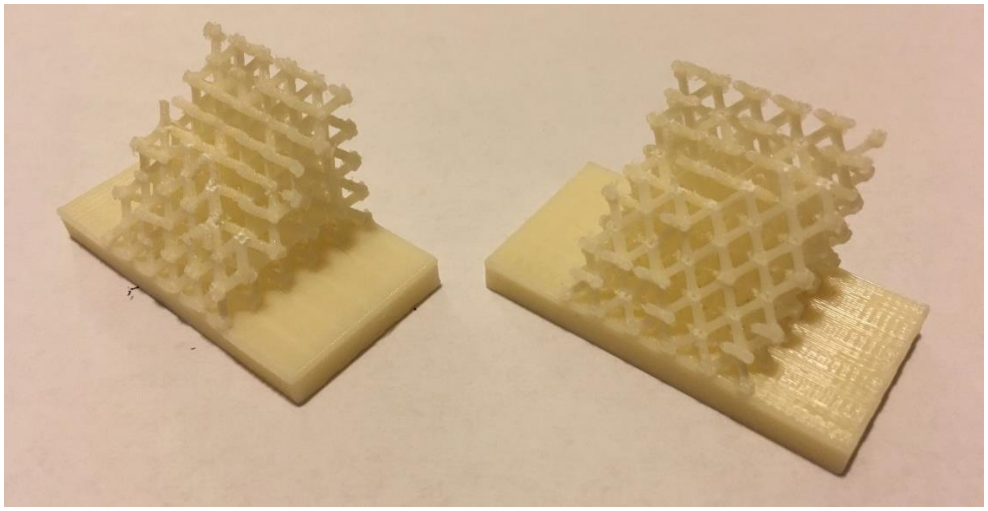


Figure 7.11: Sparse high 0.010 45°

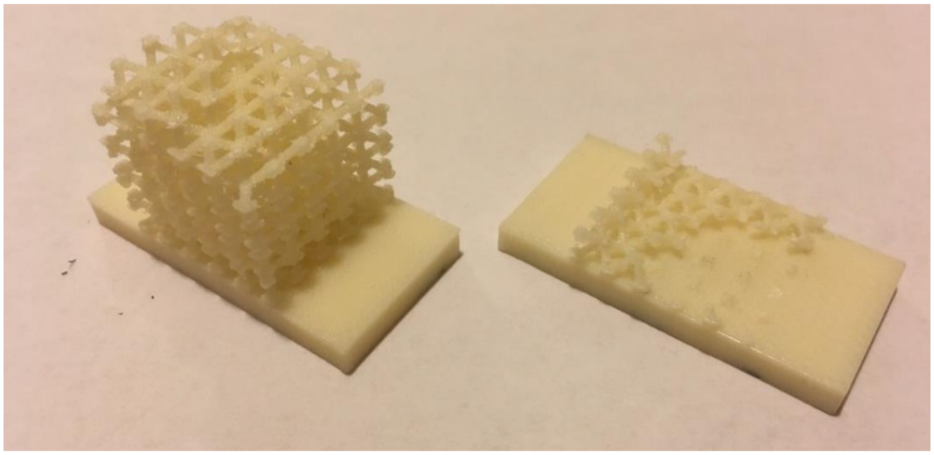


Figure 7.12: Sparse high 0.010 90°

CHAPTER 8: CONCLUSION

8.1 Summary

3D printed polymer lattice structure has been investigated under compression and tensile tests. Experimental methods were carried out in this research and comparison is done between all experimental configurations only.

The comparison between all 16 configurations of Compression and 12 configurations of tensile was done mainly based on absorption energy. Each configuration has 3 specimens to consider uncertainty but there are couple of configurations in tensile test which has only one specimen. The difference between all the specimens is layer thickness the dangle of printing and the infill density. Solid works is used to print a BCC structure and Stratasys printer is used to print the specimens.

The specimens were applied under compression test using INSTRON universal testing machine which had a software to convert all the data into excel worksheet. Load Displacement curve and Stress strain curve were plotted using excel sheet. For tension test a special fixture is created and specimens are crated according to the fixture and all the tensile test are done under INSTRON universal testing machine. To calculate absorbed energy the area under the load displacement curve is calculated.

8.2 Conclusions

The results were observed and compared based on Specific Energy Absorption (SEA). In compression results the highest SEA was there for Sparse 0.013 45° opposite and Solid 0.013 45° opposite configurations and they are collapsed after first failure right away. Solid 0.010 90°configuration has highest value after 45° configuration. All 45° configurations are completely failed for one collapse only whereas 0° and 90° configurations have progressive failures. These lattice structures can be optimized further to absorb more energy due to flexibility of AM. The stiffness doesn’t improve the energy absorption capability.

Tensile Specimens were also compared using SEA. It is showing that only one configuration stood out Sparse high 0.010 0° configuration. All the other configurations are failed and have low values.

The main parameter to be considered is infill density and thickness coming to any configuration. It would not be considered if the results came in a different way.

Coming to the infill density sparse high density which is not complete a solid consumes less material and takes less time to print. It is observed while printing the specimens. Since the sparse and solid didn't show much variation in the behaviors it's better to consider sparse high density taking time and amount of material into consideration.

8.3 Recommendations for Future Work

There are many recommendations for future work, but there are some important ones too like, the specimens design can be changed to check the energy absorption behavior. It might change the values and the failures may happen in different locations of unit cell. Impact test and shear test can be even done in these configurations to compare with these results. Finite element analysis (FEA) can be done to compare the results. Material can also be changed and tests can be done.

References

[1] M. J. Rezvani and A. Jahan, "Effect of initiator, design, and material on crashworthiness performance of thin-walled cylindrical tubes: A primary multi-criteria analysis in lightweight design," *Thin-Walled Struct.*, vol. 96, pp. 169–182, 2015.

[2] G. C. Jacob, J. F. Fellers, and J. M. Starbuck, "Energy Absorption in Polymer Composite Materials for Automotive Crashworthiness," *J. Compos. Mater.*, vol. 36, no. 7, pp. 813–850, 2002.

[3] T. Tancogne-Dejean, A. B. Spierings, and D. Mohr, "Additively-manufactured metallic micro-lattice materials for high specific energy absorption under static and 82 dynamic loading," *Acta Mater.*, vol. 116, pp. 14–28, 2016.

[4] M. S. Zahran, P. Xue, M. S. Esa, M. M. Abdelwahab, and G. Lu, "A new configuration of circular stepped tubes reinforced with external stiffeners to improve energy absorption characteristics under axial impact," *Lat. Am. J. Solids Struct.*, vol. 14, no. 2, pp. 292–311, 2017

[5] Frida Johansson,"Mechanical properties of trabecular structures produced by SLM, as a function of the trabecular morphology".

[6] Olaf Andersen ,Matej Vesenjak, Thomas Fiedler , Ulrike Jehring and Lovre Krstulović-Opara "Experimental and Numerical Evaluation of the Mechanical Behavior of Strongly Anisotropic Light-Weight Metallic Fiber Structures under Static and Dynamic Compressive Loading"

[7] Ahmed A. D. Sarhan, Chong Feng Duan, "Investigate the Effects of Geometrical Structure and Layer Orientation on Strength of Rapid Prototyped Specimens",

[8] R Umer, Z Barsoum, HZ Jishi,"Analysis of the compression behaviour of different composite lattice designs"

[9] N A Endut1, M H F Al Hazza1, A A Sidek, E T Y Adesta1, N A Ibrahim1 "Compressive Behaviour and Energy Absorption of Aluminium Foam Sandwich"

[10] ThomasTancogne-Dejean [b]Adriaan B.Spierings [c]DirkMohr" Additively-manufactured metallic micro-lattice materials for high specific energy absorption under static and dynamic loading"

[11] ChunzeYan[a] LiangHao[a] DavidRaymont[b] "Evaluations of cellular lattice structures manufactured using selective laser melting"

[12] ChunzeYan[a] LiangHao[a] DavidRaymont[b] "Evaluation of light-weight AlSi10Mg periodic cellular lattice structures fabricated via direct metal laser sintering"

[13] Compression behavior of three-dimensional printed polymer lattice structures Mohammed Al Rifaie, Ahsan Mian and Raghavan Srinivasan

[14] Low-Velocity Impact Behavior of Sandwich Structures with Additively Manufactured Polymer Lattice Cores Andrew J. Turner, Mohammed Al Rifaie, Ahsan Mian & Raghavan Srinivasan

[15] Stratasys, "uPrint SE Plus," 2017. [Online]. Available: http://www.stratasys.com/3d-printers/uprint-se-plus. [Accessed: February 21, 2018].

[16] Stratasys, http://www.stratasys.com/materials/search/absplus. [Accessed: February 21, 2018]

[17] N. Vidakis, M. Petousis, A. Vairis, K. Savvakis, and A. Maniadi, "On the compressive behavior of an FDM Steward Platform part," Journal of Computational Design and Engineering, vol. 4, no. 4, pp. 339-346, October 2017.

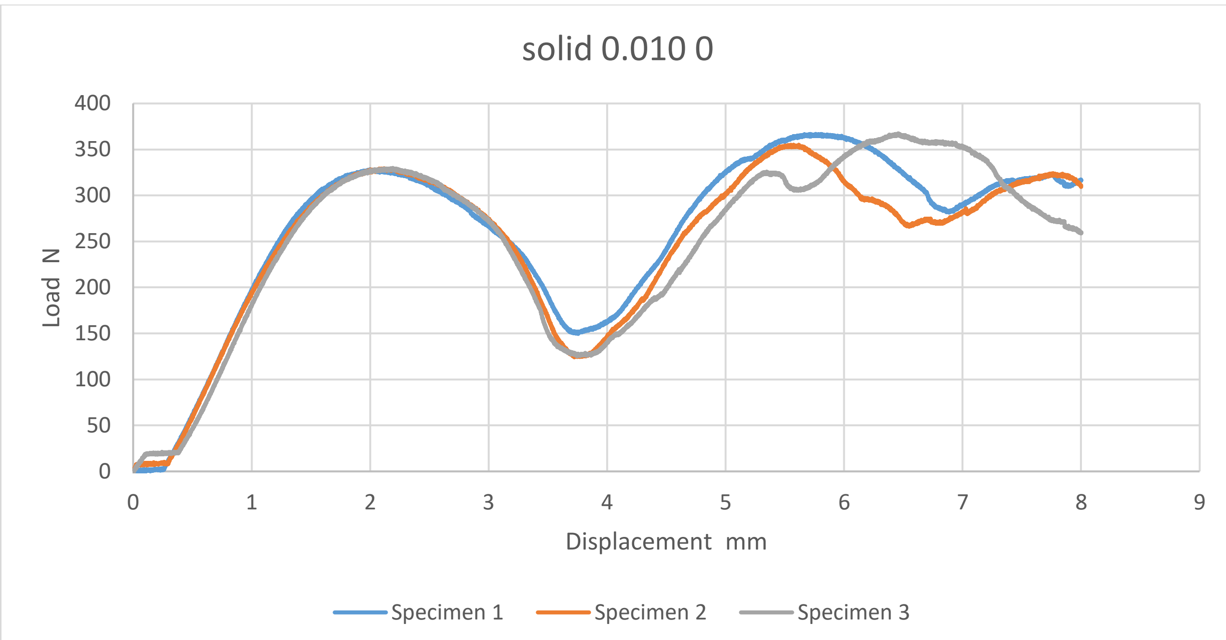
[18] P.F. Egan, V.C. Gonella, M. Engensperger, S.J. Ferguson, K. Shea, 2017, "Computationally designed lattices with tuned properties for tissue engineering using 3D printing," PLoS ONE 12(8): e0182902 https://doi.org/10.1371/journal.pone.0182902

Appendix

Experimental Results of each configuration for Compression Test

BCC printed with layer thickness 0.010, infill density solid and at an angle of 0° (Solid 0.010 0°)

Figure shows the Load Displacement curve for the specimens. Three specimens were plotted in one graph to shows the effect of uncertainty. Results are same till the start of first failure for all specimens. When the failure started the behavior still remained same until start of second failure.

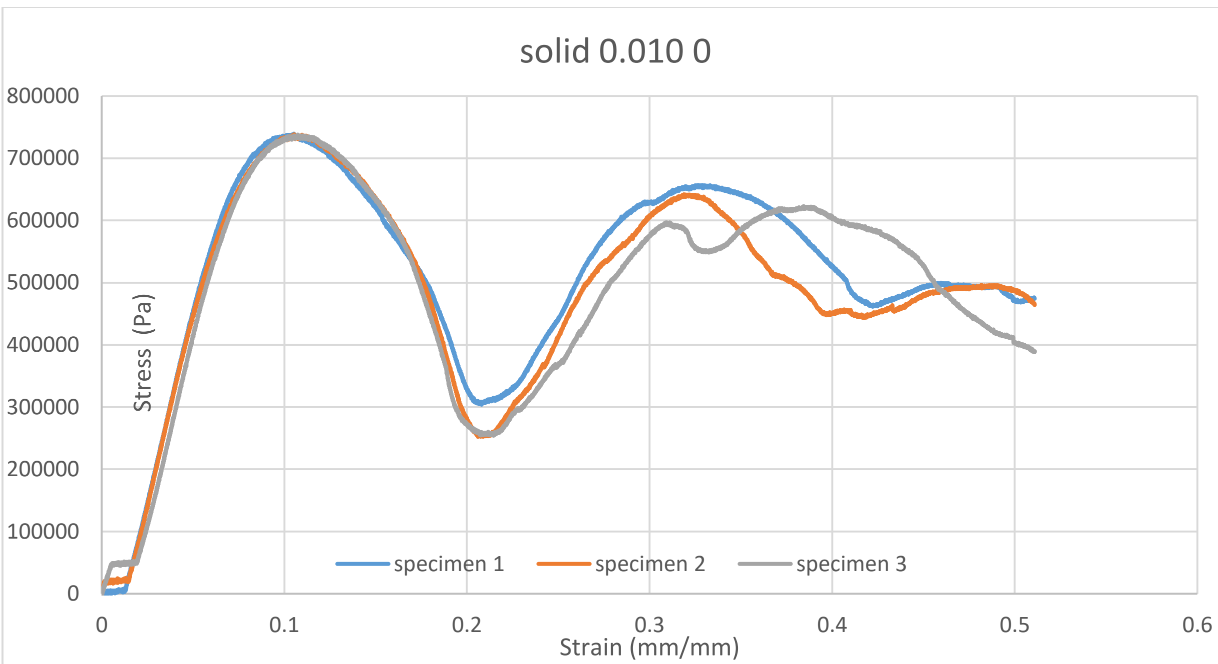


Load Displacement curve of Solid 0.010 0° configuration

Specimens have same behavior up to second failure. The first failure started at approximately 2mm and ended at about 3.6mm. Second failure started at 5.3mm approximately. By the end of the test the load again increases and doesn't stop because there are no more layers to collapse. The maximum load was almost about 325N. These specimens had an average weight of 1.72 grams. SEA for specimens 1, 2 and 3 till the start of first failure are 212.99 J/Kg, 214.01 J/Kg and 206.94 J/Kg.

The average SEA for this configuration is 211.31 J/Kg till the start of first failure. The stiffness for all the specimens is 202.94 N/mm, 197.33 N/mm and 189.15 N/mm for the specimens 1, 2 and 3 till start of first failure. The average Stiffness is 196.47 N/mm till the start of first failure.

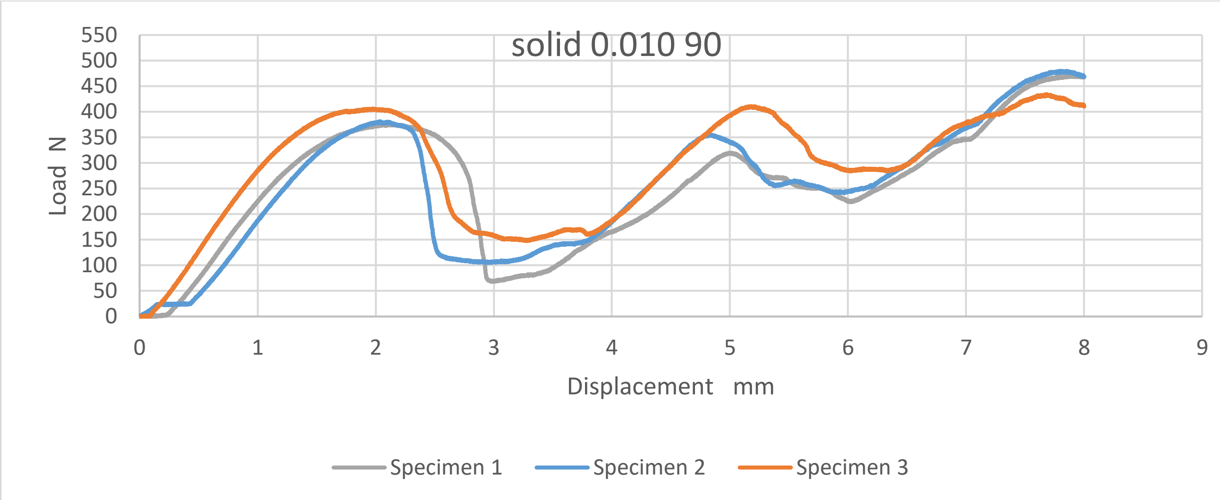
Figure shows the Stress Strain graph for this configuration. The Peak load i.e. the ultimate strength for specimens 1, 2 and 3 are 734.430 Kpa, 731.189 Kpa and 731.112 Kpa. The Modulus of Elasticity is 9213.37Kpa, 9006.2 Kpa and 8705.8 Kpa. All the values above are till start of first failure only. The average peak load for this configuration is 732.81 Kpa.



Stress Strain curve of Solid 0.010 0° configuration

BCC printed with layer thickness 0.010, infill density solid and at an angle of 90° (Solid 0.010 90°)

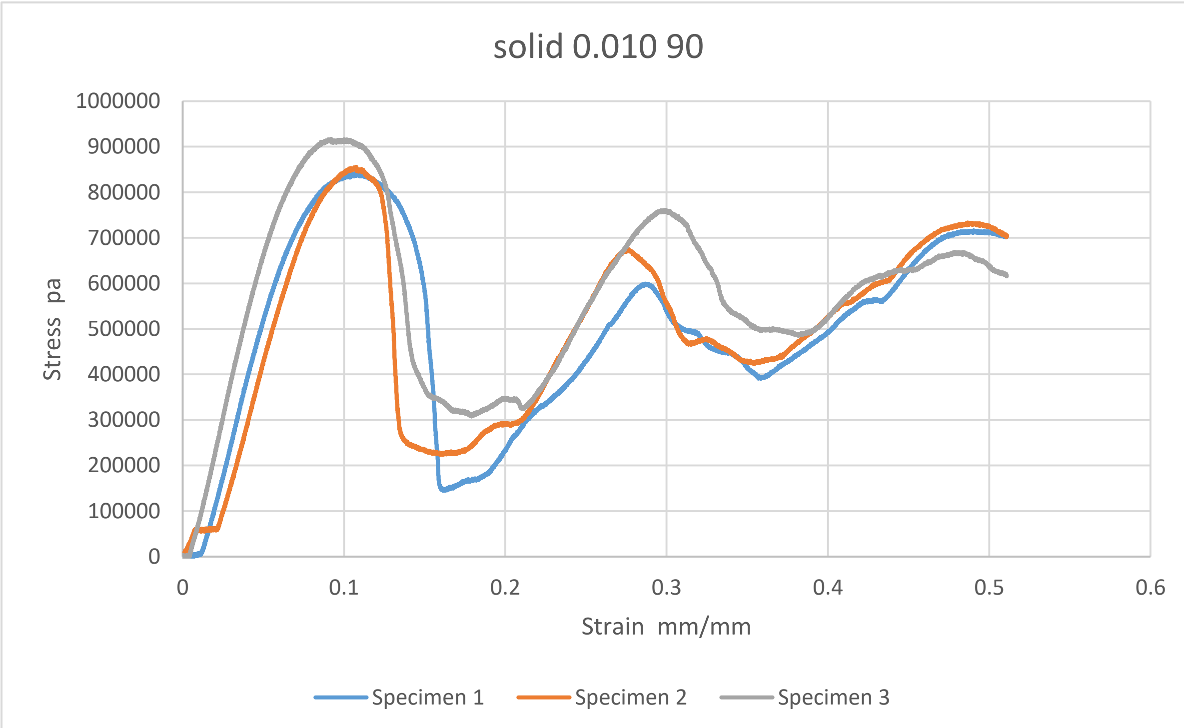
Figure shows the Load displacement curve for the specimens. Three specimens were plotted in one graph to show the uncertainty.



Load Displacement curve of Solid 0.010 90° configuration

Results are same till the start of first failure for all specimens. When the failure started the behavior varied from specimen to specimen. The first failure started at approximately 2.05 mm and ended between 2.5mm - 3.2 mm. Second failure started at 5.12mm approximately for all the specimens. By the end of the test the load again increases and doesn't stop because there are no more layers to collapse. The maximum load is around 380N on average for the 3 specimens. Specimens had average weight around 1.7 grams similar to that of the previous Solid 0.010 0° configuration. SEA for the specimens 1, 2 and 3 are 255.30 J/kg, 246.71 J/Kg and 289.81 J/Kg till the start of first failure. The stiffness values for the specimens are 229.1072 N/mm, 241.332 N/mm and 284.70 N/mm till the start of first failure. The average stiffness is 241.33 N/mm till the start of first failure.

Figure shows the Stress Strain Curve for this configuration. The peak load for the specimens 1, 2 and 3 are 836.925 Kpa, 846.534 Kpa and 911.32 Kpa

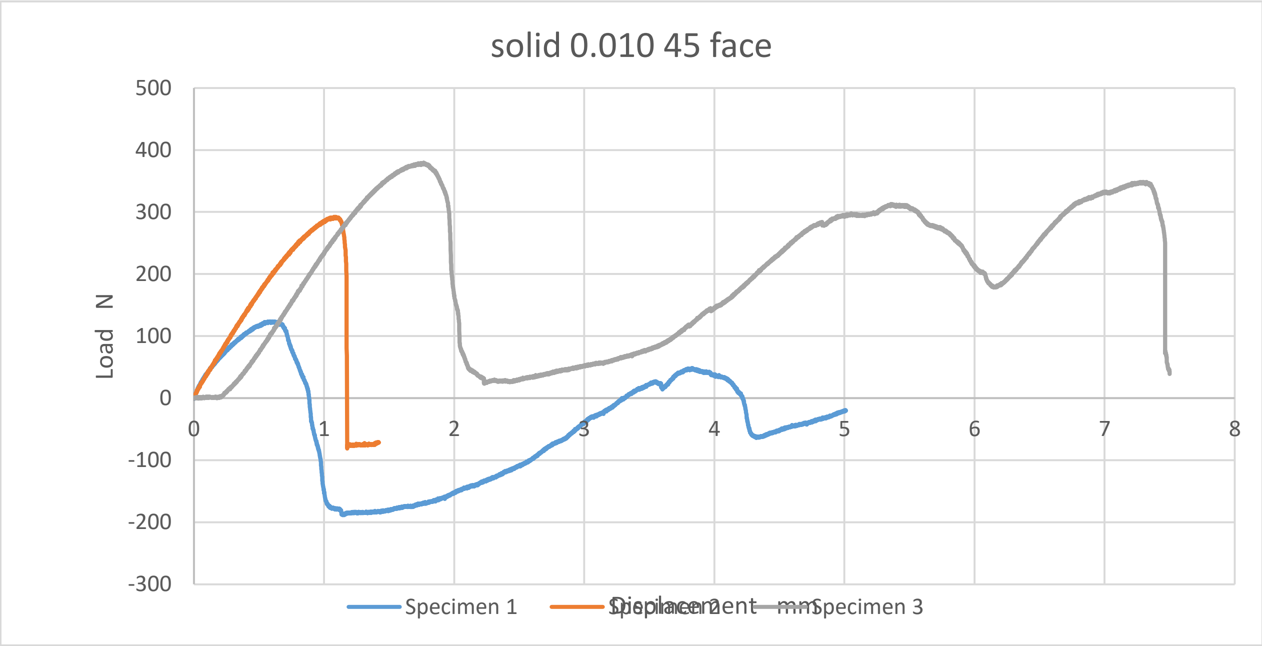


Stress Strain Curve of Solid 0.010 90° configuration

The average peak load is 864.927 Kpa. The modulus of elasticity is 104523 Kpa, 9426.6 Kpa and 13224.778 Kpa till start of first failure.

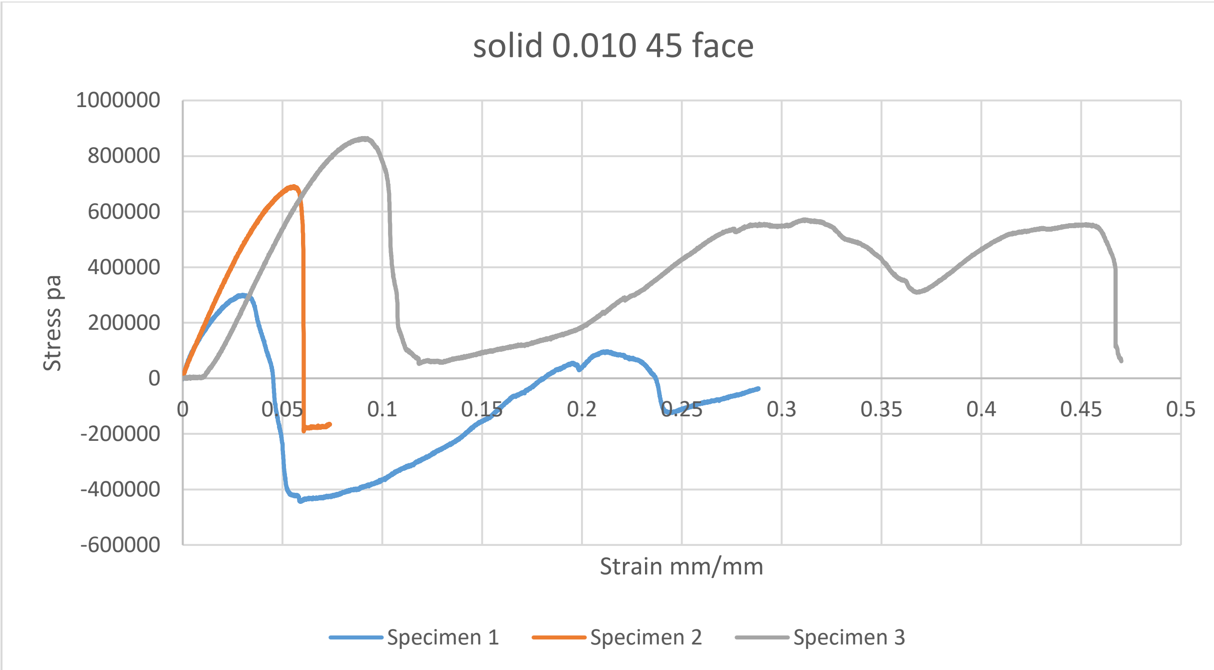
BCC printed with layer thickness 0.010, infill density solid and at an angle of 45° (Solid 0.010 45° face)

Figure shows Load Displacement curve for the specimens. Three specimens were plotted in one graph to show the uncertainty. The first failure started at approximately 0.61 mm for specimen 1 and ended at 1.7mm for specimen 3. After the first failure Both Specimens 1 & 2 failed and Specimen 3 still went up after the collapse of first failure and second failure started at 5.57 mm.



Load Displacement curve of Solid 0.010 45° face configuration

The average weight of the Specimens are 1.81 grams where it has a max load of 371N. Specimen 1& Specimen 2 failed so early when compared to Specimen 3. So, the results are good for the Specimen 3 as expected. But when we see the time lapse videos of the Test for all three specimens the Specimen 1 & Specimen 2 failed at angle of printing 45°. So, it might be an indication to show specimen 3 is failed. Seeing the max load, it can be thought as these Specimens are Brittle. The SEA of the specimens are 30 J/Kg, 108.47 J/Kg and 196.28 J/Kg. The stiffness is found to be 304.45 N/mm, 320.58 N/mm and 241.87 N/mm till the start of first failure. The Average stiffness is 288.97 N/mm.

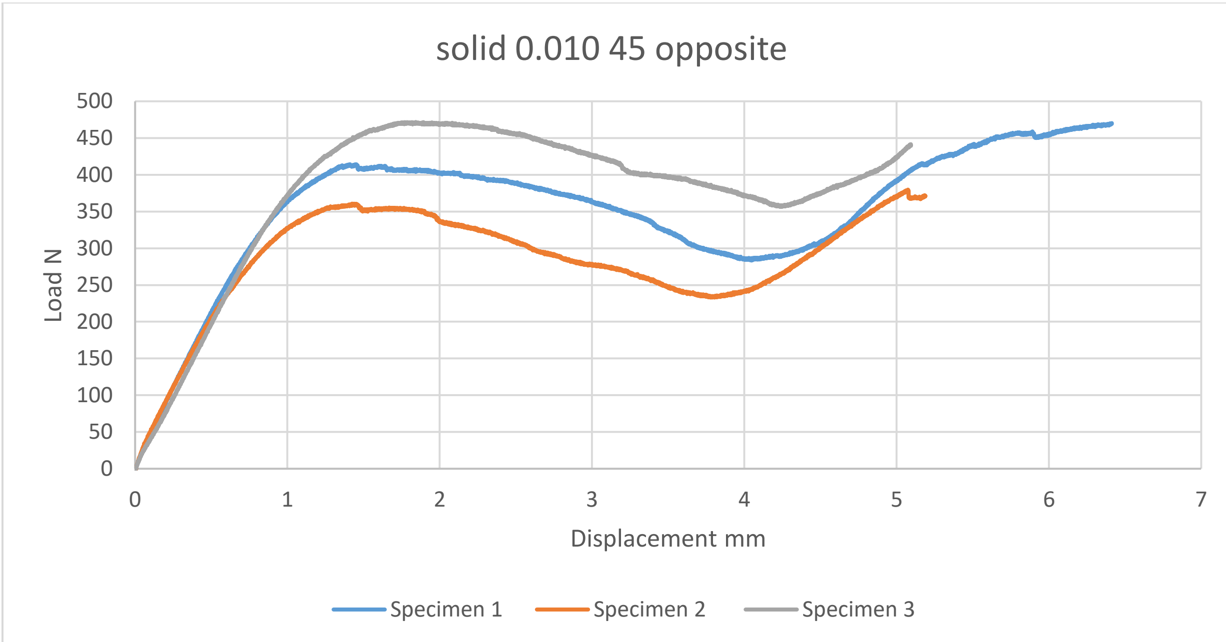


Stress Strain curve of solid 0.010 45° face configuration

Figure shows the stress strain curve of solid 0.010 45° face configuration. The peak load for the specimens is 294.28 Kpa, 687.15 Kpa and 858.75 Kpa till the start of first failure. The Modulus of elasticity is 13350.621 Kpa, 16090.554 Kpa and 10922.606Kpa.

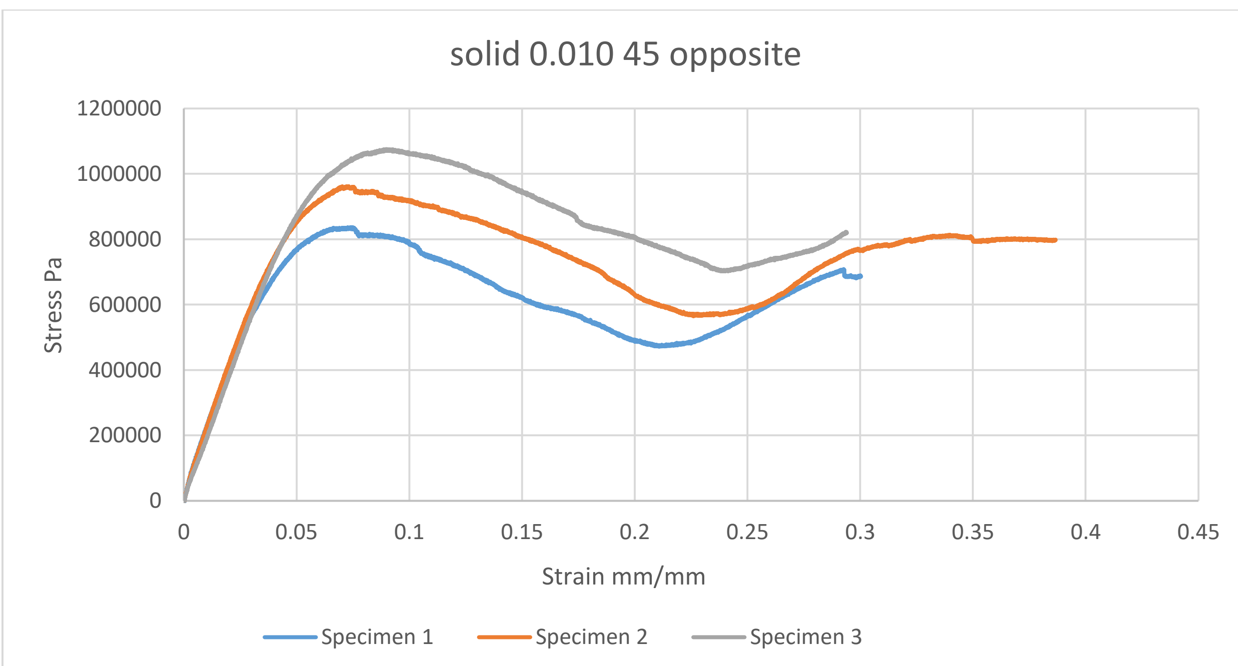
BCC printed with layer thickness 0.010, infill density solid and at an angle of 45° (Solid 0.010 45° opposite)

Figure shows Load displacement curve for the specimens; Three Specimens were plotted in one graph to show the uncertainty. The average weight of these specimens are 1.81 grams. First failure started at approximately 1.28 mm for every specimen and all 3 specimens continued in the same pattern till the end of first failure between 3.8mm and 4.2 mm. By the time second failure is occurred the layer is collapsed at an angle of 45°. SEA for the specimens are found to be 212.92 J/Kg, 198.87 J/Kg and 431.62 J/Kg till the start of first failure. The average SEA till start of first failure of the specimens is 234.18 J/Kg.



Load Displacement curve for Solid 0.014 45 opp configuration.

The stiffness values of the specimens are 401.13 N/mm, 387.96 N/mm and 375.91 N/mm till the start of first failure. These specimens have more peak loads compared to other configuration of 45° with same build parameters.

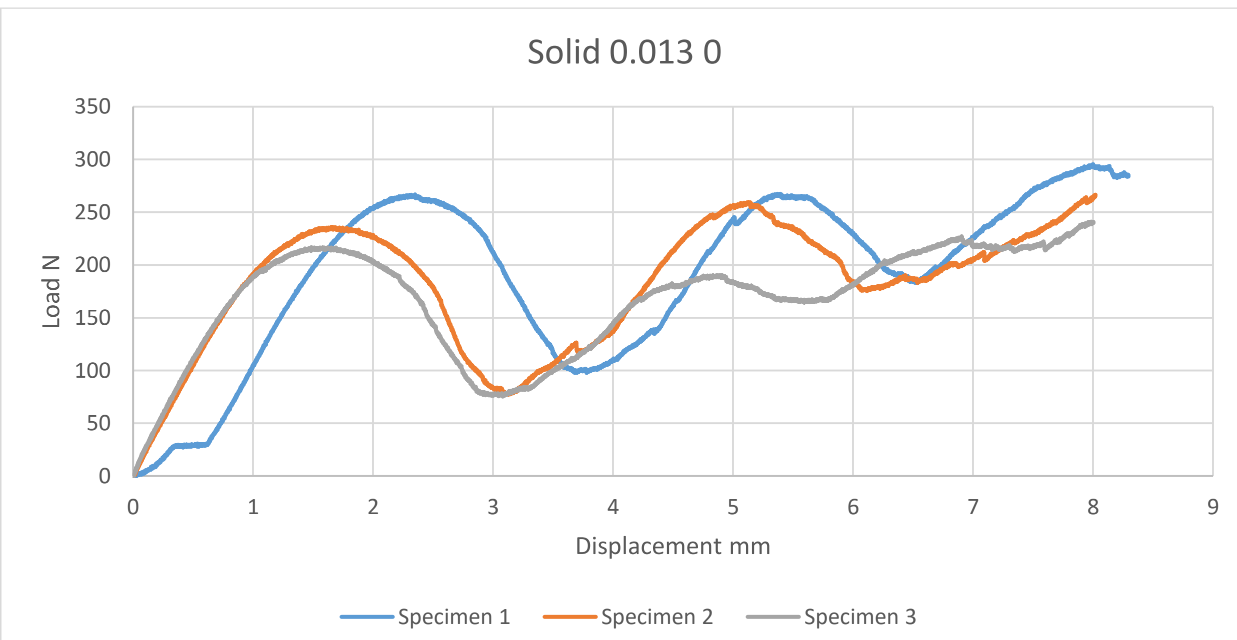


Stress Strain curve for solid 0.010 45° opposite configuration

Figure 6.8 shows Stress strain graph of same configuration. The ultimate strength is found to be 829.36 Kpa, 948.66Kpa and 1067. 96Kpa.The average is found to be 948.66 Kpa. The Young's modulus till the start of first layer for three specimens are 2414.99 Kpa, 18683.45 Kpa and 17546.9 Kpa till the start of first failure. With the same build parameters i.e. solid 0.010 taking all angle orientations into consideration the configuration Solid 0.010 45° opposite has highest values.

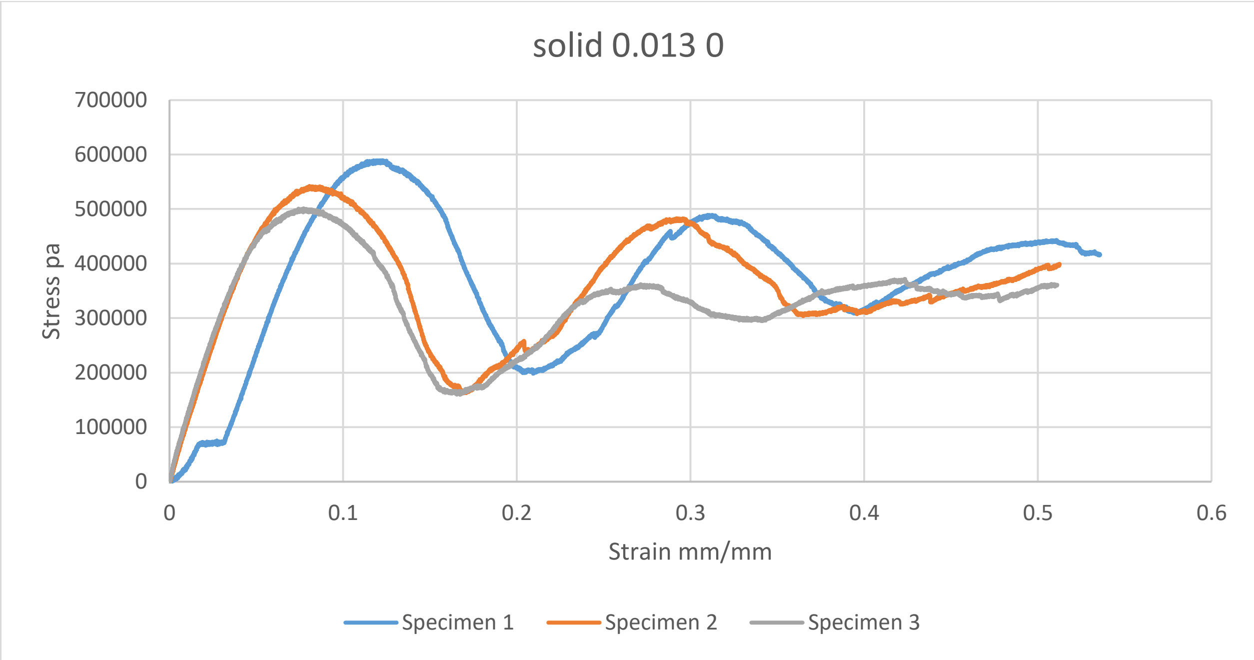
BCC printed with layer thickness 0.013, infill density solid and at an angle of 0° (Solid 0.013 0°)

Figure shows Load displacement curve for the specimens, Three Specimens were plotted in one graph to show the uncertainty. The average weight of these specimens are 1.67 grams. First failure started between1.48mm and 2.3mm. After first failure between 3.04 mm and 3.7 mm the load is still applied and continued till second failure. SEA for the specimens are found to be 169.75 J/Kg, 151.60 J/Kg and 145.24 J/Kg till the start of first failure. The average SEA till start of first failure of the specimens is 155.53 J/Kg. The stiffness values are found to be 132.62 N/mm, 198.43 N/mm and 201.15 N/mm till the start of first failure. The average stiffness till the end of first failure is 177.4 N/mm.



Load displacement curve for solid 0.013 0° configuration.

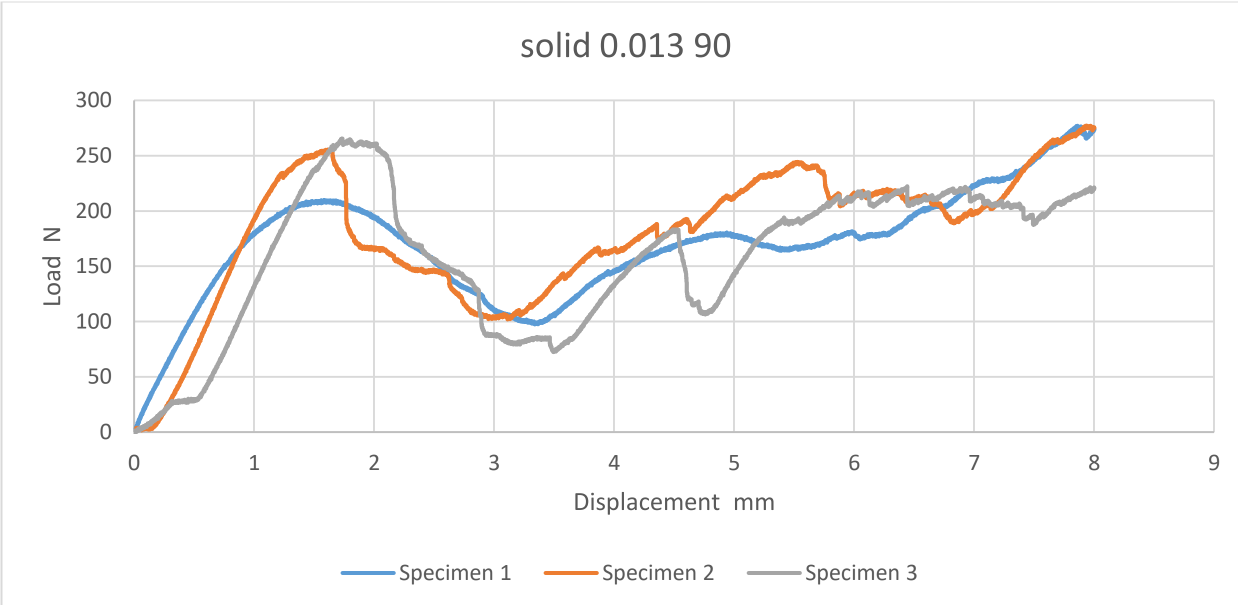
Figure describes the stress strain curve for solid 0.013 0° configuration. The peak loads or ultimate tensile strength of the three specimens are 581.68 Kpa, 533.9 Kpa and 490.14 Kpa till the start of first failure. The young's modulus values for all the 3 specimens are 5837.107 Kpa, 8831.46 Kpa and 9163.0 Kpa.



Stress Strain curve for solid 0.013 0° configuration

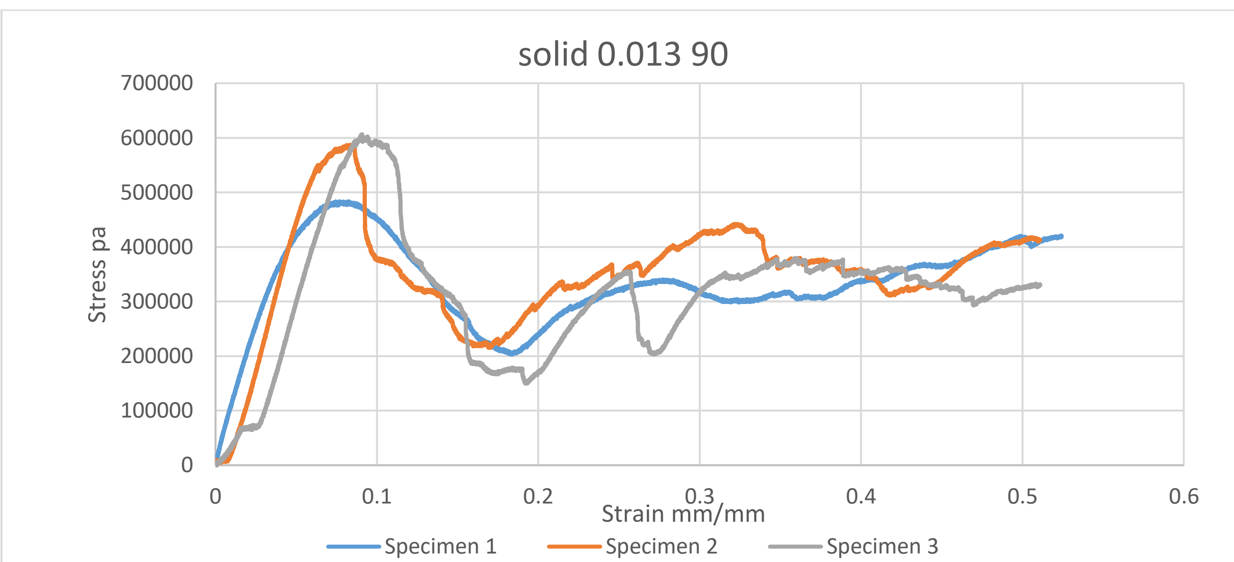
BCC printed with layer thickness 0.013, infill density solid and at an angle of 90° (Solid 0.013 90°)

Figure shows Load displacement curve for the specimens, Three Specimens were plotted in one graph to show the uncertainty. The average weight of these specimens are 1.67 grams. First failure started between1.3mm and 1.95mm. After first failure between 2.8 mm and 3.5 mm the load is still applied and continued till second failure. Specimen 2 and 3 showed same pattern throughout the test where specimen 1 is bit off compared to both of them. SEA for the specimens are found to be 112.11 J/Kg, 139.63 J/Kg and 137.27 J/Kg till the start of first failure. The average SEA till start of first failure of the specimens is 129.67 J/Kg. The stiffness values are found to be 191.74 N/mm, 192.34 N/mm and 157.30 N/mm till the start of first failure. The average stiffness till the end of first failure is 180.46 N/mm.



Load Displacement curve for solid 0.013 90° configuration.

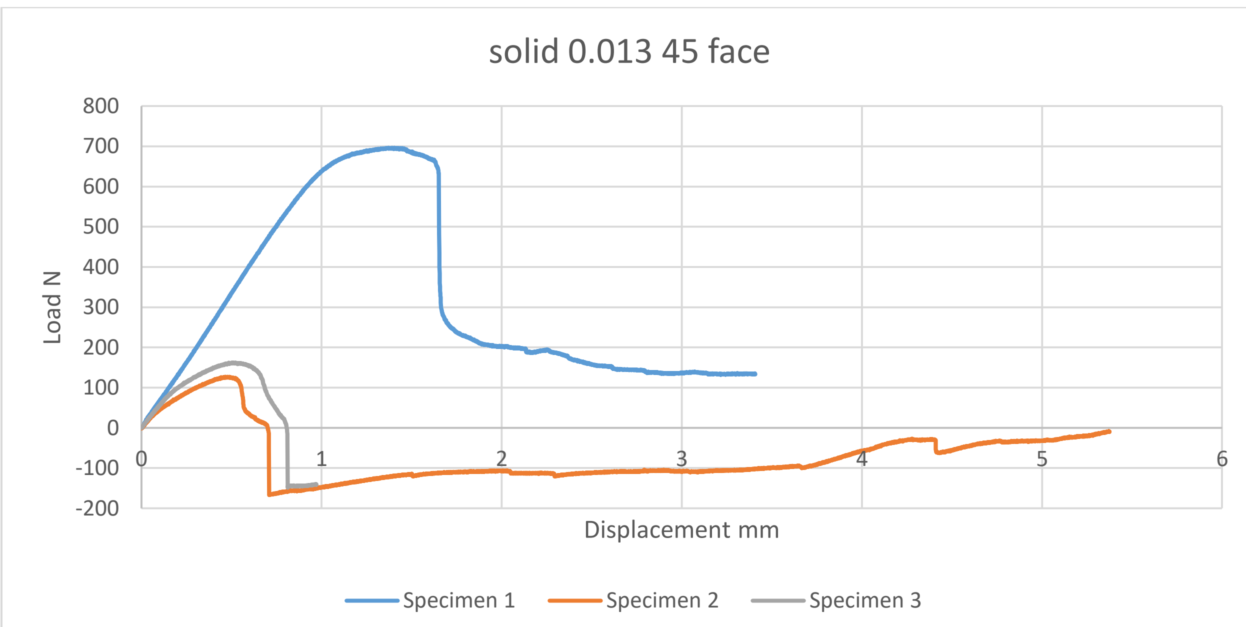
Figure describes Stress Strain curve of Solid 0.013 90° configuration. The Peak loads are 467.82 Kpa, 561.91 Kpa and 602.52 Kpa till the start of first failure. The Modulus of Elasticity values are 8995.61 Kpa, 8748.21 Kpa and 7044.9 Kpa till the start of first failure where the average is 8262.9 Kpa.



Stress Strain curve for solid 0.013 90° configuration

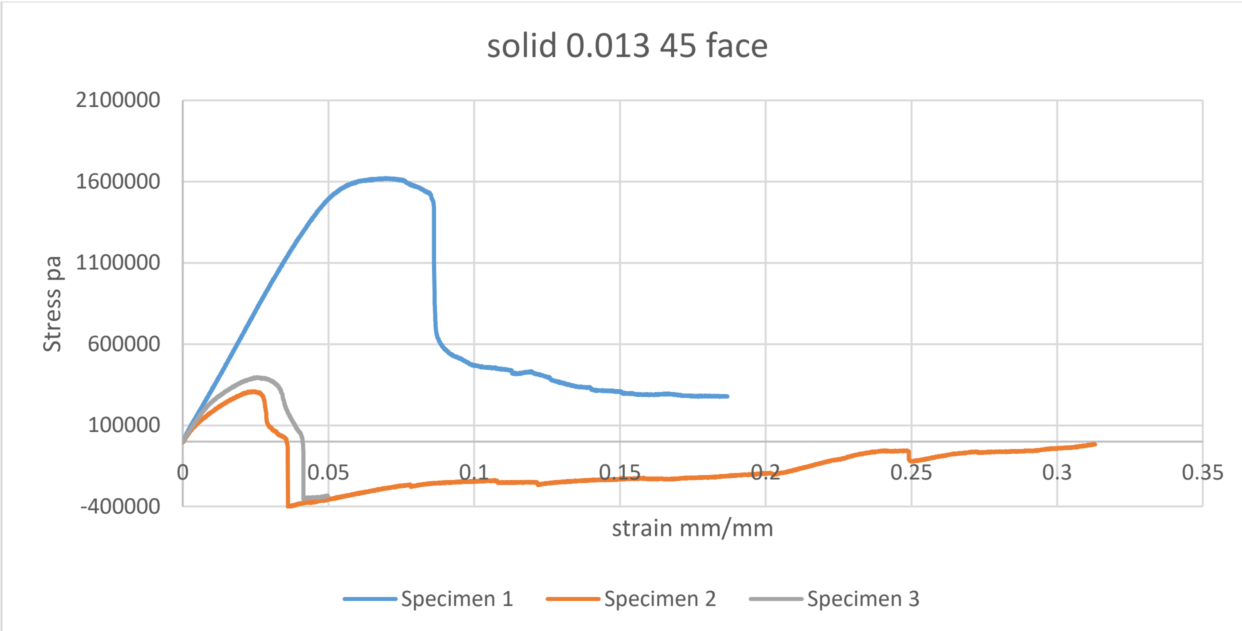
BCC printed with layer thickness 0.013, infill density solid and at an angle of 45° (Solid 0.013 45° face)

Figure shows Load displacement curve for the specimens, Three Specimens were plotted in one graph to show the uncertainty. The average weight of these specimens are 1.90 grams. First failure started between1.3mm and 1.95mm. After first failure between 0.54 mm and 1.37 mm the load is still applied and continued till second failure but the specimens collapsed there is no second failure. Specimen 2 and 3 showed same pattern throughout the test where specimen 1 is bit off compared to both of them. SEA for the specimens are found to be 343.28 J/Kg, 23.36 J/Kg and 29.92 J/Kg till the start of first failure. The average SEA till start of first failure of the specimens is 132.19 J/Kg. The stiffness values are found to be 662.73 N/mm, 390.46 N/mm and 528.55 N/mm till the start of first failure. The average stiffness till the end of first failure is 527.25 N/mm.



Load Displacement curve for solid 0.013 45° face configuration

Figure describes Stress Strain curve of Solid 0.013 45° face configuration. The Peak loads are 1615.27 Kpa, 298.82 Kpa and 390.95 Kpa till the start of first failure. The Modulus of Elasticity values are 30968.73 Kpa, 16758.42 Kpa and 26253.71Kpa till the start of first failure where the average is 24660.29 Kpa.

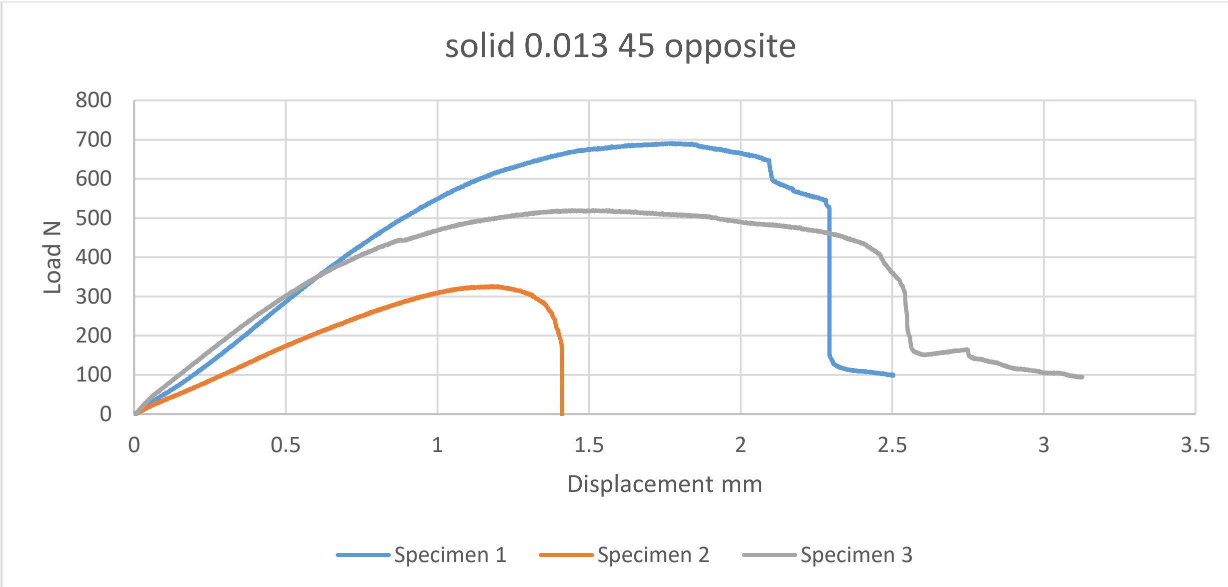


Stress Strain curve for solid 0.013 45° face configuration

Both Specimen 2 and Specimen 3 are showing same pattern and they are very brittle which shows their immediate collapse and these both specimens were collapsed exactly at 45° whereas specimen 3 collapsed in a different way. The same case is repeated as in Solid 0.010 45° face configuration.

BCC printed with layer thickness 0.013, infill density solid and at an angle of 45° (Solid 0.013 45° opposite)

Figure shows Load displacement curve for the specimens, Three Specimens were plotted in one graph to show the uncertainty. The average weight of these specimens are 1.90 grams. First failure started between1.3mm and 1.95mm. After first failure between 1.09 mm and 2.02 mm the load is still applied and specimens collapsed there is no second failure. Specimen 1 and 3 showed same pattern throughout the test where specimen 2 is bit off it collapsed earlier compared to both of them. SEA for the specimens are found to be 413.71 J/Kg, 116.61 J/Kg and 272.77 J/Kg till the start of first failure. The average SEA till start of first failure of the specimens is 267.705 J/Kg. The stiffness values are found to be 563.84 N/mm, 336.10 N/mm and 615.33 N/mm till the start of first failure. The average stiffness till the end of first failure is 505.096 N/mm.



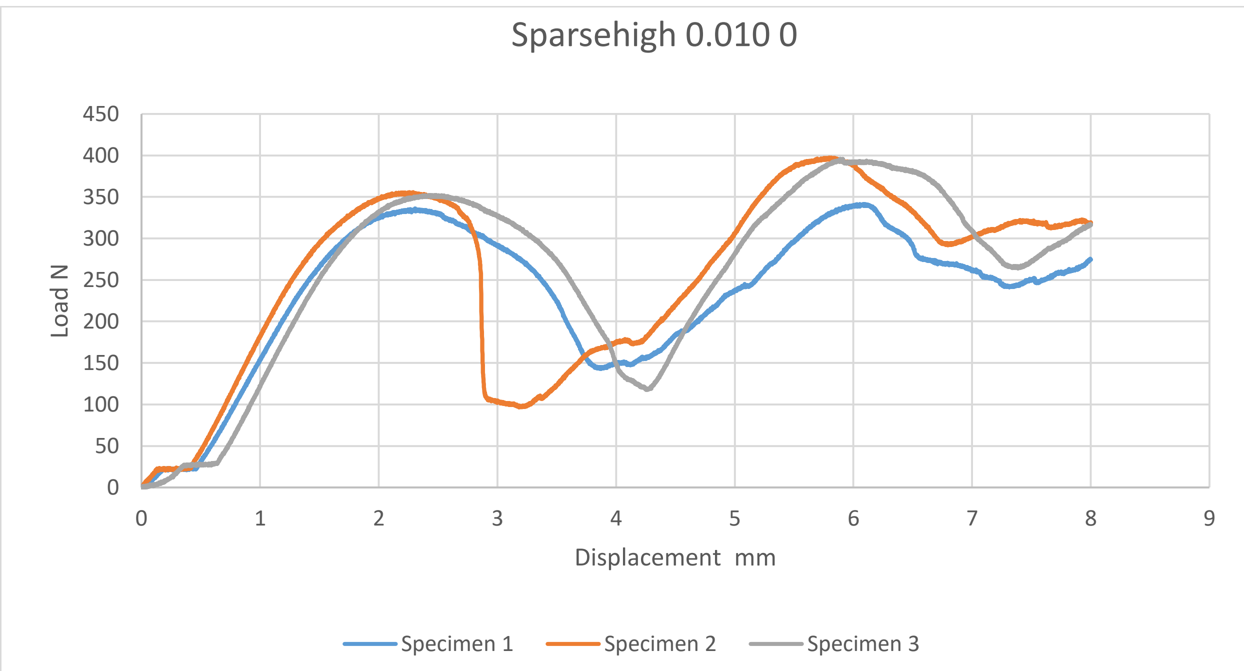
Load Displacement for Solid 0.013 45° opposite Configuration.

Figure describes Stress Strain curve of Solid 0.013 45° face configuration. The Peak loads are 1571.07 Kpa, 761.726 Kpa and 1200.63 Kpa till the start of first failure. The Modulus of Elasticity values are 27199.38 Kpa, 15762.74 Kpa and 27411.91Kpa till the start of first failure where the average is 23458.18 Kpa.

Stress Strain curve for Solid 0.013 45° opposite Configuration

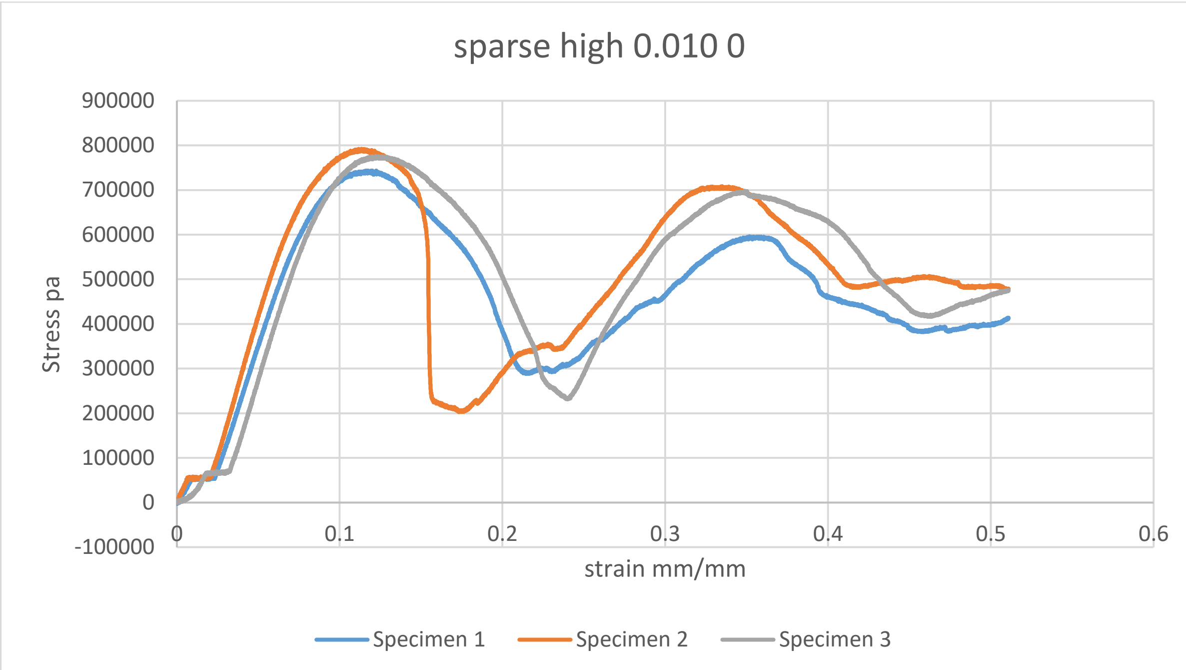
BCC printed with layer thickness 0.010, infill density Sparse high density and at an angle of 0° (Sparse high 0.010 0°)

Figure shows Load displacement curve for the specimens, Three Specimens were plotted in one graph to show the uncertainty. The average weight of these specimens are 1.72 grams. First failure started approximately around 2.07mm for every specimen. After first failure between 2.9 mm and 4.2 mm the load is still applied till second failure. Specimen 1 and 3 showed same pattern throughout the test where specimen 2 is bit off it collapsed earlier compared to both of them. SEA for the specimens are found to be 235.15 J/Kg, 267.88 J/Kg and 261.14 J/Kg till the start of first failure. The average SEA till start of first failure of the specimens is 254.72 J/Kg. The stiffness values are found to be 177.14 N/mm, 197.11 N/mm and 168.91 N/mm till the start of first failure. The average stiffness till the end of first failure is 181.04 N/mm.



Load Displacement for Sparse high 0.010 0° Configuration

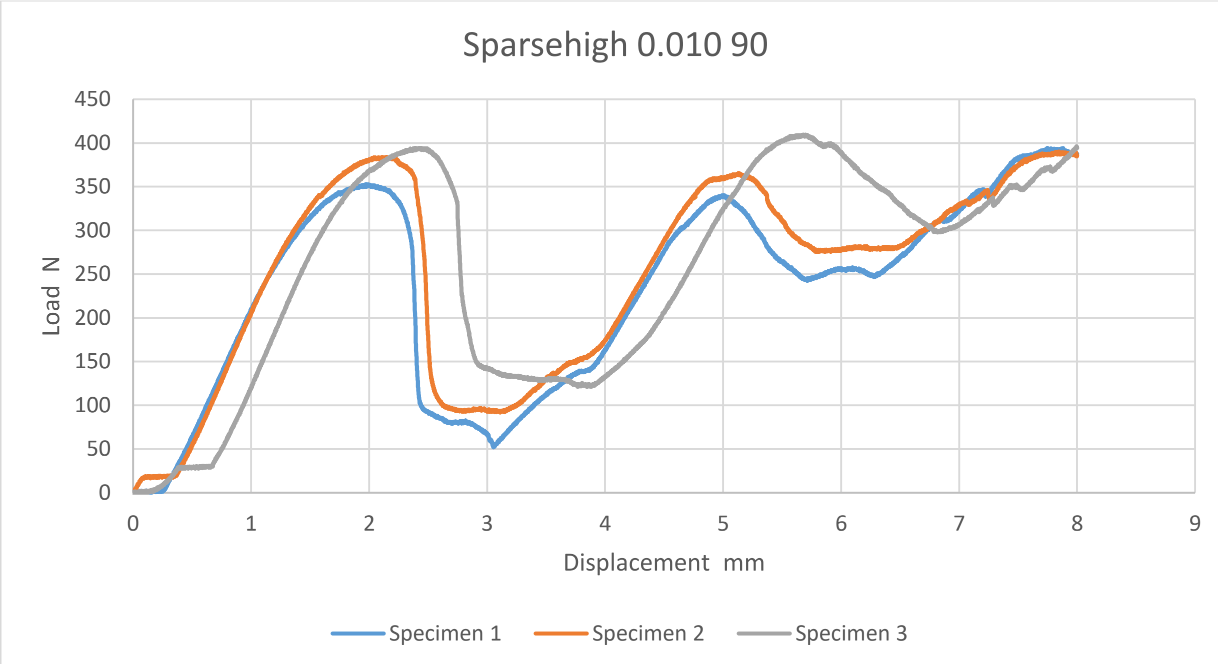
Figure describes Stress Strain curve of Sparse high 0.010 0° configuration. The Peak loads are 734.6 Kpa, 783.1 Kpa and 765.3 Kpa till the start of first failure. The Modulus of Elasticity values are 7883.77 Kpa, 8939.78 Kpa and 7506.18 Kpa till the start of first failure where the average is 8109.91 Kpa.



Stress Strain curve for Sparse high 0.010 0° Configuration

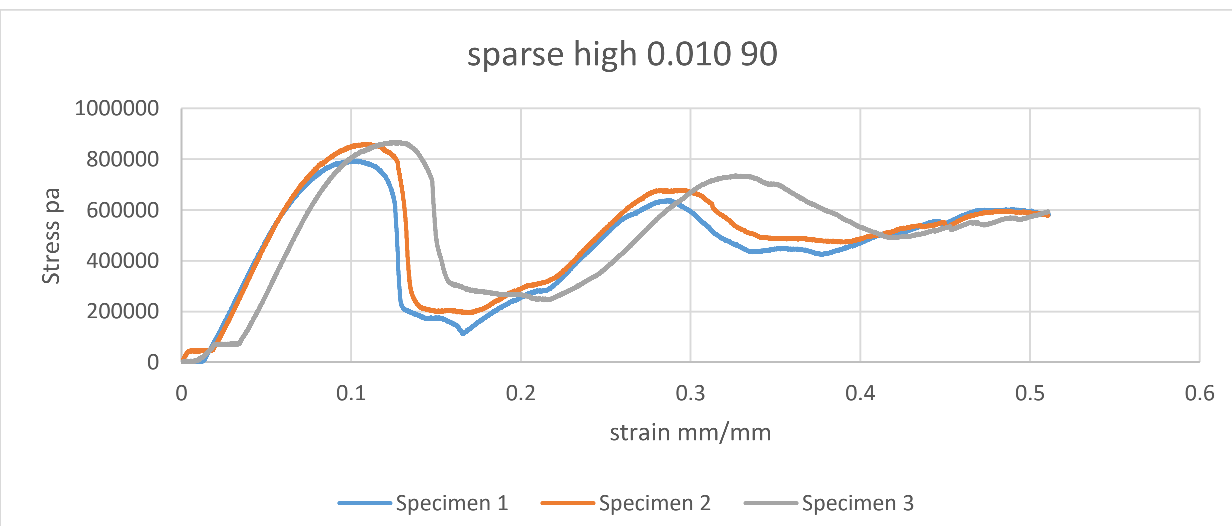
BCC printed with layer thickness 0.010, infill density Sparse high density and at an angle of 90° (Sparse high 0.010 90°)

Figure shows Load displacement curve for the specimens, Three Specimens were plotted in one graph to show the uncertainty. The average weight of these specimens are 1.72 grams. First failure started approximately between 1.66 mm and 2.44 mm for every specimen. After first failure between 2.5 mm and 3.9 mm the load is still applied till second failure. Almost all the specimen shows the same behavior. SEA for the specimens are found to be 222.13 J/Kg, 257.03 J/Kg and 284.64 J/Kg till the start of first failure. The average SEA till start of first failure of the specimens is 254.60 J/Kg. The stiffness values are found to be 215.61 N/mm, 219.27 N/mm and 185.16 N/mm till the start of first failure. The average stiffness till the end of first failure is 206.68 N/mm.



Load Displacement curve for sparse high 0.010 90° configuration.

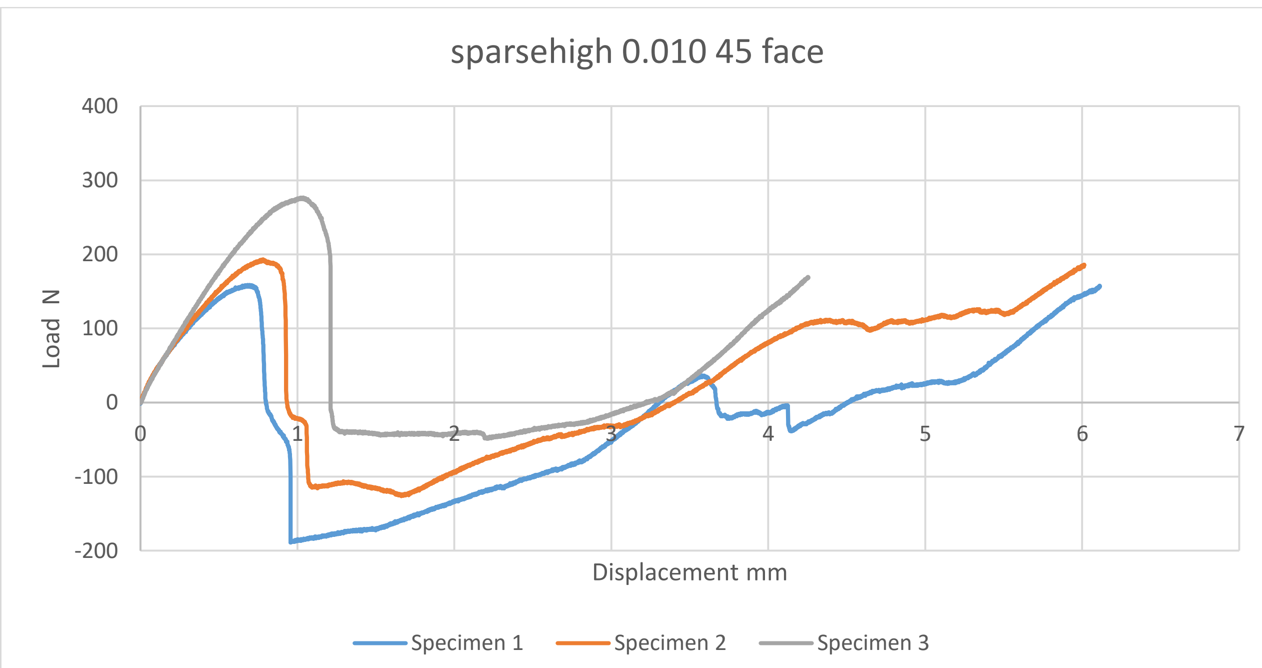
Figure describes Stress Strain curve of sparse high 0.010 90° configuration. The Peak loads are 787.94 Kpa, 851.22 Kpa and 857.33 Kpa till the start of first failure. The Modulus of Elasticity values are 9754.36 Kpa, 9991.19 Kpa and 8238.89 Kpa till the start of first failure where the average is 9872.777 Kpa



Stress Strain curve for sparse high 0.010 90° Configuration

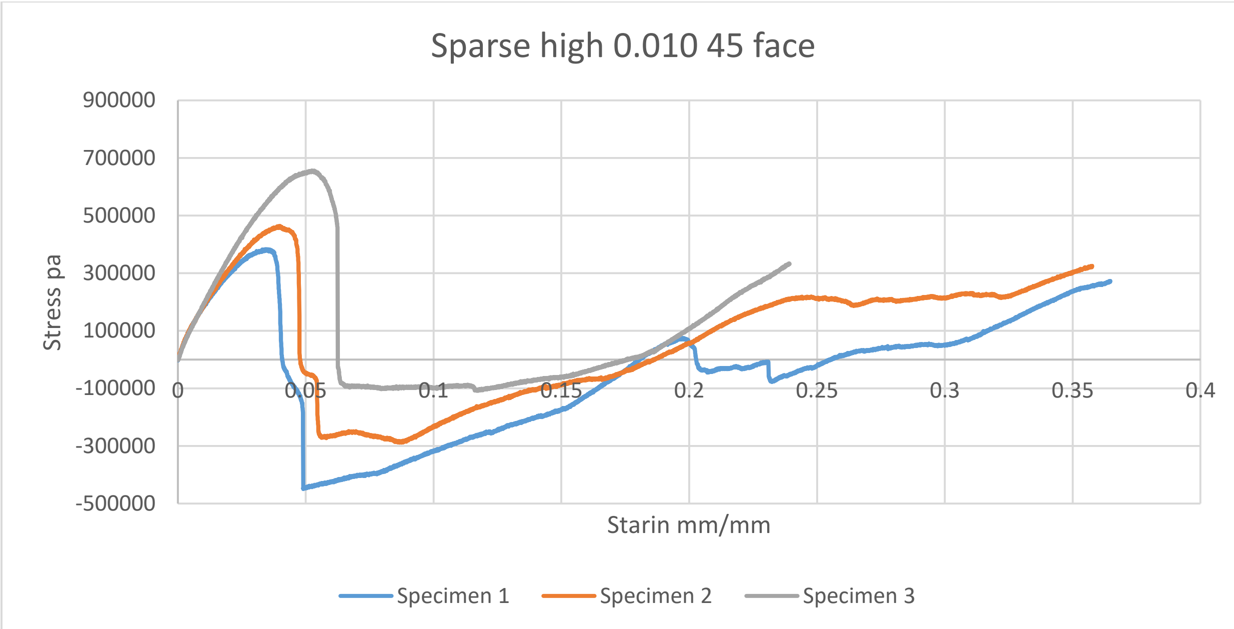
BCC printed with layer thickness 0.010, infill density sparse high density and at an angle of 45° (Sparse high 0.010 45° face)

Figure shows Load displacement curve for the specimens, Three Specimens were plotted in one graph to show the uncertainty. The average weight of these specimens are 1.82 grams. First failure started approximately between 0.64 mm and 1.06 mm for every specimen. After first failure between 0.9 mm and 1.2 mm the load is still applied till second failure. Every specimen is collapsed after first failure. Almost all the specimen show the same behavior. SEA for the specimens are found to be 42.61 J/Kg, 56.44 J/Kg and 99.7 J/Kg till the start of first failure. The average SEA till start of first failure of the specimens is 66.25 J/Kg. The stiffness values are found to be 347.98 N/mm, 315.53 N/mm and 346.50 N/mm till the start of first failure. The average stiffness till the end of first failure is 331.76 N/mm.



Load Displacement curve for sparse high 0.010 45° face configuration.

Figure describes Stress Strain curve of sparse high 0.010 45° face configuration. The Peak loads are 381.31 Kpa, 451.41 Kpa and 640.73 Kpa till the start of first failure. The Modulus of Elasticity values are 15872.18 Kpa, 15267.78 Kpa and 16777.23 Kpa till the start of first failure where the average is 15569.9 Kpa

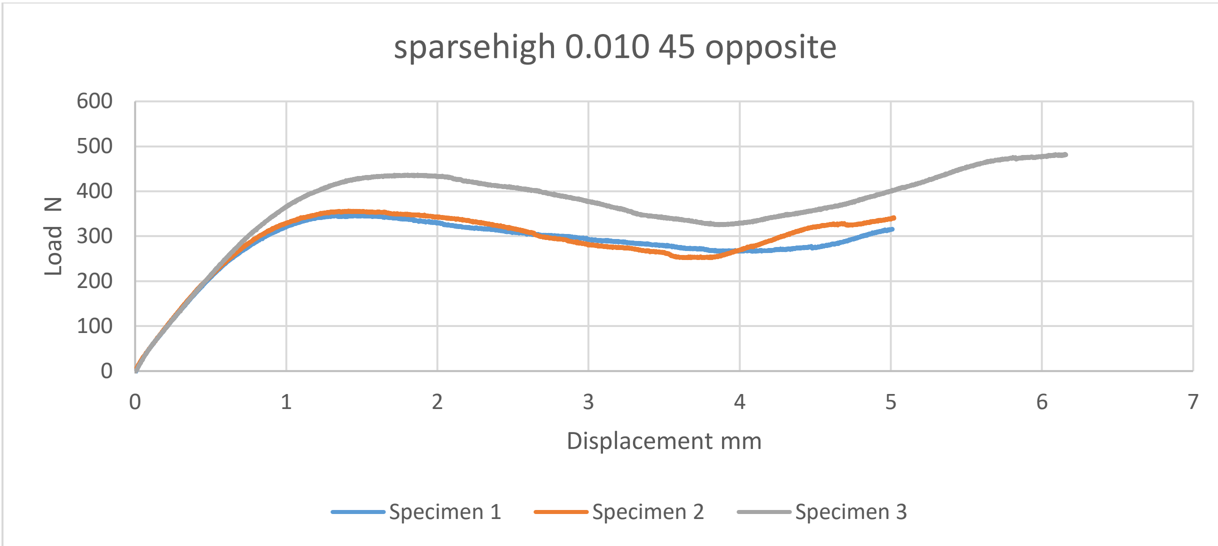


Stress Strain curve for sparse high 0.010 45° face configuration

This configuration showed the same behavior as the other previous configurations with 45° face orientation.

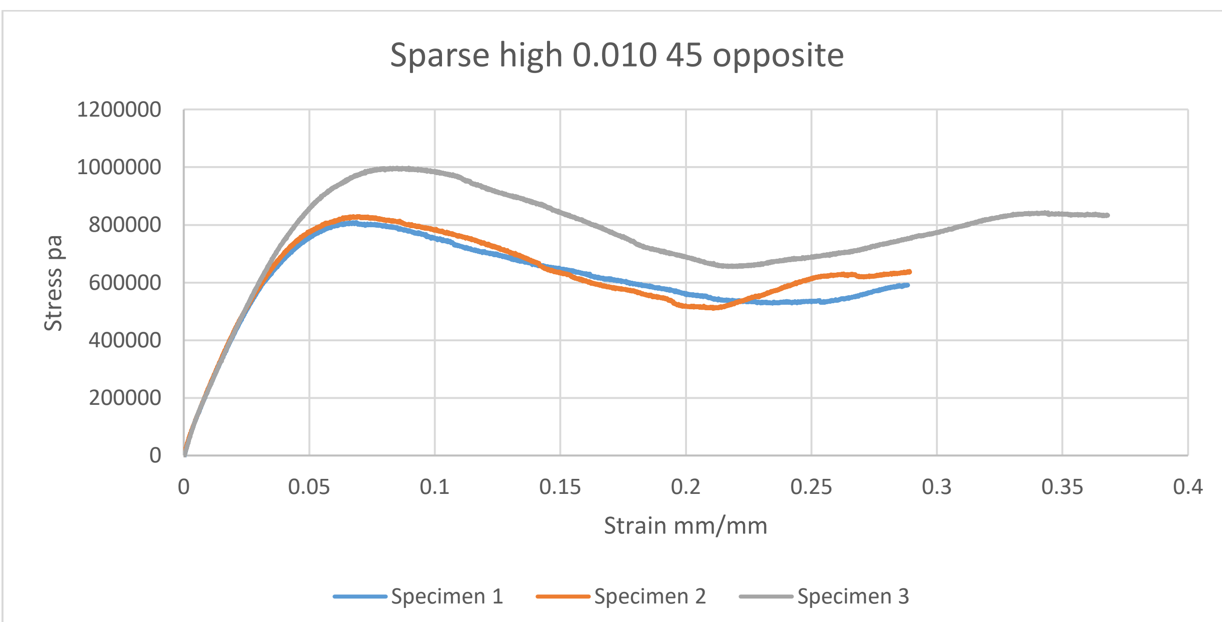
BCC printed with layer thickness 0.010, infill density sparse high density and at an angle of 45° (Sparse high 0.010 45° opposite)

Figure shows Load displacement curve for the specimens, Three Specimens were plotted in one graph to show the uncertainty. The average weight of these specimens are 1.82 grams. First failure started approximately between 1.24 mm and 1.5 mm for every specimen. After first failure between 3.5 mm and 4.2 mm the load is still applied till second failure. By the time second failure is occurred the layer is collapsed at an angle of 45°. Every specimen is collapsed after first failure. Almost all the specimen shows the same behavior. SEA for the specimens are found to be 177.1 J/Kg, 182.41 J/Kg and 286.17 J/Kg till the start of first failure. The average SEA till start of first failure of the specimens is 215.23 J/Kg. The stiffness values are found to be 399.49 N/mm, 410.17 N/mm and 402.62 N/mm till the start of first failure. The average stiffness till the end of first failure is 404.09 N/mm.



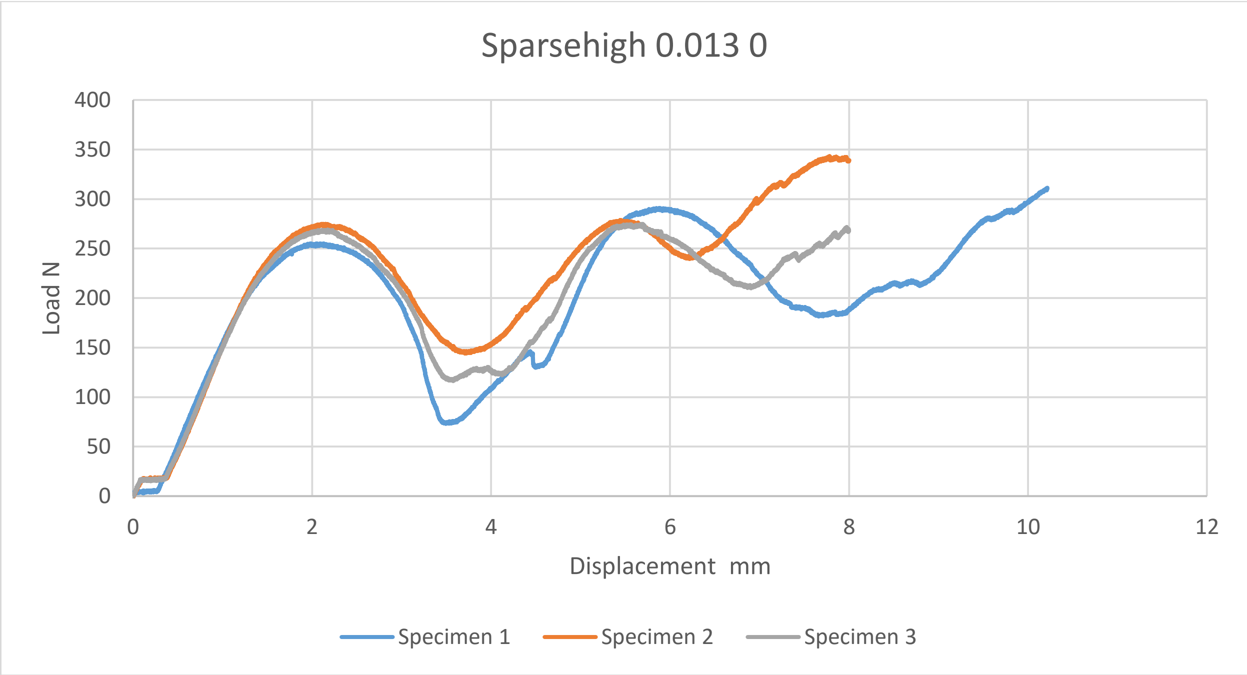
Load Displacement curve for sparse high 0.010 45° opposite configuration

Figure describes Stress Strain curve of sparse high 0.010 45° face configuration. The Peak loads are 803.35 Kpa, 825.69 Kpa and 993.1 Kpa till the start of first failure. The Modulus of Elasticity values are 19479.56 Kpa, 19982.16 Kpa and 19149.04 Kpa till the start of first failure where the average is 19536.92 Kpa. This configuration repeated the same behavior as previous 45° opposite configurations.



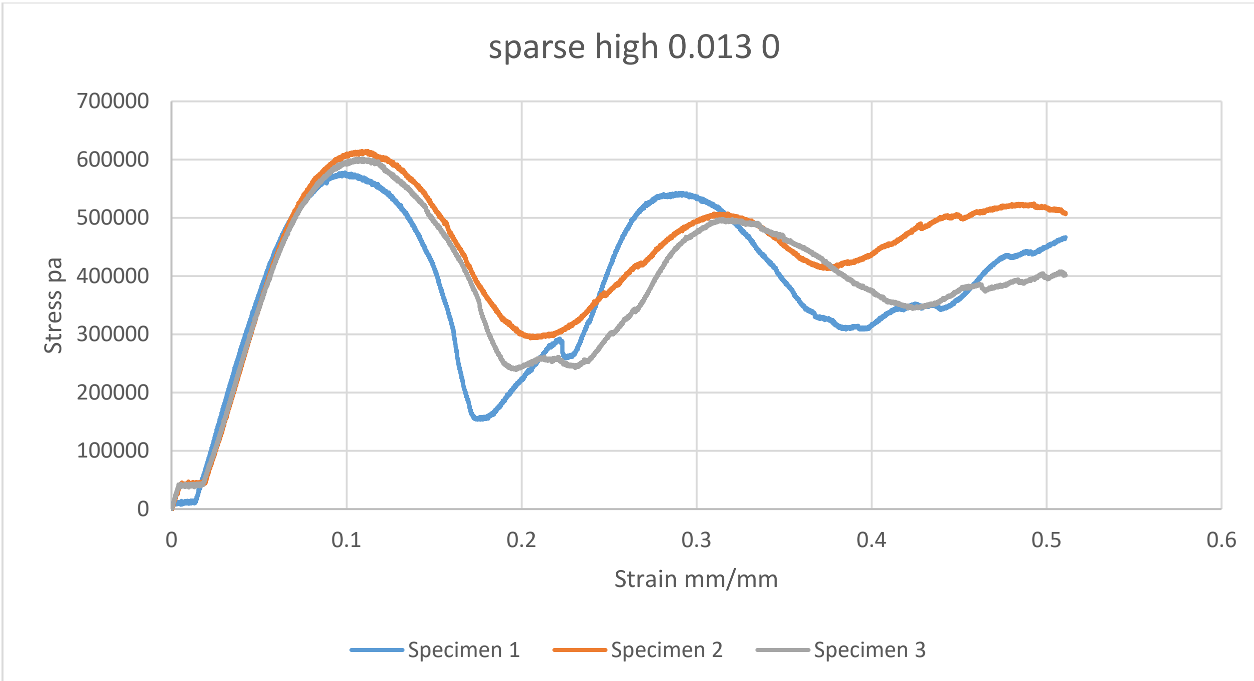
Stress Strain curve for sparse high 0.010 45° opposite configuration

BCC printed with layer thickness 0.013, infill density Sparse high density and at an angle of 0° (Sparse high 0.013 0°)



Load Displacement curve for sparse high 0.013 0° configuration.

Figure shows Load displacement curve for the specimens, Three Specimens were plotted in one graph to show the uncertainty. The average weight of these specimens are 1.69 grams. First failure started approximately at 1.8mm for every specimen. After first failure between 3.4 mm and 3.7 mm the load is still applied till second failure. Almost all the specimen show the same behavior. Specimen 1 showed a bit different behavior after first failure compared to other 2 specimens. SEA for the specimens are found to be 170.78 J/Kg, 198.42 J/Kg and 174.37 J/Kg till the start of first failure. The average SEA till start of first failure of the specimens is 181.19 J/Kg. The stiffness values are found to be 158.59 N/mm, 160.74 N/mm and 157.13 N/mm till the start of first failure. The average stiffness till the end of first failure is 158.82 N/mm.



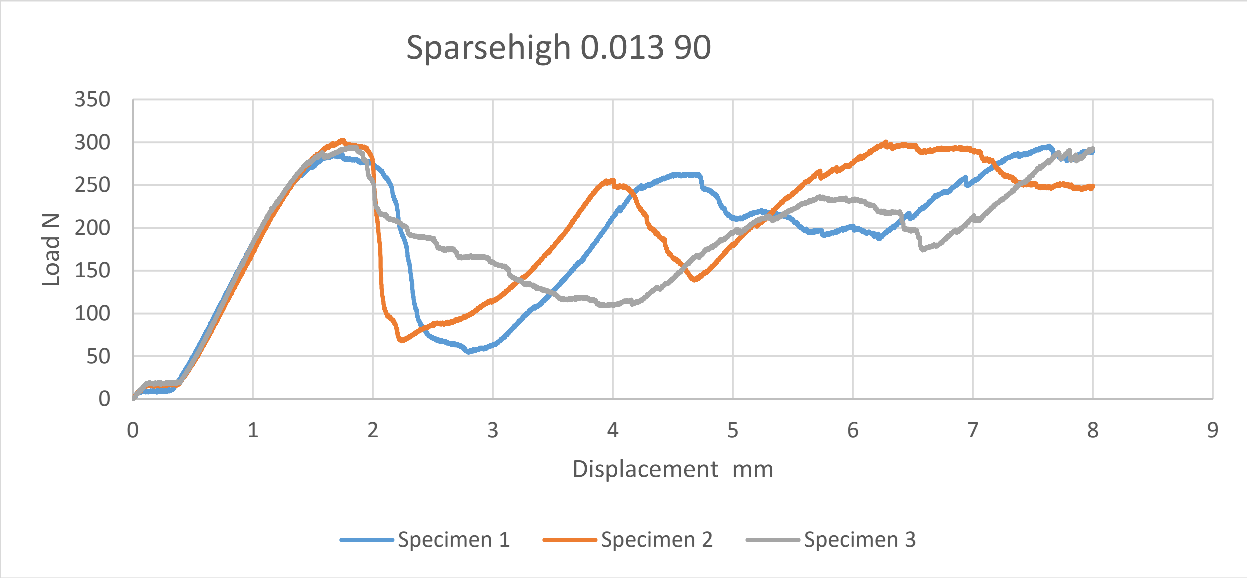
Stress Strain Curve for sparse high 0.013 0° configuration.

Figure describes Stress Strain curve of sparse high 0.013 0° configuration. The Peak loads are 569.58 Kpa, 610.16 Kpa and 595.87 Kpa till the start of first failure. The Modulus of Elasticity values are 7397.81 Kpa, 7264.13 Kpa and 7184.9 Kpa till the start of first failure where the average is 7282.28 Kpa.

BCC printed with layer thickness 0.013, infill density sparse high density and at an angle of 90° (Sparse high 0.013 90°)

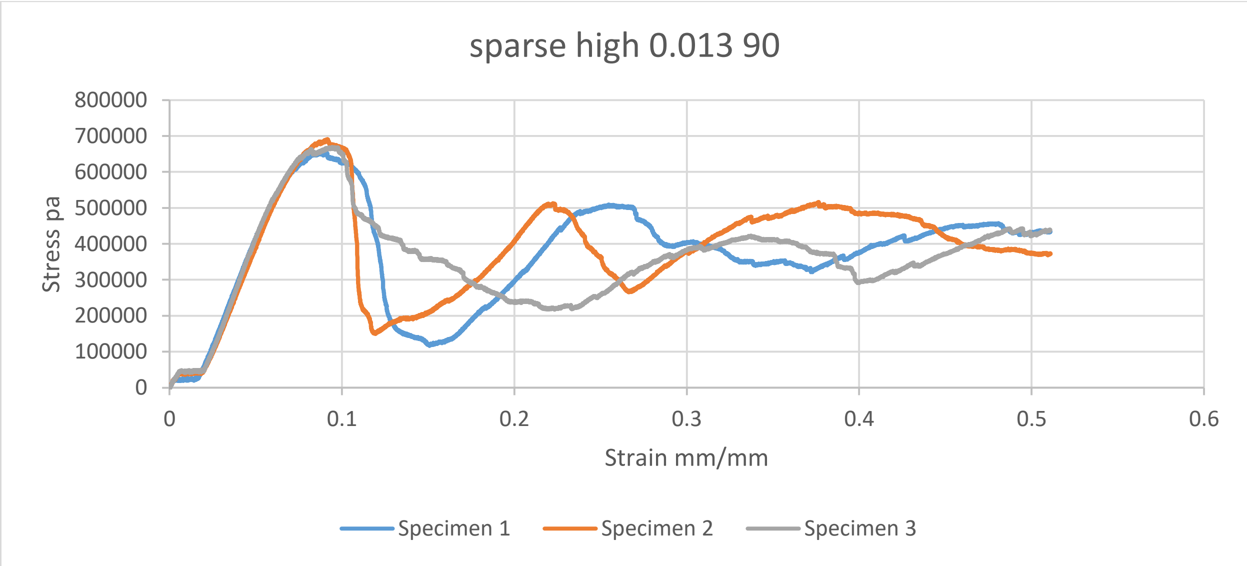
Figure shows Load displacement curve for the specimens, Three Specimens were plotted in one graph to show the uncertainty. The average weight of these specimens are 1.69 grams. First failure started approximately between 1.6mm and 1.8mm for every specimen. After first failure between 2.2 mm and 4.1 mm the load is still applied till second failure. Specimens 1 & 2 show the same behavior. Specimen 3 showed a bit different behavior compared to other 2 specimens. SEA for the specimens are found to be 156.16 J/Kg, 162.91 J/Kg and 171.71 J/Kg till the start of first failure. The average SEA till start of first failure of the specimens is 163.59 J/Kg. The stiffness values are found to be 190.74 N/mm, 187.7 N/mm and 63.46 N/mm till the start of first failure.

The average stiffness till the end of first failure is 147.3 N/mm. Specimen 3 showed a different curve than the other 2 specimens. So, if we take that off the average stiffness is 189.2 N/mm.



Load Displacement curve for sparse high 0.013 90° configuration

Figure describes Stress Strain curve of sparse high 0.013 90° configuration. The Peak loads are 638.22 Kpa, 683.82 Kpa and 631.36 Kpa till the start of first failure. The Modulus of Elasticity values are 8687.31 Kpa, 8494.80 Kpa and 8722.62 Kpa till the start of first failure where the average is 8634.91 Kpa.

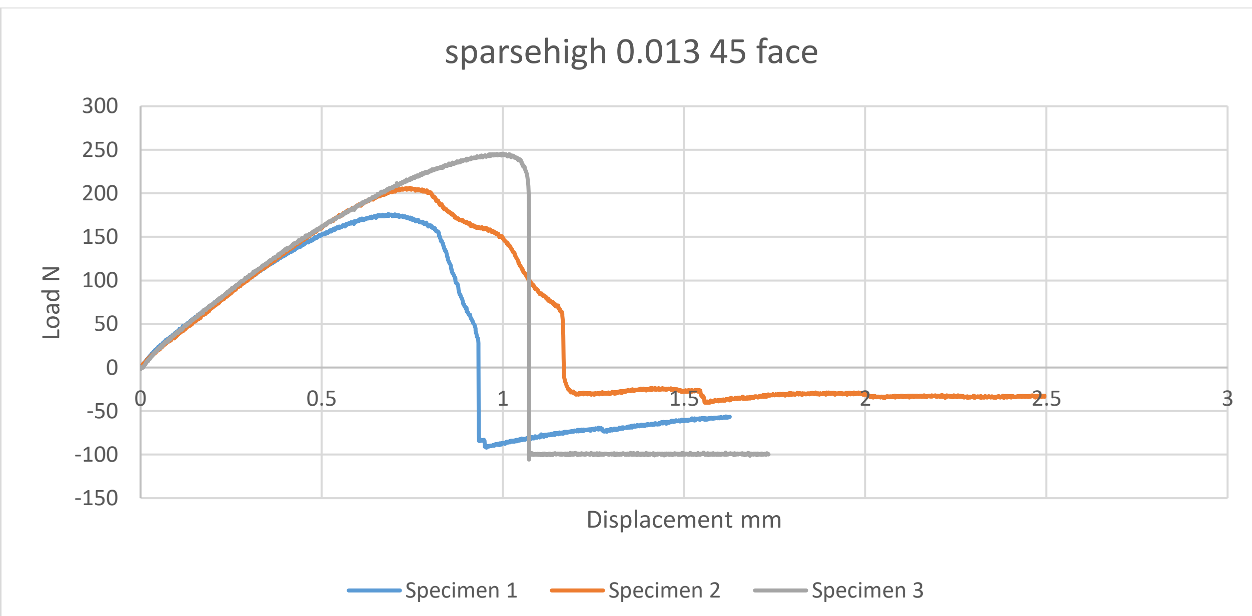


Stress Strain Curve for sparse high 0.013 90° configuration.

In this configuration Specimen 3 had different behavior it might be due to some broken struts or any uneven truss elements.

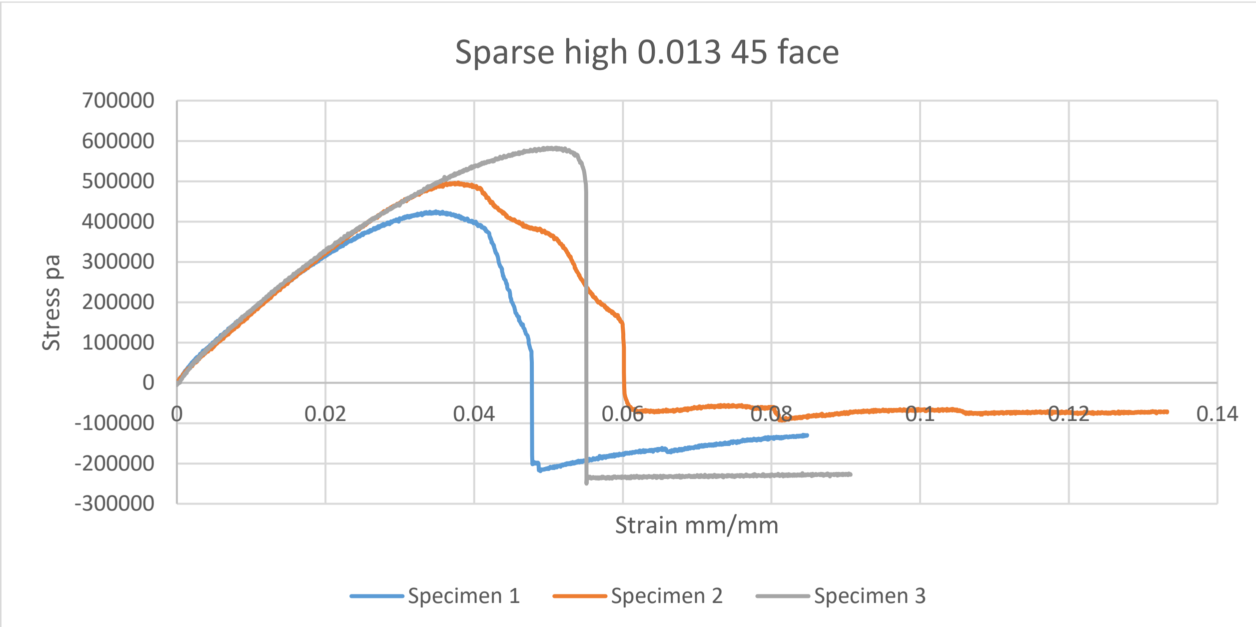
BCC printed with layer thickness 0.013, infill density sparse high density and at an angle of 45° (Sparse high 0.013 45° face)

Figure shows Load displacement curve for the specimens, Three Specimens were plotted in one graph to show the uncertainty. The average weight of these specimens are 1.90 grams. First failure started approximately between 0.69 mm and 1.15 mm for every specimen. After first failure between 0.95 mm and 1.2 mm the load is still applied till second failure. But all the Specimens collapsed after first failure only. SEA for the specimens are found to be 39.88 J/Kg, 47.89 J/Kg and 81.59 J/Kg till the start of first failure. The average SEA till start of first failure of the specimens is 56.45 J/Kg. The stiffness values are found to be 333.70 N/mm, 327.47 N/mm and 325.25 N/mm till the start of first failure. The average stiffness till the end of first failure is 328.81 N/mm.



Load Displacement curve for sparse high 0.013 45° face configuration

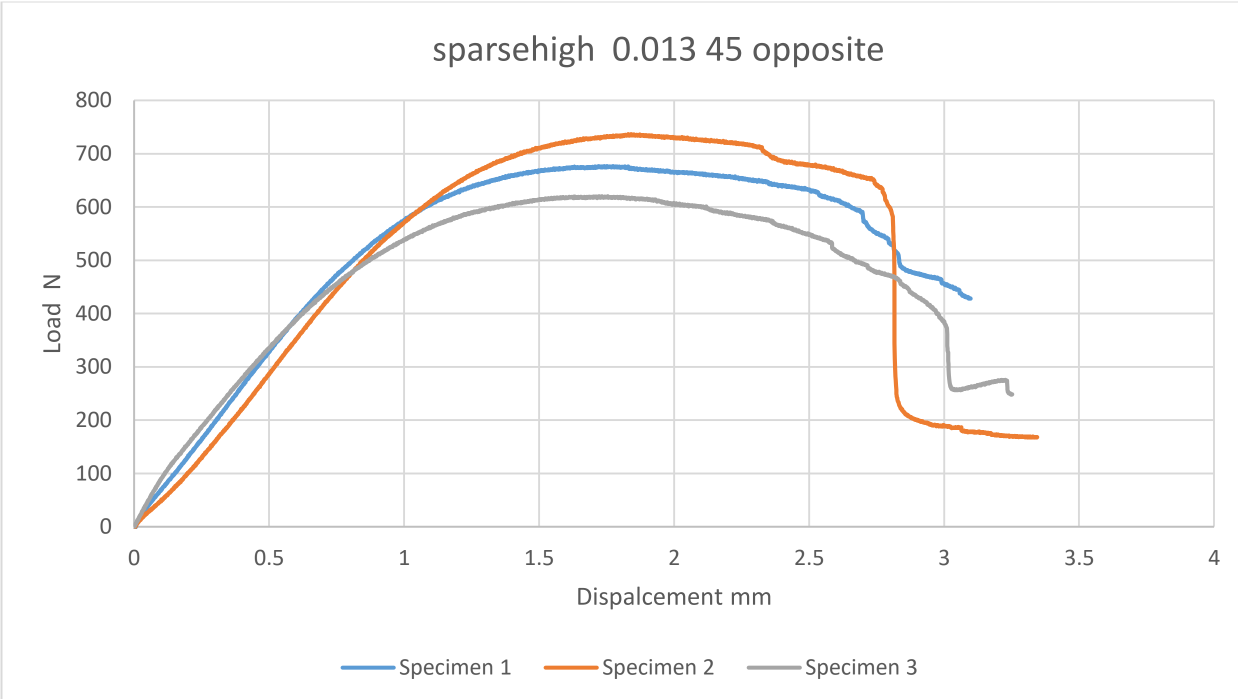
Figure describes Stress Strain curve of sparse high 0.013 45° face configuration. The Peak loads are 421.63 Kpa, 488.66 Kpa and 576.62 Kpa till the start of first failure. The Modulus of Elasticity values are 15186.6 Kpa, 15143.1 Kpa and 14685.5 Kpa till the start of first failure where the average is 15005.11 Kpa.



Stress Strain curve for sparse high 0.013 45° face configuration

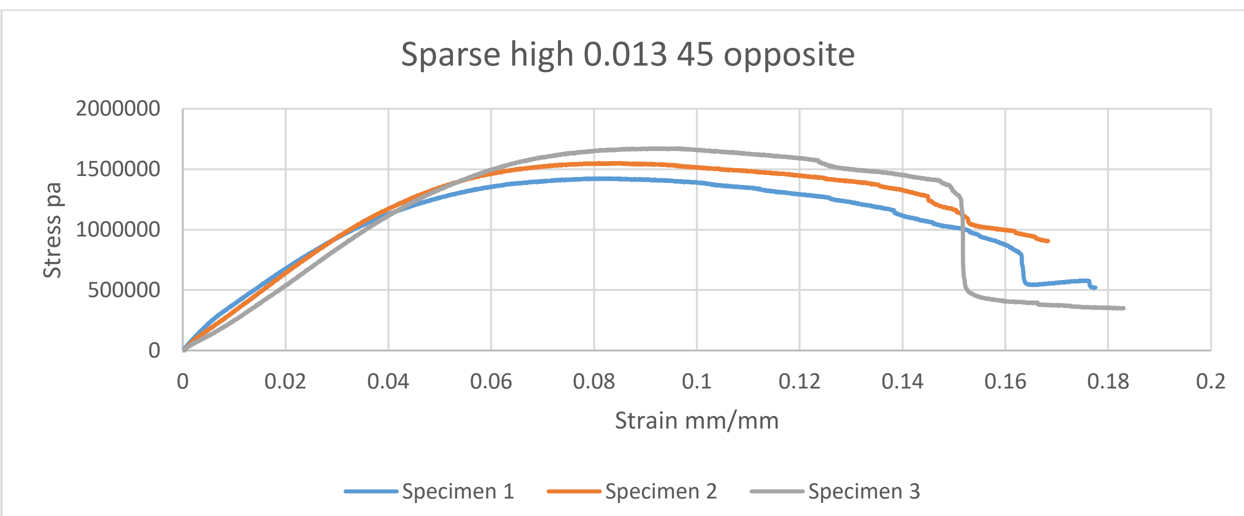
BCC printed with layer thickness 0.013, infill density sparse high density and at an angle of 45° (Sparse high 0.013 45° opposite)

Figure shows Load displacement curve for the specimens; Three Specimens were plotted in one graph to show the uncertainty. The average weight of these specimens are 1.90 grams. First failure started approximately at 1.8 mm for every specimen. After first failure at 2.5 mm the load is still applied till second failure. But all the Specimens collapsed after first failure only. SEA for the specimens are found to be 342.97 J/Kg, 454.24 J/Kg and 337.41 J/Kg till the start of first failure. The average SEA till start of first failure of the specimens is 378.21 J/Kg. The stiffness values are found to be 639.10 N/mm, 586.62 N/mm and 650.54 N/mm till the start of first failure. The average stiffness till the end of first failure is 625.42 N/mm.



Load Displacement curve for sparse high 0.013 45° opposite configuration

Figure describes Stress Strain curve of sparse high 0.013 45° opposite configuration. The Peak loads are 1418.43 Kpa, 1544.09 Kpa and 1666.61 Kpa till the start of first failure. The Modulus of Elasticity values are 30826.6 Kpa, 30194.5 Kpa and 27667.08 Kpa till the start of first failure where the average is 29562.7 Kpa.



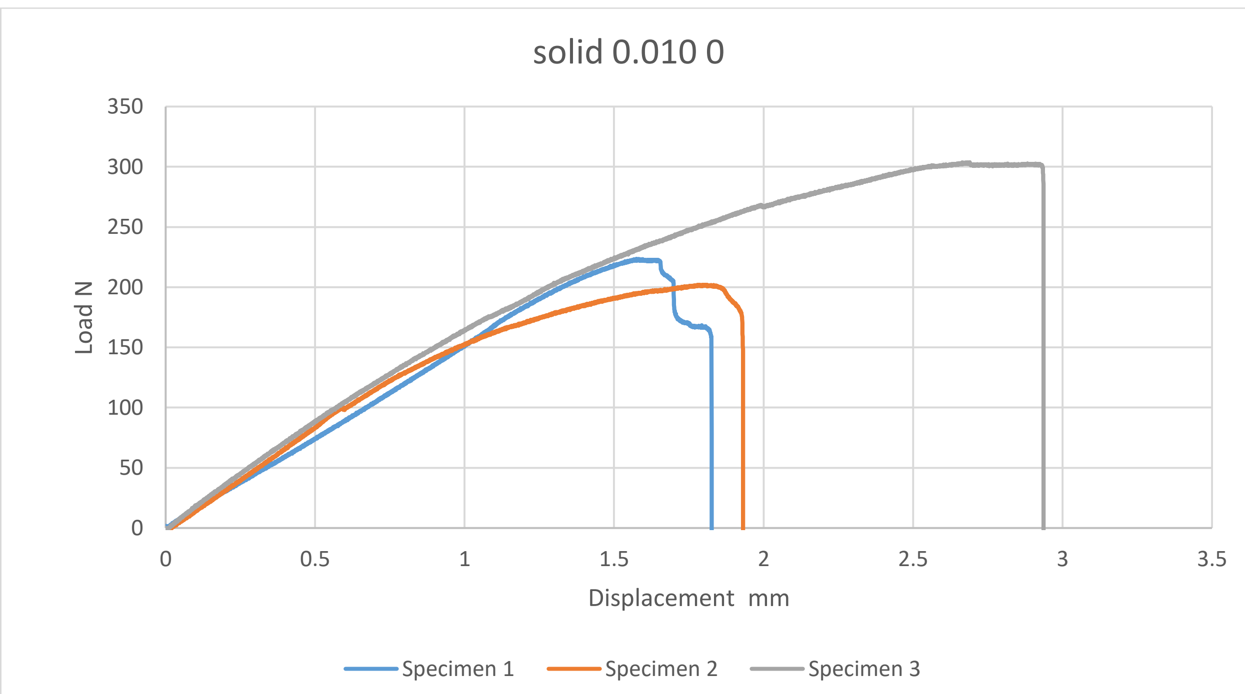
Stress Strain Curve for sparse high 0.013 45° opposite configuration

Experimental Results for Tension Test.

For all tensile specimens the specimen breaks away at one point and there will be only one curve.

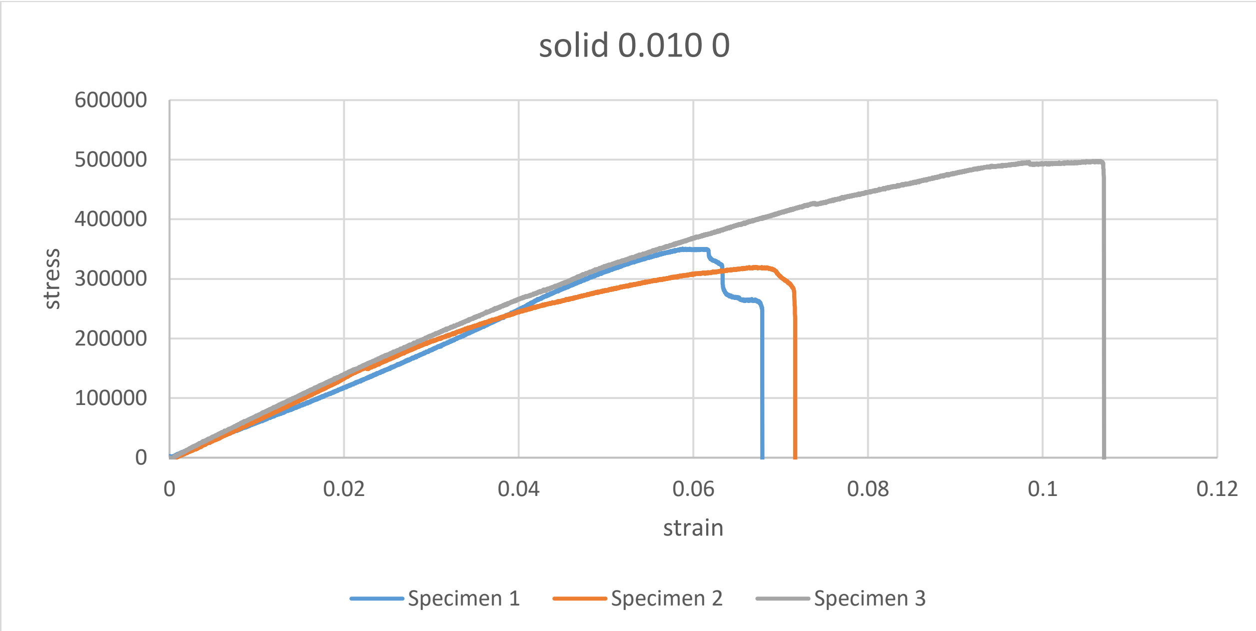
BCC printed with layer thickness 0.010, infill density solid and at an angle of 0° (Solid 0.010 0°)

Figure shows Load displacement curve for the specimens; Three Specimens were plotted in one graph to show the uncertainty. The average weight of these specimens are 4.69 grams. First failure started approximately at 1.6 mm, 1.8 mm and 2.9 mm for specimens 1, 2 & 3. SEA for the specimens are found to be 43.2 J/Kg, 51.12 J/Kg and 123 J/Kg till the start of first failure. The average SEA till start of first failure of the specimens is 72.44 J/Kg. The stiffness values are found to be 148.73 N/mm, 137.57 N/mm and 134.57 N/mm till the start of first failure. The average stiffness till the end of first failure is 140.29 N/mm.



Load Displacement curve for Solid 0.010 0° configuration.

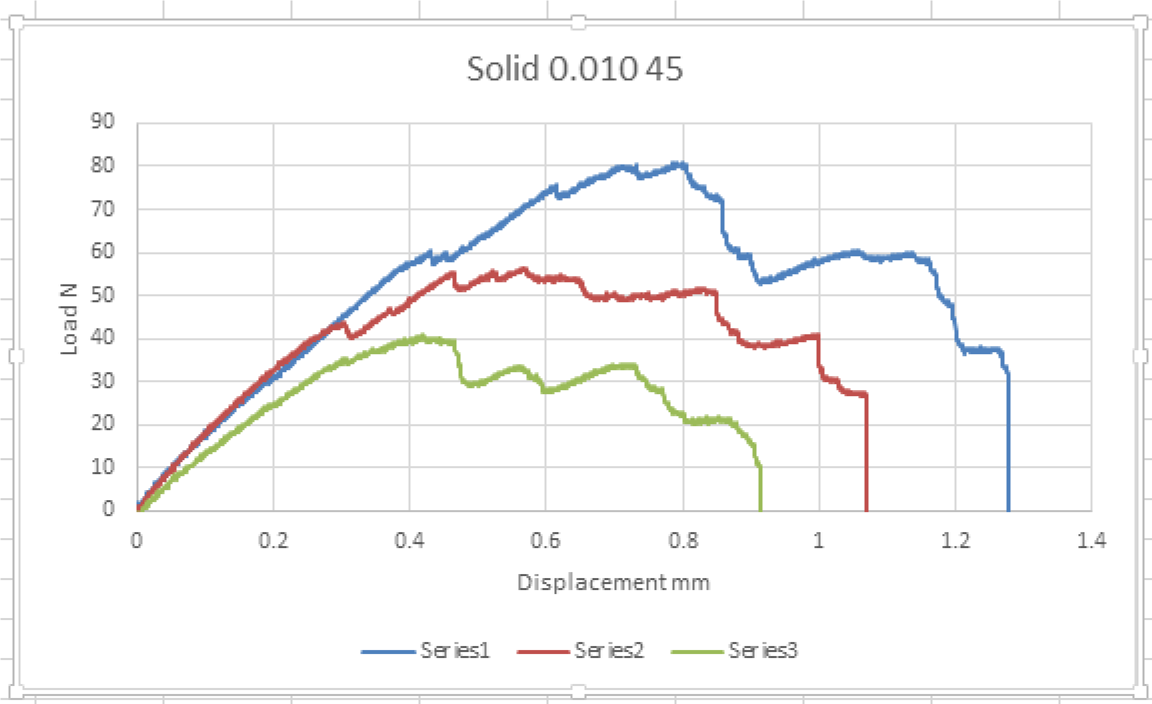
Figure 6.34 describes Stress Strain curve of Solid 0.010 0° configuration. The Peak loads are 348.73 Kpa, 316.27 Kpa and 491.81 Kpa till the start of first failure. The Modulus of Elasticity values are 6084.03 Kpa, 5699.06 Kpa and 5664.98 Kpa till the start of first failure where the average is 5816.02 Kpa.



Stress strain curve for Solid 0.010 0° configuration.

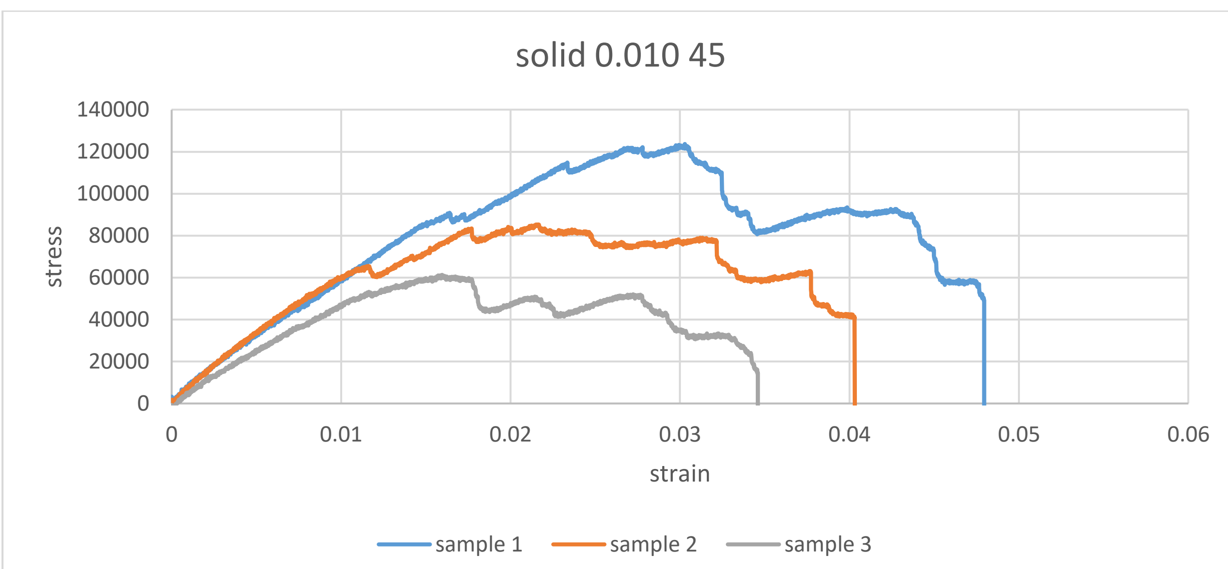
BCC printed with layer thickness 0.010, infill density solid and at an angle of 45° (Solid 0.010 45°)

Figure shows Load displacement curve for the specimens, Three Specimens were plotted in one graph to show the uncertainty. The average weight of these specimens are 4.93 grams. First failure started approximately at 0.45 mm, 0.57 mm and 4.6 mm for specimens 1, 2 & 3. SEA for the specimens are found to be 14.73 J/Kg, 6.90 J/Kg and 5.10 J/Kg till the start of first failure. The average SEA till start of first failure of the specimens is 1.79 J/Kg. The stiffness values are found to be 151.72 N/mm, 165.16 N/mm and 123.72 N/mm till the start of first failure. The average stiffness till the end of first failure is 146.87 N/mm



Load displacement curve for solid 0.010 45° configuration

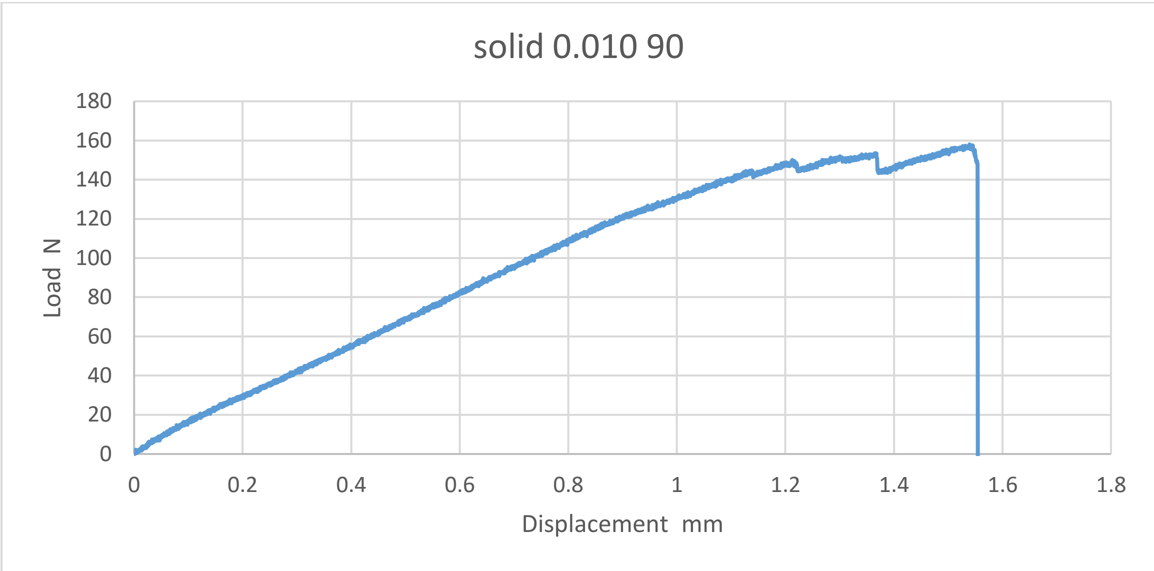
Figure describes Stress Strain curve of Solid 0.010 45° configuration. The Peak loads are 118.76 Kpa, 79.84 Kpa and 59.02 Kpa till the start of first failure. The Modulus of Elasticity values are 5933.13 Kpa, 6330.37 Kpa and 4275.70 Kpa till the start of first failure where the average is 5513.07 Kpa**.**



Stress Strain Curve for Solid 0.010 45° configuration

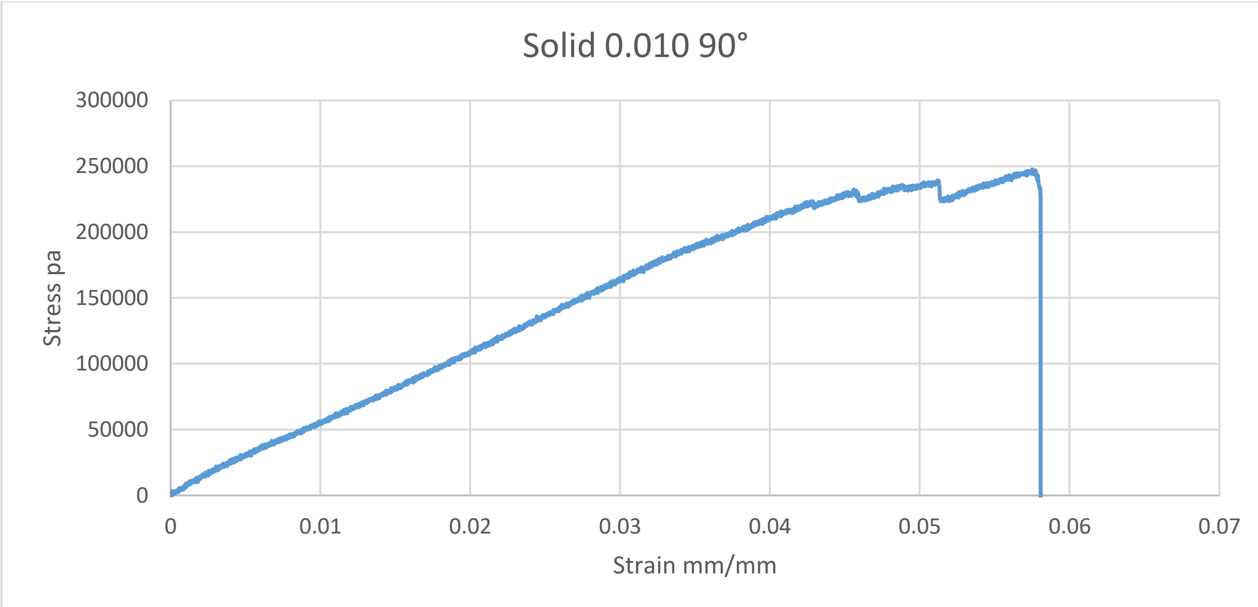
BCC printed with layer thickness 0.010, infill density solid and at an angle of 90° (Solid 0.010 90°)

Figure shows Load displacement curve for the specimens. Only one specimen is plotted. The weight of the specimen is 4.56 grams. First failure started approximately at 1.54 mm. SEA for the specimen is 19.27 J/Kg till the start of first failure. The average SEA till start of first failure of the specimens is 1.79 J/Kg. The stiffness value is 134.88 N/mm.



Load Displacement curve for solid 0.010 90° configuration.

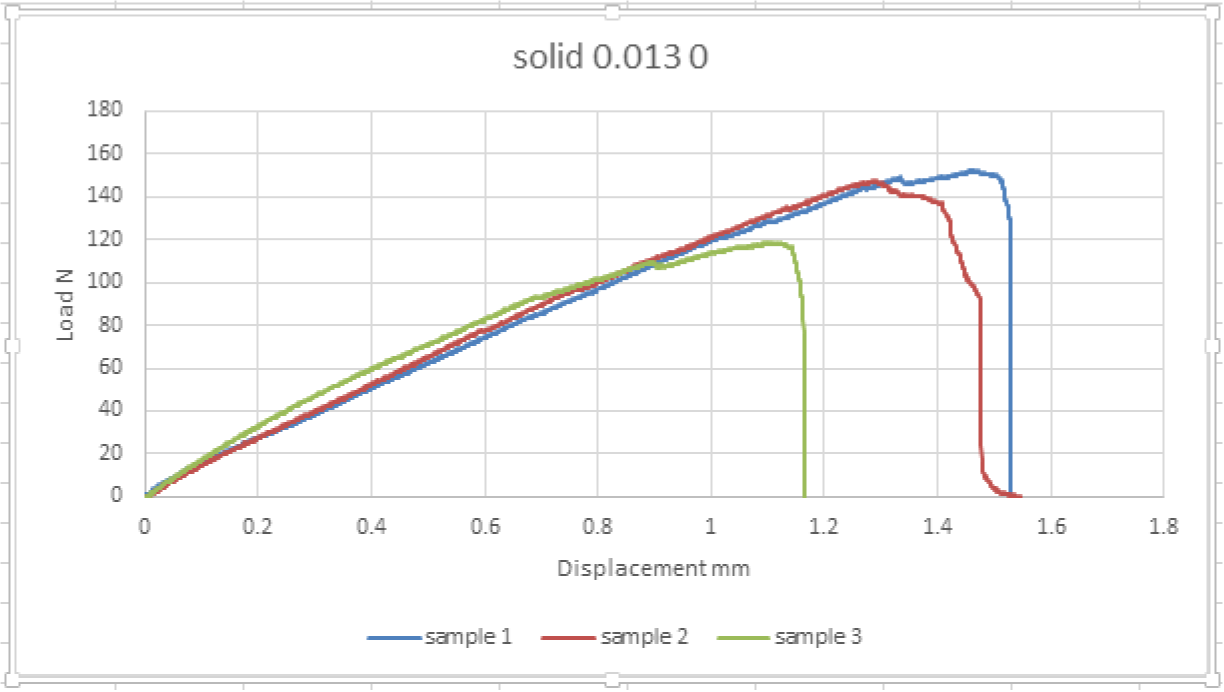
Figure describes Stress Strain curve of Solid 0.010 90° configuration. The Peak load is 242.94 Kpa till the start of first failure. The Modulus of Elasticity value is 4863.04 Kpa



Stress Strain curve for Solid 0.010 90° Configuration.

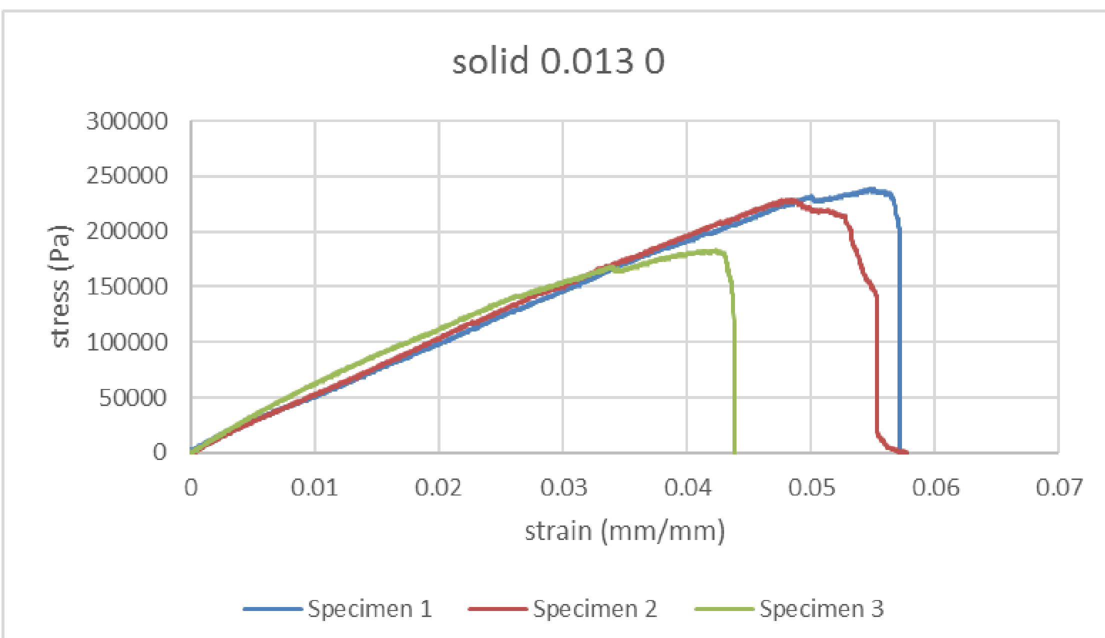
BCC printed with layer thickness 0.013, infill density solid and at an angle of 0° (Solid 0.013 0°)

Figure shows Load displacement curve for the specimens, Three Specimens were plotted in one graph to show the uncertainty. The average weight of these specimens are 4.61 grams. First failure started approximately at 1.19 mm, 1.29 mm and 1.49 mm for specimens 1, 2 &3. SEA for the specimens are found to be 23.73 J/Kg, 21.75 J/Kg and 12.41 J/Kg till the start of first failure. The average SEA till start of first failure of the specimens is 19.30 J/Kg. The stiffness values are found to be 119.84 N/mm, 124.11 N/mm and 138.33 N/mm till the start of first failure. The average stiffness till the end of first failure is 127.43 N/mm.



Load Displacement curve for Solid 0.013 0° configuration

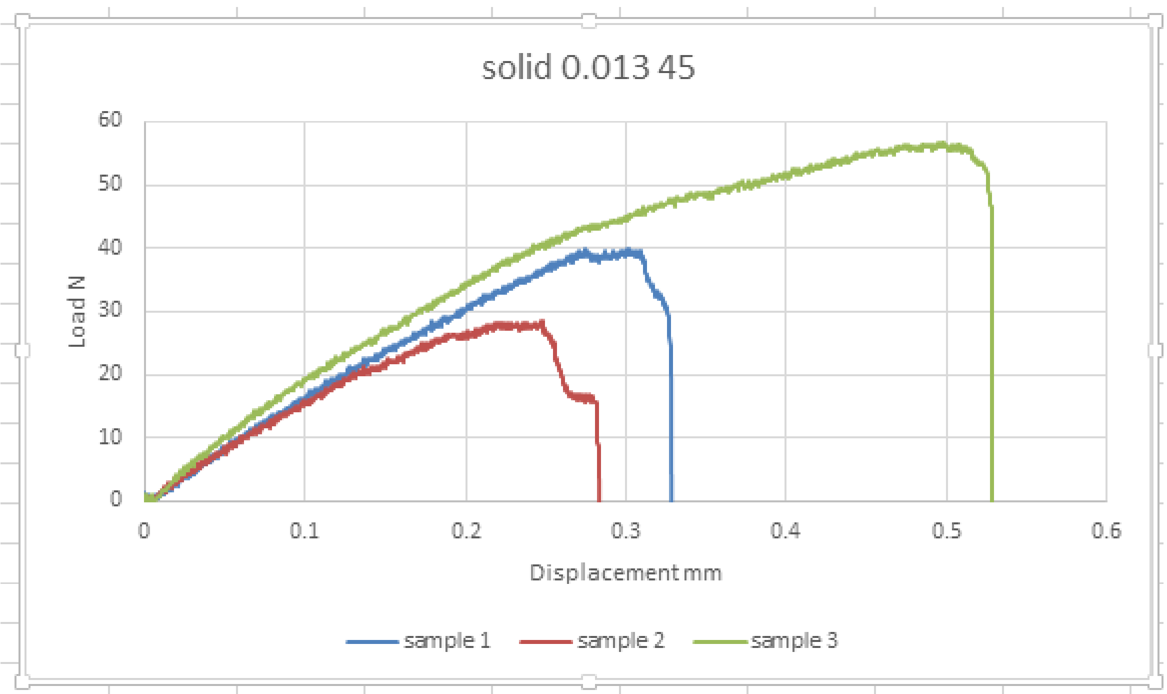
Figure describes Stress Strain curve of configuration. The Peak loads are 179.52 Kpa, 227.81 Kpa and 235.13 Kpa till the start of first failure. The Modulus of Elasticity values are 4854.41 Kpa, 5009.85 Kpa and 5505.44 Kpa till the start of first failure where the average is 5123.23 Kpa**.**



Stress Strain curve for solid 0.013 0° Configuration

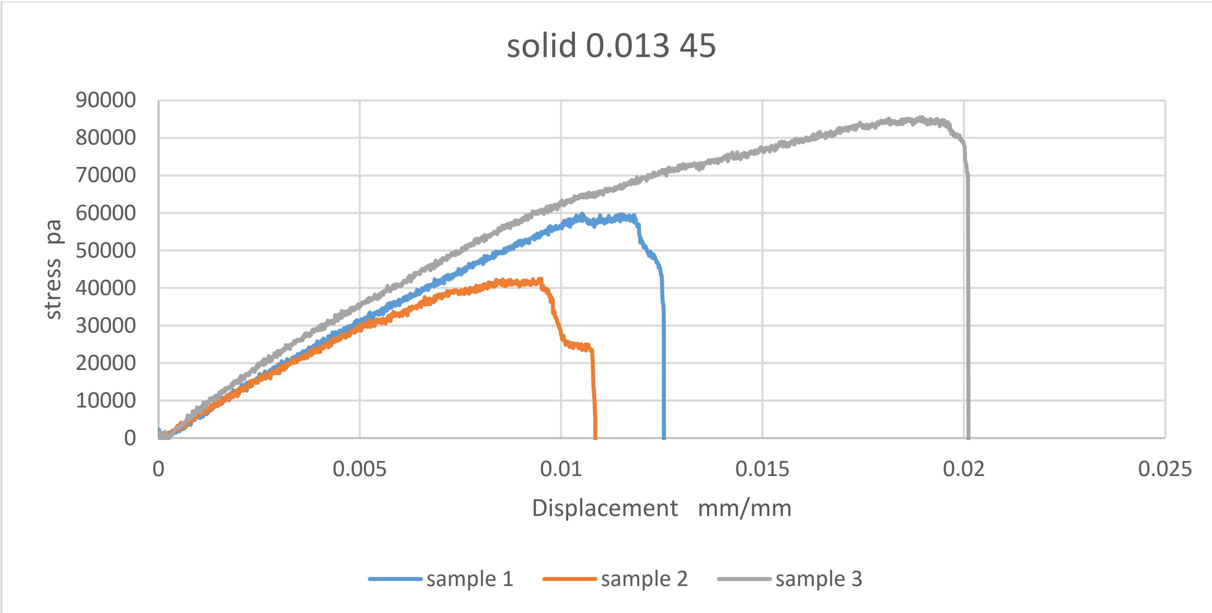
BCC printed with layer thickness 0.013, infill density solid and at an angle of 45° (Solid 0.013 45°)

Figure shows Load displacement curve for the specimens; Three Specimens were plotted in one graph to show the uncertainty. The average weight of these specimens are 5.07 grams. First failure started approximately at 1.19 mm, 1.29 mm and 1.49 mm for specimens 1, 2 &3. SEA for the specimens are found to be 1.14 J/Kg, 0.85 J/Kg and 3.74 J/Kg till the start of first failure. The average SEA till start of first failure of the specimens is 1.9 J/Kg. The stiffness values are found to be 153.09 N/mm, 138.45 N/mm and 141.64 N/mm till the start of first failure. The average stiffness till the end of first failure is 144.39 N/mm.



Load Displacement curve for Solid 0.013 45° configuration

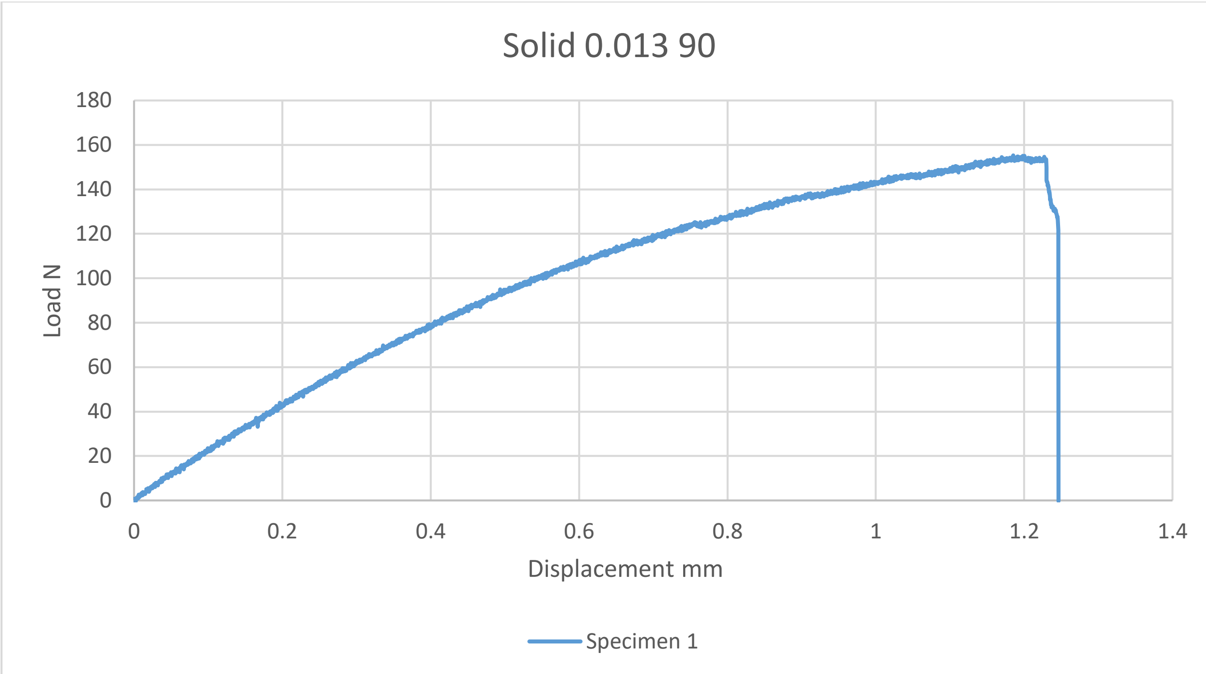
Figure describes Stress Strain curve of configuration. The Peak loads are 39.662 Kpa, 57.894 Kpa and 83.551 Kpa till the start of first failure. The Modulus of Elasticity values are 5992.66 Kpa, 5377.86 Kpa and 5567.14 Kpa till the start of first failure where the average is 5645.89 Kpa**.**



Stress Strain curve for solid 0.013 45° configuration.

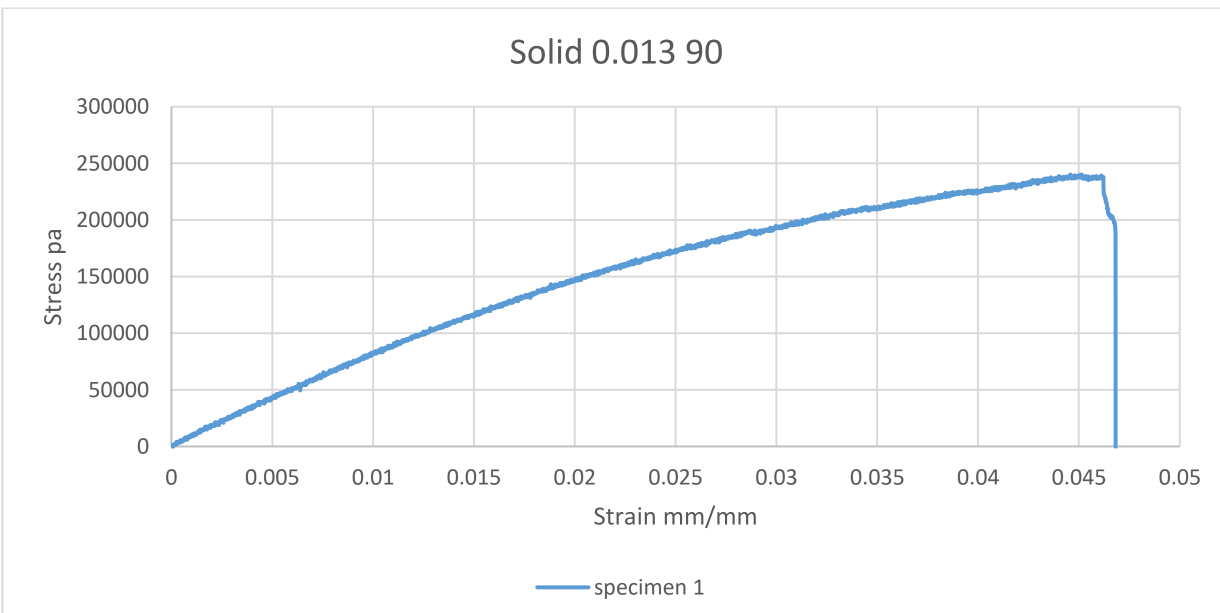
BCC printed with layer thickness 0.013, infill density solid and at an angle of 90° (Solid 0.013 90°)

Figure shows Load displacement curve for the specimens, Three Specimens were plotted in one graph to show the uncertainty. The average weight of these specimens are 5.07 grams. First failure started approximately at 1.22 mm. SEA for the specimen is 23.17J/Kg, till the start of first failure. The stiffness value is 121.87 N/mm till the start of first failure.



Load Displacement curve for Solid 0.013 90° configuration

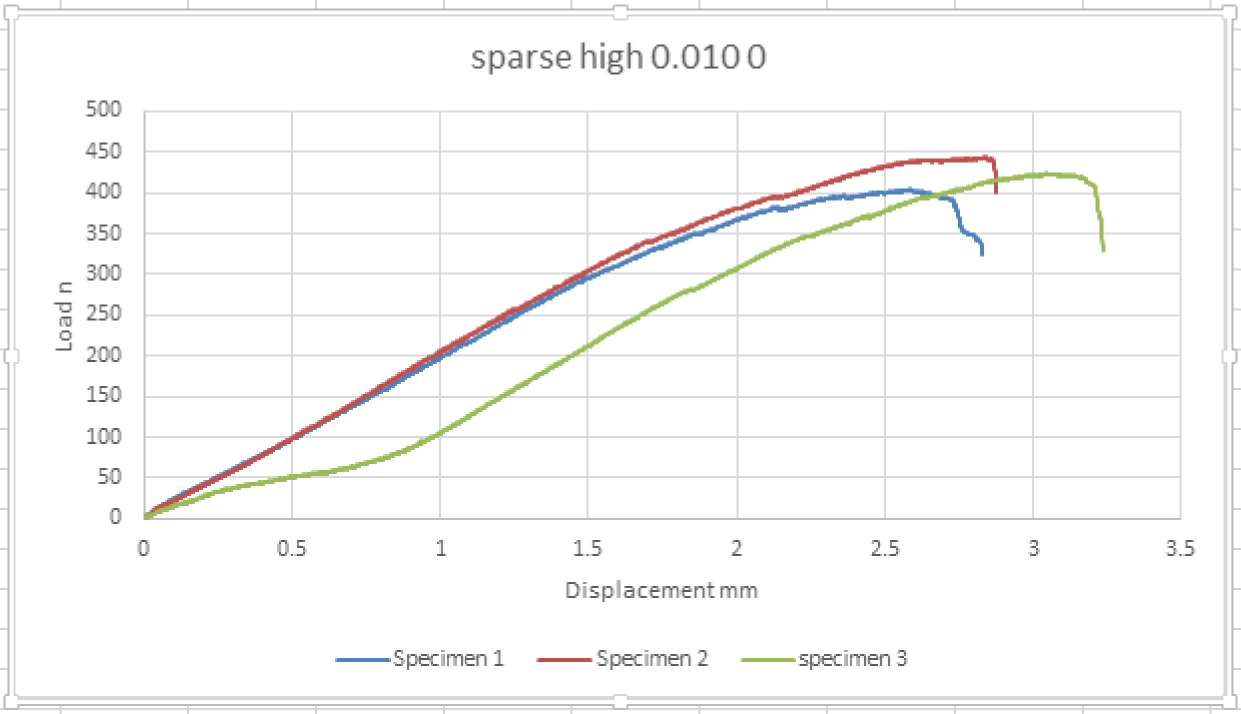
Figure describes Stress Strain curve of configuration. The Peak load is 232.259 Kpa, till the start of first failure. The Modulus of Elasticity values are 6980.92 Kpa till start of first failure.



Stress Strain curve for solid 0.013 90° configuration

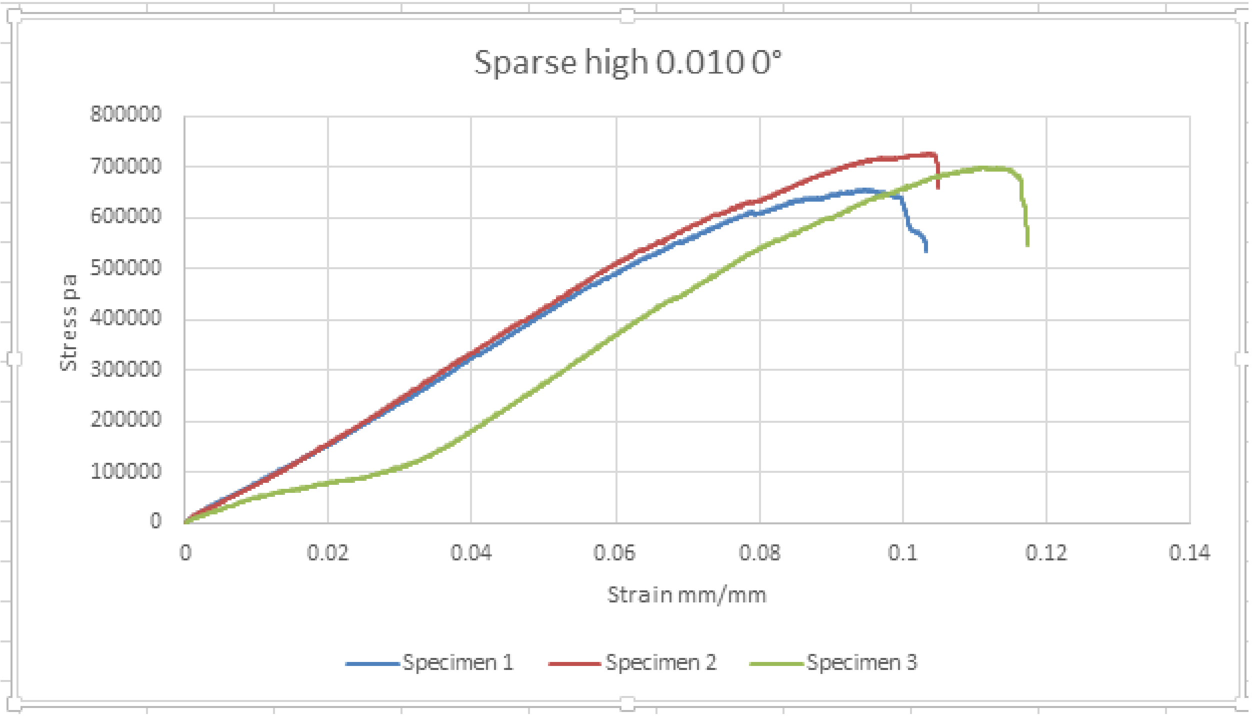
BCC printed with layer thickness 0.010, infill density sparse high and at an angle of 0° (Sparse high 0.010 0°)

Figure shows Load displacement curve for the specimens, Three Specimens were plotted in one graph to show the uncertainty. The average weight of these specimens are 4.5 grams. First failure started approximately at 2.6 mm, 2.8 mm and 3.1 mm for specimens 1, 2 &3. SEA for the specimens are found to be 146.56J/Kg, 169.28 J/Kg and 150.94 J/Kg till the start of first failure. The average SEA till start of first failure of the specimens is 155.6 J/Kg. The stiffness values are found to be 147.8 N/mm, 154.4 N/mm and 150.9 N/mm till the start of first failure. The average stiffness till the end of first failure is 146.01 N/mm.



Load Displacement curve for sparse high 0.010 0°

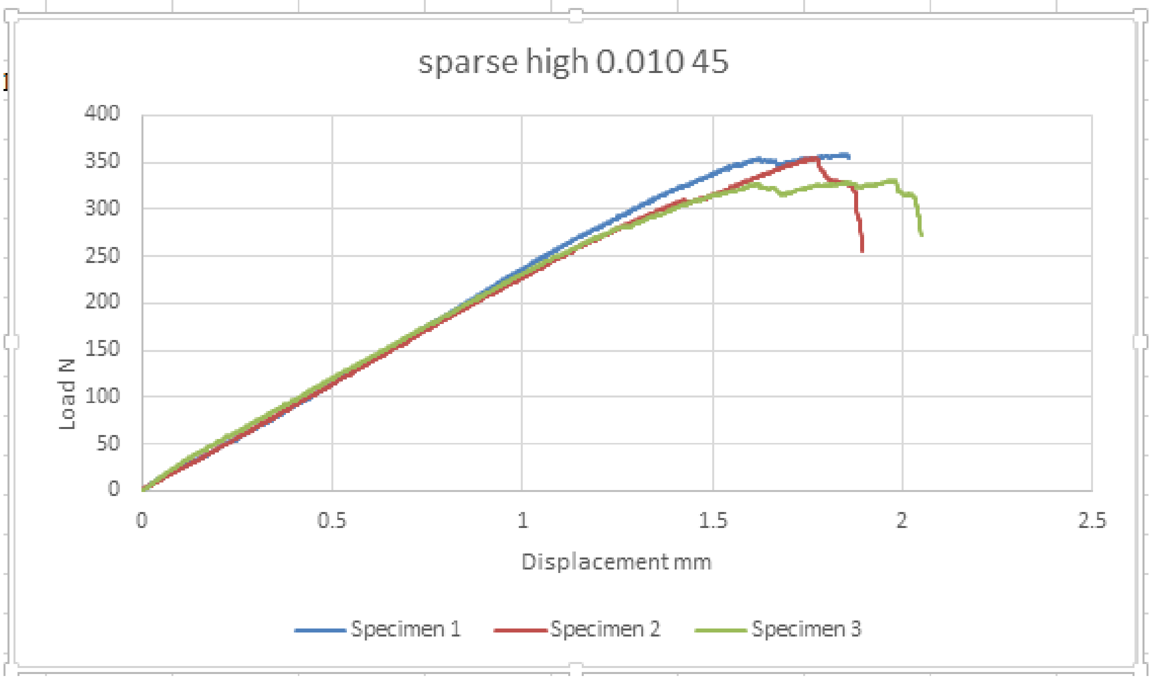
Figure describes Stress Strain curve of configuration. The Peak loads are 638.62 Kpa, 725.99 Kpa and 681.30 Kpa till the start of first failure. The Modulus of Elasticity values are 6722.32 Kpa, 6980.72 Kpa and 5873.3 Kpa till the start of first failure where the average is 6525.44 Kpa**.**



Stress Strain curve for sparse high 0.010 0°

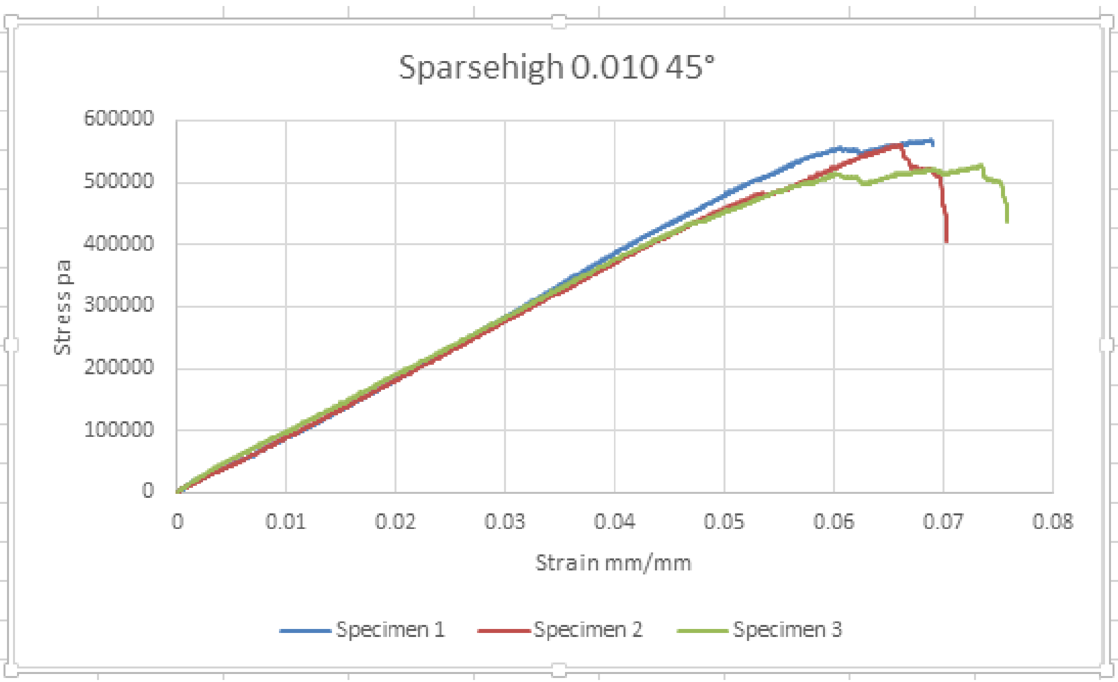
BCC printed with layer thickness 0.010, infill density sparse high and at an angle of 45° (Sparse high 0.010 45°)

Figure show Load displacement curve for the specimens, Three Specimens were plotted in one graph to show the uncertainty. The average weight of these specimens are 4.7 grams. First failure started approximately at 1.6 mm, 1.8 mm and 1.9 mm for specimens 1, 2 &3. SEA for the specimens are found to be 67.92 J/Kg, 73.96 J/Kg and 61.01 J/Kg till the start of first failure. The average SEA till start of first failure of the specimens is 67.63 J/Kg. The stiffness values are found to be 210.62 N/mm, 194.19 N/mm and 203.61 N/mm till the start of first failure. The average stiffness till the end of first failure is 202.8 N/mm.



Load Displacement curve for sparse high 0.010 45°

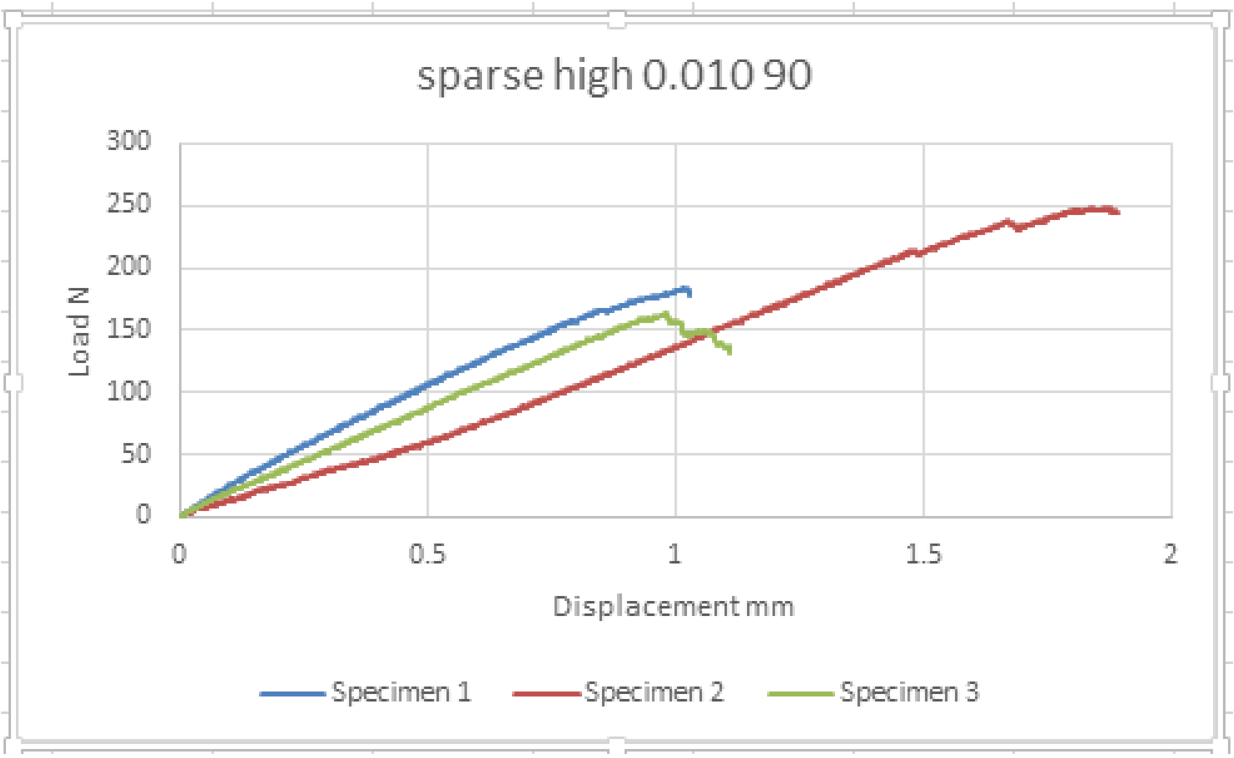
Figure describes Stress Strain curve of configuration. The Peak loads are 524.13 Kpa, 546.37 Kpa and 507.06 Kpa till the start of first failure. The Modulus of Elasticity values are 8766.21 Kpa, 8278.41 Kpa and 8555.10 Kpa till the start of first failure where the average is 8533.24 Kpa**.**



Stress Strain curve for sparse high 0.010 45°

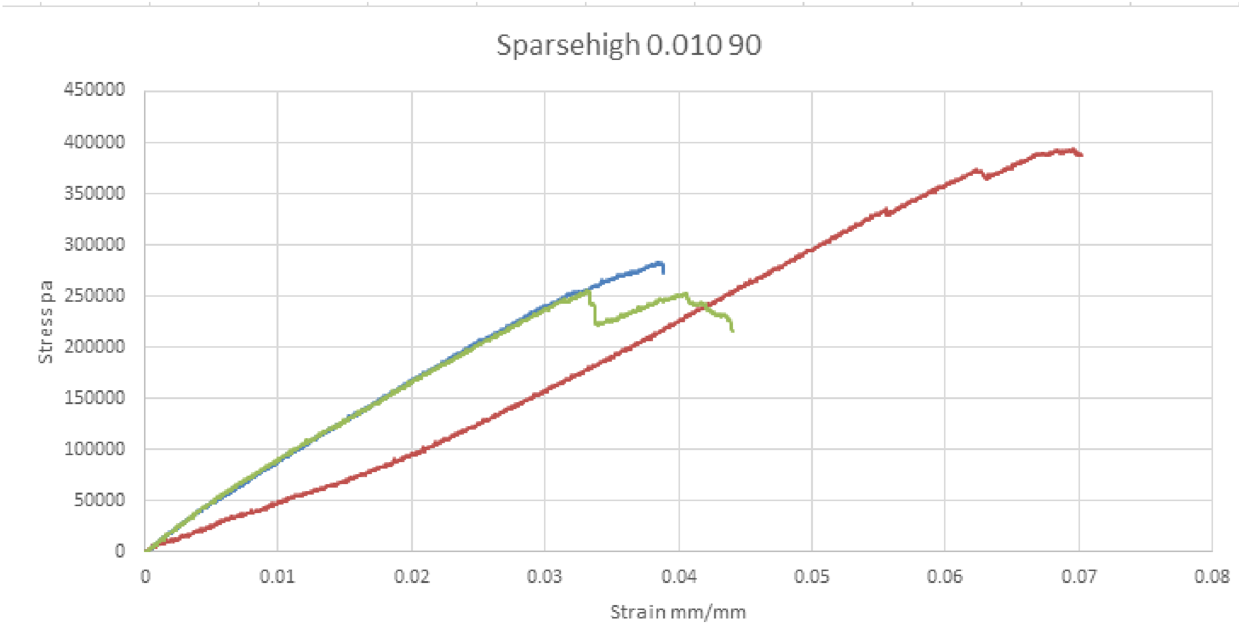
BCC printed with layer thickness 0.010, infill density sparse high and at an angle of 90° (Sparse high 0.010 90°)

Figure show Load displacement curve for the specimens, Three Specimens were plotted in one graph to show the uncertainty. The average weight of these specimens are 4.5 grams. First failure started approximately at 1 mm, 1.8 mm and 0.9 mm for specimens 1, 2 &3. SEA for the specimens are found to be 23.52 J/Kg, 50.82 J/Kg and 19.47 J/Kg till the start of first failure. The average SEA till start of first failure of the specimens is 31.27 J/Kg. The stiffness values are found to be 178.57 N/mm, 134.46 N/mm and 155.25 N/mm till the start of first failure. The average stiffness till the end of first failure is 156.095 N/mm.



Load Displacement curve for sparse high 0.010 90°

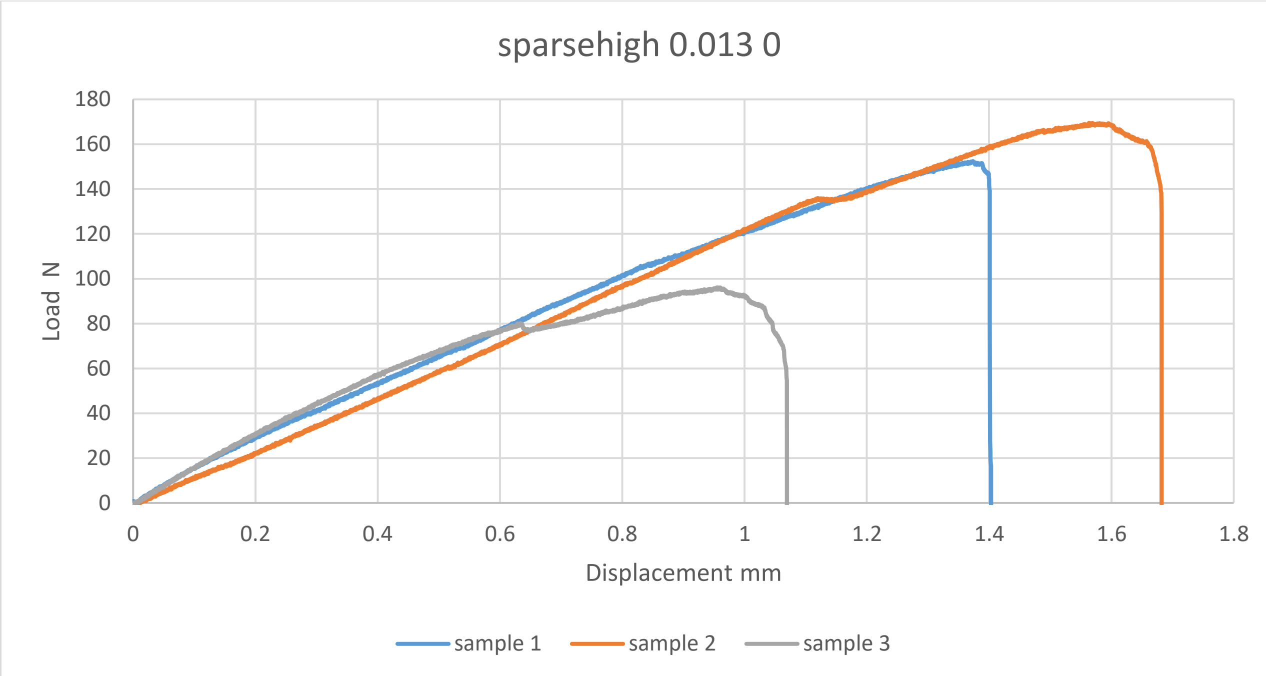
Figure describes Stress Strain curve of configuration. The Peak loads are 273.27 Kpa, 389.8 Kpa and 249.88 Kpa till the start of first failure. The Modulus of Elasticity values are 7036.88 Kpa, 5681.65 Kpa and 7266.35 Kpa till the start of first failure where the average is 6661.63 Kpa**.**



Stress strain curve for sparse high 0.010 90° configuration.

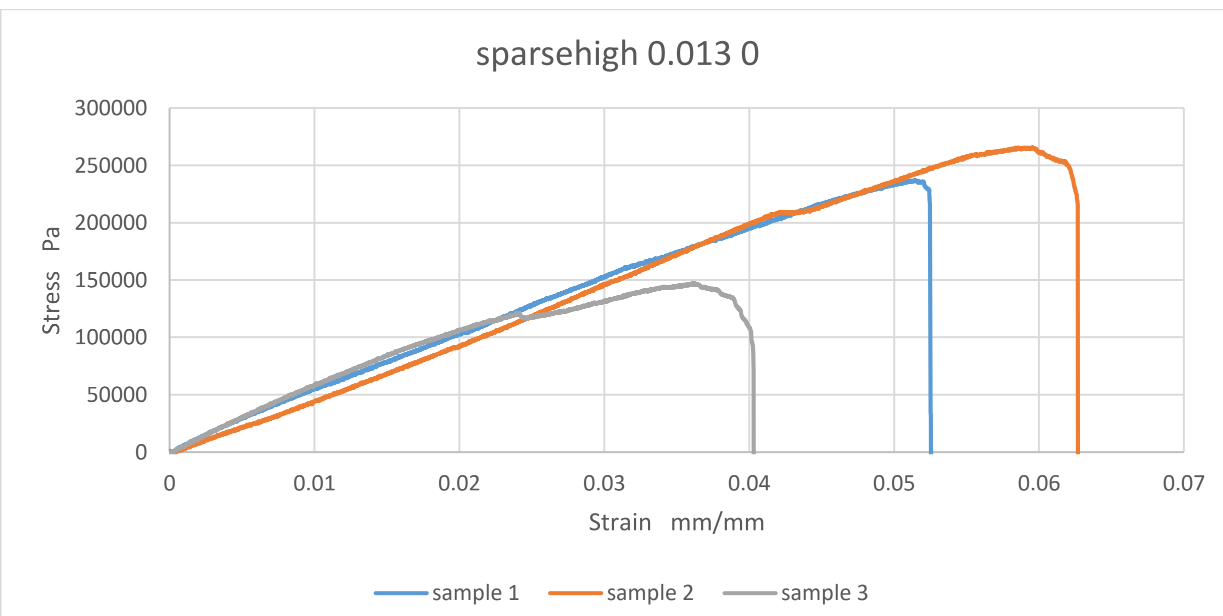
BCC printed with layer thickness 0.013, infill density sparse high and at an angle of 0° (Sparse high 0.013 0°)

Figure show Load displacement curve for the specimens, Three Specimens were plotted in one graph to show the uncertainty. The average weight of these specimens are 4.62 grams. First failure started approximately at 1.37 mm, 1.61 mm and 0.94 mm for specimens 1, 2 &3. SEA for the specimens are found to be 25.52 J/Kg, 16.51 J/Kg and 6.15 J/Kg till the start of first failure. The average SEA till start of first failure of the specimens is 67.63 J/Kg. The stiffness values are found to be 122.60 N/mm, 119.06 N/mm and 139.32 N/mm till the start of first failure. The average stiffness till the end of first failure is 126.99 N/mm.



Load Displacement curve for sparse high 0.013 0° configuration

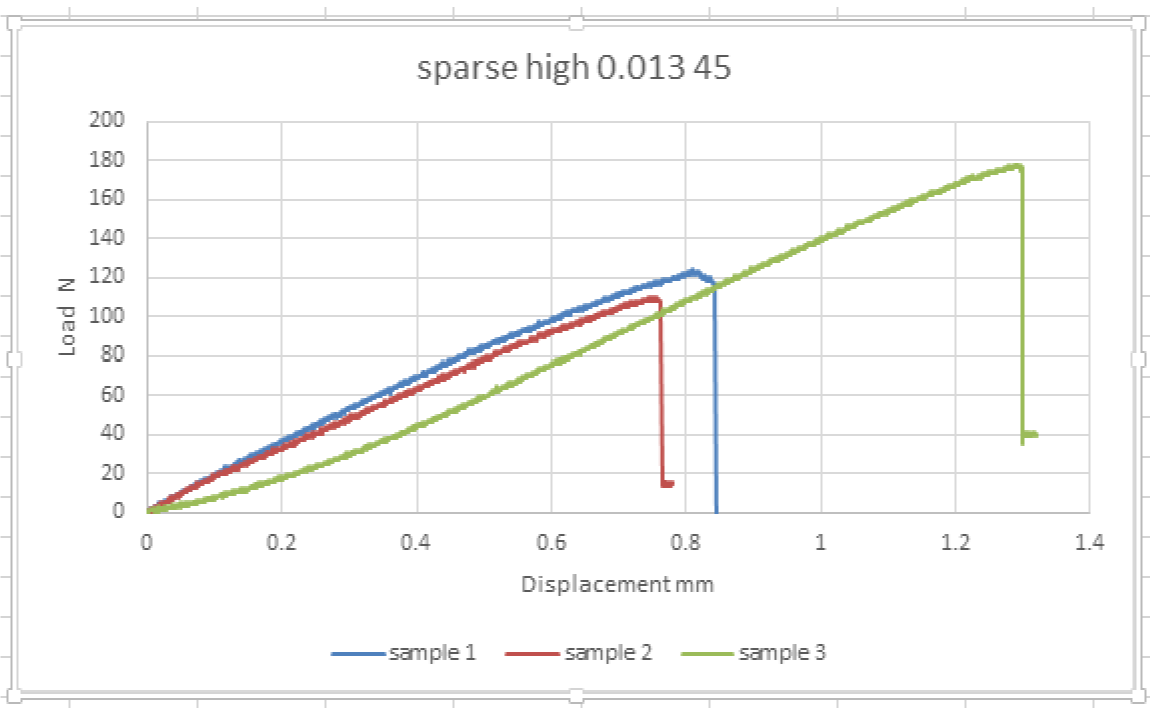
Figure describes Stress Strain curve of configuration. The Peak loads are 240.67 Kpa, 260.95 Kpa and 140.82 Kpa till the start of first failure. The Modulus of Elasticity values are 4966.07 Kpa, 5087.53 Kpa and 4536.94 Kpa till the start of first failure where the average is 4863.51 Kpa**.**



Stress Strain curve for Sparse high 0.013 0° configuration

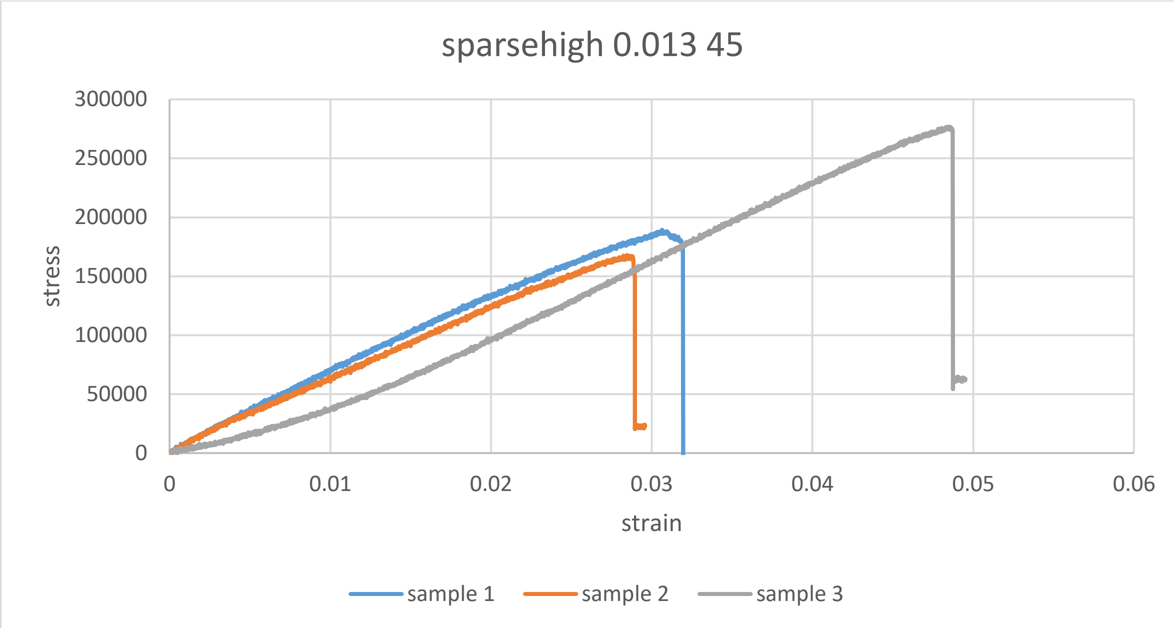
BCC printed with layer thickness 0.013, infill density sparse high and at an angle of 45° (Sparse high 0.013 45°)

Figure show Load displacement curve for the specimens, Three Specimens were plotted in one graph to show the uncertainty. The average weight of these specimens are 5.07 grams. First failure started approximately at 0.82 mm, 0.7 mm and 1.29 mm for specimens 1, 2 &3. SEA for the specimens are found to be 11.09 J/Kg, 8.89 J/Kg and 21.78 J/Kg till the start of first failure. The average SEA till start of first failure of the specimens is 13.92 J/Kg. The stiffness values are found to be 166.17 N/mm, 156.21 N/mm and 131.27 N/mm till the start of first failure. The average stiffness till the end of first failure is 151.22 N/mm.



Load Displacement curve for sparse high 0.013 45° configuration

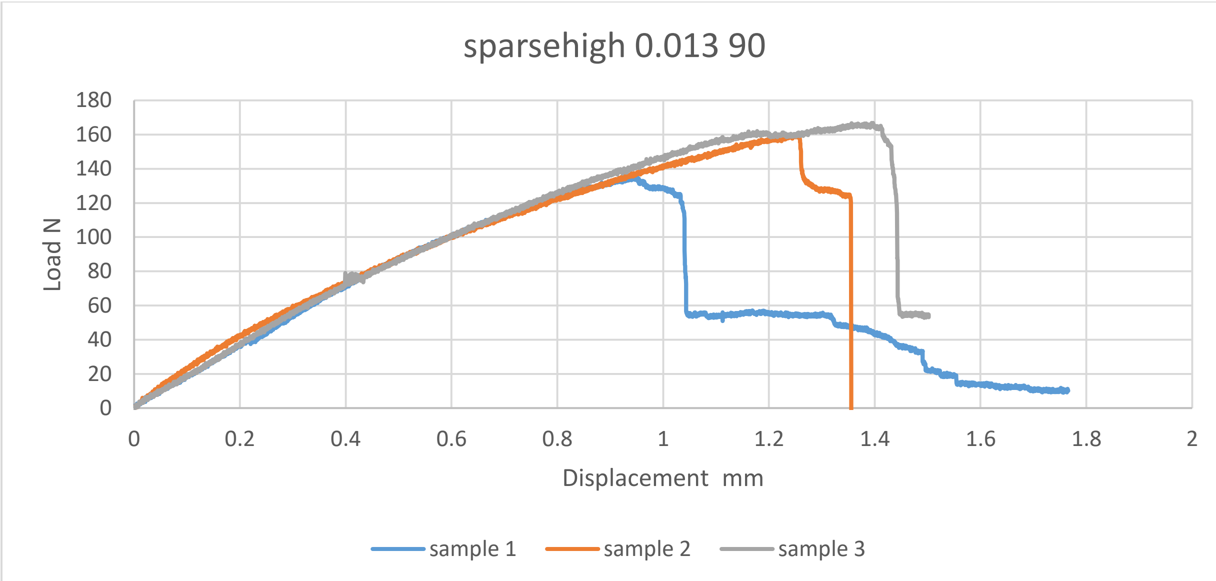
Figure describes Stress Strain curve of configuration. The Peak loads are 188.02 Kpa, 156.576 Kpa and 272.53 Kpa till the start of first failure. The Modulus of Elasticity values are 5633.18 Kpa, 5941.04 Kpa and 5308.09 Kpa till the start of first failure where the average is 5787.11 Kpa**.**



Stress strain curve for sparse high 0.013 45°

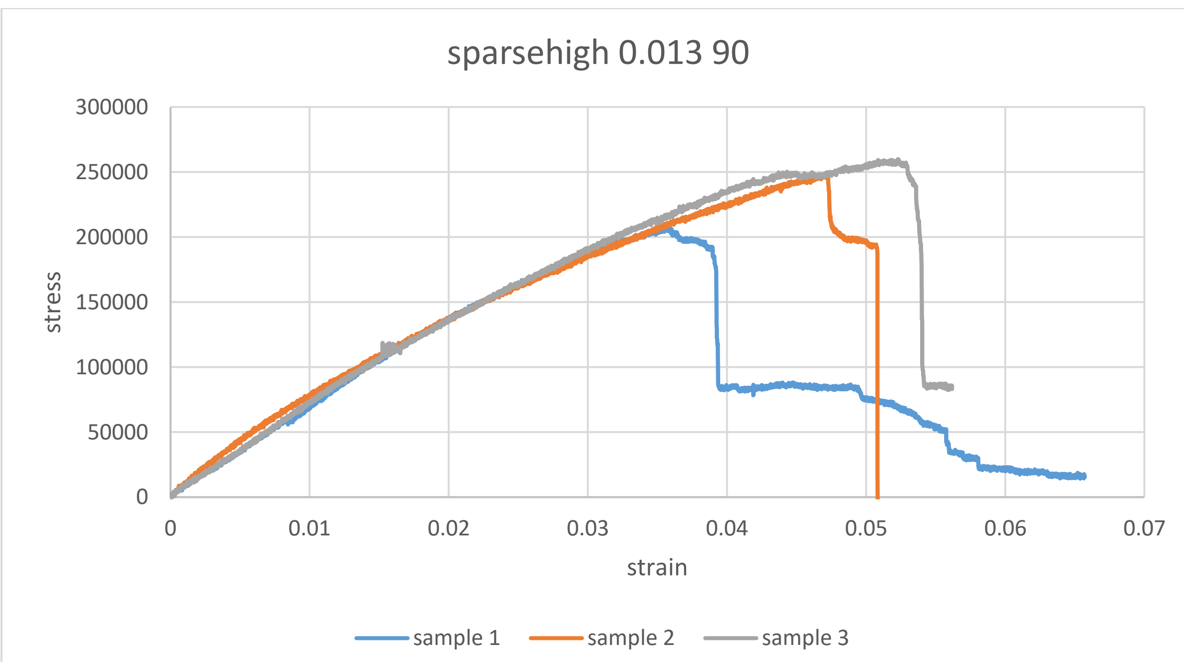
BCC printed with layer thickness 0.013, infill density sparse high and at an angle of 90° (Sparse high 0.013 90°)

Figure show Load displacement curve for the specimens, Three Specimens were plotted in one graph to show the uncertainty. The average weight of these specimens are 3.82 grams. First failure started approximately at 0.9 mm, 1.25 mm and 1.41 mm for specimens 1, 2 &3. SEA for the specimens are found to be 18.56 J/Kg, 31.79 J/Kg and 29.17 J/Kg till the start of first failure. The average SEA till start of first failure of the specimens is 26.50 J/Kg. The stiffness values are found to be 164.37 N/mm, 153.28 N/mm and 157.51 N/mm till the start of first failure. The average stiffness till the end of first failure is 158.39 N/mm.



Load Displacement curve for sparse high 0.013 90°

Figure describes Stress Strain curve of configuration. The Peak loads are 211.90 Kpa, 246.10 Kpa and 254.60 Kpa till the start of first failure. The Modulus of Elasticity values are 6508.2 Kpa, 6172.03 Kpa and 6339.92 Kpa till the start of first failure where the average is 6340.07 Kpa**.**



Stress Strain curve for sparse high 0.013 90° configuration